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Evaluation of the environmental impacts related to the wind farms end-of-life

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Abstract

In the last decades, the adoption of renewable energy, namely wind source, in Europe, have increased significantly. And it will continue to grow, as part of a strategy to reach the Paris Agreement and the Carbon-neutrality by 2050 goals.

Simultaneously, the oldest wind farms are getting into their end-of-life (EoL) and uncertainties regarding the main aspects of the possible scenarios still remain, such as standards procedures, legislation and environmental impacts (emissions, pollution, etc.). Regarding the waste management, 85% to 90% of all the components of the wind turbine may be recycled, however the final disposal of the blades represents a unique concern, as this process is not completely well-established. Thus, the environmental impacts and relevant aspects related to the wind project flow may be assessed using the life cycle assessment. Moreover, the environmental study of new projects is a good source to identify possible impacts. Thus, this research aims to identify and analyse the main environmental impacts related to the end-of-life of wind farms scenarios, based on the state of the art and a literature review. Moreover, it gives floor to the discussion regarding the uncertainties about this very important stage, the final disposal of wind farms' components emphasizing d the application of the principles of the circular economy.

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Keywords: Wind farms; End-of-life; Environmental impacts; Waste management

1. Introduction

The adoption of wind energy may be considered as an answer for current environmental concerns as climate change and other negative impacts as pollution [1]. According to the European Commission, the maximization of the deployment of renewables sources in the energy mix may achieve the reduction emission goals by 45% until 2030, according to the Paris Agreement, but also may ensure a transition towards a climate-neutral economy by 2050 [2].

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In this context, in 2020 was installed 14.7 GW of new wind capacity, representing 6% less than the capacity deployed in 2019 and 19% less than the pre-COVID prediction. Presently, the European wind capacity is 220 GW [2]. Moreover, for the horizon of 2021–2025 it is expected 105 GW of new wind farms to be installed, where over 70% will be onshore wind farms [2]. And, by 2050, it is predicted that approximately 5.5% of the world's electricity will be supplied by offshore wind farms [3]. In the other hand, ref. [4] stressed that 14.000 wind turbine blades will be decommissioned in Europe until 2025, which will generate 400.000 tons of blade waste between 2029 and 2033 [5]. Globally, 2.5 million tonnes of composite material are used in wind industry [4]. Additionally, by 2034, ref. [6] estimates a generation around the world of 225.000 ton of waste blade material and 100.000 ton in Europe per year. In this context, the waste generated and other environmental impacts due the end-of-life (EoL) of wind farms becomes a crucial issue, as the first wind farms are reaching this phase. In this framework, in Europe, between 2030 and 2040, approximately 20.000 offshore wind turbines will require an analysis of the end-of-life scenarios [7]: decommissioning, revamping or repowering [8].

This research aims using a literature review about the state of the art in order to identify and discuss the main environmental impacts of the wind farm life cycle, focusing on the possible end-of-life scenarios. Thus, the first part analyses the life cycle assessment and EoL aspects following by the discussion on the waste issues and the final part is dedicated to a qualitative evaluation of emissions and other possible environmental impacts of EoL, based on life cycle assessment (LCA) and environmental studies of new wind farms projects.

2. Literature review

2.1. Life cycle assessment and end-of-life

Wind energy is recognized a clean source, however, there are environmental impacts during the life cycle of wind projects, namely in manufacturing, transportation, installation, maintenance and, in more important terms, in the end-of-life [9].

Therefore, it is often used a widely disseminated methodology, the LCA, in order to identify and quantify the potential environmental impacts of a given product or process during its entire life cycle. Some authors [10–12] highlight that the LCA is one of the most effective techniques used to evaluate the environmental impacts through, not only the diagnosis of the energy and materials used, but also, of the waste and emissions. Most of the LCAs are performed considering the lifetime of the wind turbines as 20 years. In addition, the general boundaries applied include the following phases: production of raw materials and manufacturing of components, operational and maintenance, end-of-life (decommissioning and disposal or recycling of the turbine and other components), and the transportation [13].

In this context, ref. [1] emphasizes that the waste disposal of wind farms was not a relevant contributor to emissions, since the LCAs, in general, just consider that most of the wind farms materials will persist in situ or will be recycled.

However, general aspects associated with EoL, such as emissions and waste generated, are still not clear. Ref. [3] stressed, based on a review of 44 studies of wind power, that the EoL phase is partially explored or even omitted in the LCAs, and, therefore, the associated environmental impacts are not fully considered [3]. In addition, the lack of data and a guidance of good practices reduce the knowledge of the best strategies to be adopted to manage all the aspects about the EoL.

Given what has been said, the possible scenarios for EoL involve three alternative solutions. The first option is refurbishment, which implicates, in the replacement of certain components of the wind turbine, to preserve if viable, the tower, foundations and cables. In this scenario, the efficiency and energy generation of the existing project may be increased [8,14,15].

The second alternative is repowering, which involves the replacement of the older turbines by new ones with the latest advanced technologies [8,15], and exploring the same wind conditions of the original site, with a possibility to extend the lifetime to 40 or 50 years, instead of the time span of 20–25 years of the initial project [14].

The last option is the decommissioning, which means that the main components of the project will be partially or totally removed from the site. In fact, for ref. [14] the decommissioning may be described as the opposite phase of the project installation. In addition, is when the principle of "the polluter pays" may be applied and all the necessary measures should be implemented in order to guarantee that the site conditions will be, at least similar, as they were before the project [15]. However, as pointed out by refs. [14,15] the refurbishment or the repowering, in the end, will also require the deployment of the components.

2.2. Waste management

As described by ref. [16] most of the LCAs neglect the possibilities for recycling the components. In fact, the main concerns described by ref. [3] were: the current recycling technologies to treat the blades composite materials are not economically viable, the lack of inventory data for these technologies and the geographical variation of recycling rates. Furthermore, ref. [3] emphasizes the incertitude related to the EoL phase, namely the lifetime, the difficulty to foresee future markets and the technologies treatment.

Thus, as described by ref. [17], a regular wind turbine is composed of 89.1% steel, 5.8% fibreglass, 1.6% copper, 1.3% concrete (cement, water, aggregates, and steel reinforcement), 1.1% adhesives, 0.8% aluminium and 0.4% core materials. In this setting, for ref. [18], the recyclability rate of the wind turbines is 85% to 90%, as foundation, tower, components of the gearbox and generator may be recyclable or treated, as the recycling techniques are well-established [1]. In fact, materials as steel, copper, aluminium, and cast iron have recycling rates of 90% and non-recyclable waste (as concrete) is disposed in landfill [10].

However, the wind blades are significantly challenging due to the materials used in their manufacture [16] namely, the composite materials used to improve their performance and to become them lighter and longer [4]. According to ref. [12], the recycling/disposal rate of blades is up to 95%. In this context, ref. [1] stressed that the disposal of reinforced plastics in landfills is unacceptable, which lead to the creation of regulatory legislation as the progress of other waste treatment strategies start. For instance, disposal in landfill is becoming prohibited in some countries, such as in Germany [15]. Moreover, it is important to consider that some treatment procedures are not fully technically developed yet, and their impacts on environmental and human health are still unknown. For instance, to facilitate the transportation, blades are cut and this process may generate toxic emissions, additionally, the incineration of the blades may generate flue gas and ashes [1].

Besides the amount of composite waste produced by the wind industry is far less than other industries, the cement co-processing is the main commercial technique adopted to recycle the composite materials, which may result in a reduction up to 16% of the CO output, if the percentage of composites represent 75% of cement raw materials of the manufacturing process [4].

Although, more options for the treatment of composite materials, as solvolysis and pyrolysis, are available but require advances and industrialization [4,18]. Furthermore, the separation of the composite materials and polymer are complex, and involve high costs, environmental impacts and a lot of time spending to process [12].

In summary, some studies indicate that the recycling, at the end-of-life, may contribute to energy saving and to emissions reduction. Additionally, the recycled materials may replace or reduce the use of virgin materials in manufacturing [19]. Moreover, ref. [20] stressed that the possibilities at end of life may reduce the total global resource consumption (as steel and copper) and the unpredicted market variations, such as supply shortages for materials as rare earth magnets. Thus, the use of recycled materials may reduce the embodied energy and the CO_2 emissions, but also close the material cycles [20], turning into a more circular process.

2.3. Environmental impacts

As reported by ref. [10] the reviewed LCAs showed that 78% of the environmental impacts are concentrated in the manufacturing, and also during the installation phase.

Notably, the environmental impacts of the EoL had little importance until recently. However, it should be considered as an important stage and as part of the project, since the planning, due to the associated costs, complex logistic and the potential impacts to the environment and the society. As stated in ref. [19] the EoL should be evaluated as a reverse logistic process, analysing the supply chain challenges from the point of use back to a point of disposal (reuse, remanufacture, recycle or disposal).

Therefore, the environmental impacts, beyond the waste management, at the end of life, are critical and still undetermined if compared to the other stages of the life cycle. In this context, as stated in ref. [9] reviewed LCAs of offshore wind farms identified 21 environmental impacts in the life cycle. Most of the studies emphasize climate change as a considerable impact, which includes the emission of greenhouse gases (CO_2; CH_4; N2O GHG, SF_6, HFC and PFC).

The CO_2 overall emissions for a wind farm determined for China [11], indicate that the building construction respond for, approximately, 67%, of the total emissions, followed by manufacturing with 24%, and operation plus maintenance with 3%. As also addressed by ref. [11] in offshore wind farm's life-cycle the diesel consumption of vessel engines and material/equipment transportation represents more than 33.3% of NOx emissions, followed by embodied emissions of the manufacturing of foundation (24.91%) and wind turbines (19.15%).

In line with ref. [21] the impacts of components production, reflects this order: foundation (20%), nacelle (16%) and blades (10%). In this last case, the main pollutant sources are the manufacturing of epoxy resin (64.7%) and fibreglass (32.4%).

For ref. [1] the environmental impacts may be divided into the following categories: CO_2 emissions; climate change; cumulative energy demand; input requirements, abiotic depletion; acidification; stratospheric ozone depletion; human toxicity; particulate matter formation, dust; ecotoxicity; photochemical oxidation; nutrient enrichment, eutrophication; solid waste generation; land use, land transformation; human health endpoint; natural environment endpoint; natural resources endpoint; single score endpoint; non-toxic emissions; toxic emissions.

In the framework of the end of life, the dismantling scenario involves the partially or fully removal of the wind farm components', aboveground and sub-grade structures. Later, in case of onshore, are executed activities related to the recovery of the site, as re-vegetation; seeding; topsoil restoration, in addition, a period of monitoring and remediation [20].

Regarding offshore wind farms, ref. [7] pointed out the issues associated to the impacts to the marine environment due the removal of total or partial structures. In this setting, there are two ways to extract the foundations: (i) fully removal or (ii) cutting from a certain high leaving the rest in situ and do not disturb the site's activities [14]. As described by refs. [7,14], substructures of an offshore may create habitats, artificial reefs, for marine wildlife, such as fish or crustaceans and threatened species. Thus, these constructions may increase the attractiveness of overfished species and the production of fish biomass, acting as foraging sites for top-order predators, but also increase the diversity of benthic organisms and the quantity of commercially fishes [22]. Moreover, specialists consider that offshore installations may protect marine ecosystems from trawling [22].

In this context, compared with the full removal, the partial removal may be a better solution, as creates environmental and economic benefits. For ref. [22] removing the entire components, such as sea cables, will disturb the seabed, generate atmospheric emissions; produce noise effects to marine mammals; re-open areas for fishing and bottom trawling; re-suspend sediments; spread invasive species bet also reduce biological connectivity.

Thus, this removal requires more environmentally sustainable waste disposal. Type, size and weight of the turbine structure are parameters which will affect the selection of the vessel. Furthermore, ref. [14] stressed that the size of the piles, the depth into the seabed and its weight will influence the complexity of the removal process which may offer high risks to the employees and produce significant environmental impact as demand a deeper excavation, specialized equipment for longer periods and complex marine conditions. And the distance between the site and the facilities centres is also a relevant factor that influences the environmental impact of the onshore and offshore [10,23].

With respect to the repowering scenario, ref. [8] stressed the benefits of reusing the same site to explore the full wind condition with better equipment, avoiding the interference in other areas. Furthermore, as the number of wind turbine units in the site will diminish, it is expected a reduction of avian collision and mortality. In this context, the landscape is already changed and it has a better acceptance by the local community as less turbines implies an easier integration in the landscape, reducing the visual impacts. On the other hand, ref. [24] highlights the changing image of the landscape, which may affect areas undergoing a transition to tourist locations. Moreover, besides the economic advantages, the author also emphasizes the higher resistance in society for repowering compared to deployment, namely due to the visual impacts (even long distances) and their proximity from residential areas or forests [24], as the size of the new turbines will enlarge and increase the visibility aspect [25]. In addition, ref. [24] addressed the impacts associated to the road pattern and vegetation in this area and natural heritage are also stressed, at the same time as measures to protect the landscape from negative impacts are required.

Refs. [14,23] addressed that the decommissioning impacts resulting from construction phase, and may be consider likely to be similar to or less than the impacts verified during the construction. In this sense, ref. [23] identified 26 potential impacts from EoL activities, 5 just found in onshore, 16 only in offshore, and 5 relevant to both.

Moreover, ref. [23] highlights the importance of evaluating the impacts of EoL in the stage of environmental impacts assessment (EIA) and their temporality, and highlighted that disturbed environments or areas might not fully recover to its previous condition and the real influences of the wind farms in environment. As also stated by Hall et al. [23], the absence of a guide and experience and incertitude regarding what will happen and what procedures will be adopted at the EoL, lead to succinct and superficial environmental statements. Nevertheless, EIAs may provide more accurate information about the possible impacts, namely for the installation and operation stages. This data is the basis of the analysis of environmental agencies and the focus of control, prevention and mitigation measures. As the environmental licencing procedures of EoL are still not completely established and there is still a lack of experience in using it for this purpose, the EoL may be seen as the reverse process of the installation. In this context, based on EIAs of new onshore wind farms projects in Brazil, the following impacts for the installation phase were investigated: changes in the local landscape, quality of water and air, noise levels, interference in soils and increase in the production of sediments, development and/or acceleration of erosion processes, interferences with mining areas and natural drainage, reduction in botanical populations and availability of vegetal resources to local residents, enlarge environmental fragmentation and edge effect, loss of fauna specimens, change in the structure of faunistic communities, increase hunting pressure, creation of temporary workplaces, increase municipalities taxes payments, pressure on social infrastructure (as healthy system), interferences in the daily life of local residents, increased traffic and workers movement, interference in constructions and traditional populations [26]. Thus, these possible impacts should be considered, once they may occur during the EoL associated activities, as well as, specific impacts for each scenario of the EoL.

3. Conclusion

Wind energy is considered a "green" source, however, when its entire life cycle is analysed, as it should, including end-of-life options, relevant environmental impacts are observed, namely, emissions, waste generation and pollution. Based on LCAs, most of these impacts are concentrated on the manufacturing, due to the material consumption, namely steel for towers. Moreover, the extraction of raw materials, installation and decommissioning also involve considerable impacts. However, the possible EoL (namely decommissioning, refurbish and repowering) scenarios present a lack of knowledge and experience regarding the environmental aspects and impacts. But likewise, the waste management in the EoL, as the components may be recycled, treated or disposed in a landfill, and the contribution of each one in the total embodied energy, costs and socio-environmental impacts are uncertain. Regarding the environmental impacts, the EoL may be analysed as the reverse process of installation, and thus the knowledge of the impacts of their phase may be used as a base to understand and predict the potential impacts of possible scenarios, considering their particularities and the onshore and offshore wind farms characteristics. Thus, this research aimed to present a preliminary analysis of the environmental impacts at the end of life but also to stimulate a discussion regarding the sustainability of the process involved in energy projects. Therefore, for further research, the environmental impacts related to the end-of-life of wind farms may be more detailed for each considered scenario. Furthermore, the lack of environmental regulatory legislation and standardization for these scenarios should also be explored.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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