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Sustainable Development Goals as a Guide for Sustainability Evaluation of Wind Turbine Decommissioning Scenarios Applying an Integrated LCA and DEA Approach

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Abstract

A top priority for most countries and major organizations is to focus on actions to align with the 17 Sustainable Development Goals (SDGs) established by the United Nations in 2015. Today, the installed capacity of wind generation is steadily growing worldwide, while 34,000 wind turbines are 15 years or older. Furthermore, the number of decommissioned wind turbines is expected to increase significantly in the coming years. In this context, the evaluation of the waste management processes for wind turbine decommissioning in terms of sustainability is imperative. Wind turbine decommissioning options have to comply with SDGs linked to the safe disposal and/or recycling of energy production systems. This study aims to develop an indicator-oriented framework to evaluate the environmental, economic, and social impacts generated by different decommissioning scenarios of a wind turbine system to ensure it complies with these goals. Initially, a Life Cycle Assessment (LCA) is performed to generate values for indicators that are related to each decommissioning scenario. Next, those indicators that are directly related to selected SDGs are identified. The proposed methodology applies Data Envelopment Analysis (DEA) to assess the efficiency of alternative wind turbine decommissioning scenarios based on selected criteria. These criteria are directly related to the previously identified indicators satisfying specific SDGs. Alternative decommissioning scenarios are benchmarked using different sustainability criteria/indicators as DEA inputs/outputs and utilized to determine best practice-based decision-making strategies. The joint application of LCA and DEA could represent a methodological framework for sustainability assessment and benchmark definition of waste management alternatives.

Keywords

Sustainable development goals (SDGs), Wind turbine decommissioning, Life Cycle Assessment (LCA), Data Envelopment Analysis (DEA), and End-of-life (EoL) alternatives

1. Introduction

In 2000, United Nations (UN) declared the Millennium Development Goals (MDGs) to fight against poverty, hunger, and disease by the target date of 2015. MDGs were focused on meeting the needs of the world's poorest, to which rich countries were to add their solidarity and assistance through financial contribution and technology (Sachs, 2012). In 2015, Sustainable Development Goals (SDGs) succeeded MDGs as part of the UN's 2030 Agenda for Sustainable

Development (United Nations, 2015). The Sustainable Development Goals are given in Figure 1. In contrast to MDGs, SDGs refer to all the countries and they constitute an attempt of the world to avoid the exceedance of the planetary boundaries (Rockström et al., 2009; Sachs, 2012). The planetary boundaries are related to the era of the Anthropocene, a new era where humans shape every aspect of the biosphere and human activities are affecting the stability and resilience of the Earth system (Olsson et al., 2017). It is considered that the transgression of these thresholds would create substantial risk for abrupt, uncontrollable, and irreversible repercussions for humanity and the ecosystems (Steffen et al., 2015). SDGs were inspired by the concept of sustainability which could be broadly defined as the capacity to meet our own needs without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). The meeting of humanity's needs over the long term depends on the maintenance of the resources, which could be natural, social, or economic. This definition leads to the three-pillar concept of sustainability with its environmental, economic, and societal aspects (Purvis et al., 2019). According to the latest SDGs progress report, the 2030 Agenda for Sustainable Development is in grave peril due to the multiple, cascading, and intersecting crises of the COVID-19 pandemic, climate change, and the predominance of conflicts (United Nations, 2022). In this context, it is critical to evaluate the sustainability performance even of the technologies that are considered sustainable a priori.

Figure 1. The Sustainable Development Goals (SDGs) as presented in the United Nations 2030 Agenda for Sustainable Development

The wind energy industry is often considered sustainable by default. The wind is a primary energy generation source characterized as an everlasting and renewable resource, while it is considered to provide the ultimate energy independence because the fuel is free (Welch and Venkateswaran, 2009). Furthermore, electricity production from wind energy contributes considerably to reducing the overall emissions of the energy sector as it replaces electricity production from fossil fuels (Abrahamsen et al., 2021). Given this however, the sustainability of wind energy should be investigated by evaluating the externalities that are caused from a life cycle perspective.

The installed capacity of wind generation is steadily growing worldwide. According to the International Renewable Energy Agency, the rate of increase of the global installed capacity of Renewable Energy Sources (RES) reached the figure of 257 GW in 2021; with wind power share being 36.2%, i.e. 93 GW (International Renewable Energy Agency, 2022). The total installed wind-generation capacity has increased over 100 times from 7.5 GW in 1997 to 830 GW in 2021 (IEA, 2022). REPowerEU Plan, the European Union's (EU) strategy to reduce the dependence on imported fossil fuels and tackle the climate crisis, includes increasing the headline 2030 target for renewables to 45%, and wind energy is expected to have a significant share in this growth (European Commission, 2022).

In the year 2020, 34,000 wind turbines in Europe were already at least15 years old, representing 36 GW of onshore wind capacity. Out of the 36 GW, some 9 GW were 20-24 years old and around 1 GW were 25 years or older (Wind

Europe, 2020). Wind turbines are designed to have a lifetime of approximately 20-25 years (Dolan and Heath, 2012; Nijssen and Brøndsted, 2013; Wind Europe, 2020). Additionally, the rapid development of wind turbine technology creates the opportunity to increase the electricity output of operating wind parks by replacing old models with newer and more efficient ones (Breeze, 2016a). In this respect, the number of annual decommissioned wind turbines will increase significantly in the coming years. Therefore, identifying sustainable alternatives for the management of decommissioned wind turbines from a life cycle perspective is imperative.

2. Literature Review

Wind energy is frequently associated with SDG 7, i.e., to ensure access to affordable, reliable, sustainable, and modern energy for all, but if the production, installation, operation, and decommissioning phase of wind turbines were taken into account, it could be seen that it is also related to many other SDGs (Abrahamsen et al., 2021). In the literature, few studies investigate wind energy's sustainability performance (Kabir et al., 2022; Livzeniece et al., 2021; Msigwa et al., 2022; Wang et al., 2020; Wu et al., 2019). However, the decommissioning phase is not considered in any of them. Furthermore, it has been found that the end-of-life (EoL) phase of wind turbines is regularly excluded in many studies measuring the impact of wind energy. For instance, it is systematically not taken into account the life cycle assessments (LCA) of wind turbines. LCA is a well-established and widely used tool that assesses the energy consumption, emissions, and environmental impacts of products, processes, and services throughout the life cycle stages (Laso et al., 2018; Pehnt, 2006). Even though there are many studies applying LCA methodology to the wind industry and wind turbines, general aspects associated with end-of-life are still not clear, inconsistent, or nontransparent (Arvesen and Hertwich, 2012). Specifically, a review of 44 studies of wind power, concluded that the EoL phase is partially explored as most of the LCAs neglect the possibilities for recycling the components or even omitted in the LCAs, and therefore the associated environmental impacts are not fully considered (Mello et al., 2022). The decommissioning phase of wind turbines' life cycle is strongly related to SDG 12, i.e., to ensure sustainable consumption and production patterns. In this context, research efforts should be directed towards evaluating the sustainability performance of the EoL options for wind turbines.

The most popular wind turbine in the industry today is the three-bladed, upwind, horizontal-axis wind turbine (Breeze, 2016b). The main materials of a commercial wind turbine are steel, iron, copper, aluminum, and the composite materials found mainly in the blades, while the foundation consists of concrete and steel (Andersen et al., 2016). As a result, different waste material flows are needed to be analyzed for metals, concrete, and wind turbine blades. The recycling rate of the wind turbine itself (excluding the foundation) is estimated between 80% and 90% (Ortegon et al., 2013; WindEurope, 2020). In literature, the recyclability of the metals found in a typical wind turbine is assumed between 90-95% (Kouloumpis et al., 2020; Martínez et al., 2009; Schreiber et al., 2019; Tazi et al., 2019; Tremeac and Meunier, 2009; Zhong et al., 2011). Concerning the concrete of the foundation, it could be left in situ, disposed of in a landfill, or recovered after decommissioning (Beauson and Brøndsted, 2016). The technology for the recovery of concrete is well-established, accessible, and generally inexpensive (Wind Europe, 2020). Specifically, it is mainly recycled as a substitute for natural aggregates ensuring the safe end-of-life treatment of used concrete avoiding waste disposal in landfills, reducing the production of natural aggregates, and helping to maintain natural reserves (McNeil and Kang, 2013; Ohemeng and Ekolu, 2020).

Therefore, most of the material of the turbine after decommissioning can be appreciably recycled, although the composite materials found mainly in the blades, namely the glass fiber reinforced composites, represent a challenge (Beauson et al., 2022). It is forecasted that Europe's yearly total waste blade material in 2050 will reach 325,000 t (Lichtenegger et al., 2020). Currently, several options are available for managing composite material waste, while the mainly used waste management methods are landfill disposal and incineration (Krauklis et al., 2021). However, landfill disposal is expected to be banned or strictly reduced during the next years in the EU (van Oudheusden, 2019; WindEurope, 2020). Regarding incineration, several disadvantages have been reported as glass fibers are not combustible, they have a negative impact on the flue gas cleaning systems and an important amount of ashes is produced during the process (Beauson and Brøndsted, 2016).

In the literature, several recycling methods for the composite materials of the blades are proposed, which are divided into three categories: mechanical, thermal, and chemical. In mechanical recycling, blades are cut and shredded and then the shredded material can be used as filler, reinforcement, or raw material for the production of new plastics or cement (Baturkin et al., 2021; Paulsen and Enevoldsen, 2021; Yazdanbakhsh et al., 2018). The most widely applied thermal recycling methods for composites are pyrolysis, fluidized bed process, and microwave pyrolysis while the most common chemical recycling method is solvolysis (Mishnaevsky, 2021). Notwithstanding, the most efficient options are reuse and repurposing whereby blades are refurbished and reused as blades, and full or parts of them are utilized for different applications, respectively (Joustra et al., 2021; Nagle et al., 2020).

Currently, only a few studies are evaluating and comparing the EoL alternatives for wind turbines. Nagle et al. (Nagle et al., 2020) conducted a study to determine the least environmentally impactful disposal method for Irish blade waste by using LCA to compare three scenarios: Co-processing in cement kilns in Germany, co-processing in Ireland, and landfill in Ireland. Co-processing in Ireland is identified as the least impactful, due to the material substitution and the reduced transportation needs. The urgency to develop a policy that requires wind farm owners to set aside bonds to pay for more sustainable second-life options for blade waste is highlighted. Deeney et al. (Deeney et al., 2021) compare the relative sustainability of alternative ways to deal with wind turbine blades using dimensions of economic, social, and environmental sustainability resulting in ranking the alternatives in increasing order of sustainability as follows: landfill, incineration with heat recovery, co-processing, furniture making, and bridge fabrication.

The key objective of the aforementioned studies is to evaluate the performance of different EoL options for wind turbine blades concerning certain economic, social, and/or environmental dimensions. These studies are only focused on the comparison of EoL management of wind turbine blades. However, it is needed to explore the EoL alternatives for wind turbines in a more integrated approach including the EoL options for concrete found in the tower foundations, the main metals, and the composite materials found in the wind turbine blades. The present research work addresses the wind turbine decommissioning problem using a sustainability-oriented approach. The sustainability assessment is based on reliable indicators linked directly to the SDGs. The novelty of the proposed methodology is the joint use of LCA and DEA methodologies to perform the sustainability evaluation of different scenarios referring to different combinations of waste management options for the main materials of a typical wind turbine, considering the environmental and social impacts related to SDGs and the corresponding costs of each process. The application of the combined methodologies would identify the efficient and inefficient waste management methods in terms of sustainability, define targets for the inefficient options that could increase their overall sustainability, analyze the actions that should be taken to achieve such targets, and therefore propose specific measures to policymakers.

3. Methods

3.1. Sustainability indicators identification based on SDGs

The Sustainable Development Goals are a strategic framework for international organizations, multilateral agencies, governments, and corporates towards sustainability and a reference for the communication of the international sustainability agenda. The evaluation of sustainability for specific products, services, processes, or entities requires the identification of robust sustainability indicators that are strongly linked to the SDGs. Additionally, the proposed methodology considers the availability of data and the outcomes of specific methodologies, such as LCA. In this context, the proposed indicators for the application of the joint LCA and DEA methodology, the methods/sources for the estimation of their corresponding values, and their link with the SDGs are given in Table 1. The relation of each indicator to SDGs is based on the literature (Backes and Traverso, 2022; Maier et al., 2016; Wulf et al., 2018) and the authors' own analytical judgement and consideration.

Table 1. Sustainability indicators, methods/sources for their estimation, and their link with the SDGs for the proposed sustainability evaluation methodology for wind turbine decommissioning

Sustainability Indicators	**Sustainability Pillar**	**Source/Methods**	**SDGs**
Ecosystem quality	Environmental	LCA outcomes	1, 2, 3, 4, 5, 6, 8, 11, 12, 13, 14, 15
Climate change	Environmental	LCA outcomes	1, 2, 3, 4, 5, 6, 8, 10, 11, 12, 13, 15
Resources	Environmental	LCA outcomes	1, 2, 3, 4, 5, 6, 7, 11, 12, 13
Total cost	Economic	Primary data from the literature & calculations	8, 9
Human health	Societal	LCA outcomes	1, 2, 3, 4, 5, 8, 11, 12
Employment	Societal	Statistical services and Literature	1, 2, 3, 4, 5, 7, 8, 10

Average Salary	Societal	Statistical services and Literature	1, 2, 3, 4, 5, 7, 8, 10

3.2. Joint application of Life Cycle Assessment (LCA) and Data Envelopment Analysis (DEA)

Life Cycle Assessment is conducted to estimate the environmental impacts of the different EoL management alternatives for the materials found in a typical wind turbine. LCA is a robust technique used to evaluate the possible energy and environmental impacts associated with a product, a process, or a system throughout its life cycle making it a suitable method for sustainability evaluation frameworks. LCA is carried out following the relevant guidelines and modeling frameworks in accordance with ISO International Standards 14040 and 14044 (ISO, 2006). The Life Cycle Impact Assessment methodology IMPACT 2002+ is proposed to be employed to estimate the environmental impacts of the different decommissioning options. IMPACT 2002+ corresponds to a combined mid-point/damage-oriented method that links the LCI results throughout 14 mid-point categories to 4 damage categories: human health, ecosystem quality, climate change, and resources (Olivier et al., 2003).

Next DEA is applied in order to evaluate the sustainability performance of the decommissioning alternatives. DEA is a well-established multi-criteria method that employs mathematical programming techniques to evaluate the efficiency of multiple similar entities, modeled as homogeneous decision-making units (DMUs) with several inputs and outputs. Efficiency is defined as the ratio of the weighted sum of outputs to the weighted sum of inputs (Sofianopoulou, 2006). DEA approaches present several advantages concerning other multi-criteria techniques. Specifically, DEA methods do not require a mathematical formulation of the production function and they can handle multiple inputs and outputs without requiring the identification of any type of relation between inputs and outputs or any specific statistical distributions for the data of their variables (Tsaples and Papathanasiou, 2021). Additionally, the sources of inefficiency can be identified and quantified for every evaluated entity (Zhu, 2014). In the proposed methodology, DEA employs a linear programming model to identify the relationships between efficiency scores and the economic, environmental, and societal indicators in order to (i) identify the most efficient/sustainable EoL options and (ii) define targets for the inefficient ones to transform them into efficient/sustainable options.

For the proposed methodology, one of the most basic DEA models, known as the CCR model, could be applied (Charnes et al., 1978). Given that there are n DMUs and associated numerical data for each of the m inputs and s outputs for all DMUs, the mathematical programming problem that is solved to obtain values for the input weight (v_i) (i = 1,…,m) and the output weight (u_r) (r = 1,…,s) variables is the following (Cooper et al., 1999):

$$\max z = \frac{\sum_{r=1}^{s} u_r y_{rj_0}}{\sum_{i=1}^{m} v_i x_{ijo}} \tag{1}$$

subject to

$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1 \quad (j = 1,\ldots, n) \tag{2}$$

$$u_r \geq 0 \text{ , } (r = 1,..., s) \tag{3}$$

$$v_i \geq 0 \text{ , } (i = 1,..., m) \tag{4}$$

Where x_{ij} and y_{rj} correspond to the input and output parameter values for the j^{th} DMU, respectively. Index j_0 refers to the DMU being evaluated. The objective function (1) maximizes the ratio of virtual output to virtual input of the DMU under evaluation by calculating the appropriate weights v_i and u_r. Constraints (2) ensure that this ratio does not exceed 1 for every DMU. As a result, the objective function value lies between 0.0 and 1.0; the latter value denoting that the DMU under examination is efficient. The above non-linear program is linearized, and the solution of its linear equivalent produces the efficiency scores for all DMUs.

The joint application of LCA and DEA mitigates the intrinsic disadvantages and/or limitations of the methods and it could aggregate economic, environmental, and social indicators with different units, thus proving suitable for use in the sustainability context (Tsaples and Papathanasiou, 2021). LCA and DEA methodologies are jointly applied mainly to case studies belonging to the primary sector for the evaluation of operational and environmental efficiency, while only a few research works focus on the application to new fields (e.g., energy) and the methodological development towards sustainability assessment (Martín-Gamboa et al., 2017). In the literature, a few studies are implementing the combined LCA and DEA methodology to tackle the problem of sustainability performance evaluation in several sectors, in particular, in energy systems (Martín-Gamboa et al., 2017), transport (Yang et al., 2021), management and services (Álvarez-Rodríguez et al., 2019a, 2019b; Yang et al., 2022), public policy (Cristóbal et al., 2021), and biofuels (Cabrera-Jiménez et al., 2022). To the authors' knowledge, it is the first time that the joint application of LCA and DEA techniques is proposed for the sustainability assessment of wind turbine decommissioning alternatives using sustainability indicators directly linked to SDGs.

4. Results and Discussion

The proposed sustainability framework is based on the indicators linked to SDGs that are presented in Table **1**. The indicators of Ecosystem quality, Climate change, Resources, and Human health are estimated by conducting an extensive LCA analysis for specific scenarios standing for the different EoL alternatives for the main materials found in a typical wind turbine, namely, steel, iron, copper, aluminum, concrete, and composite materials. Next, reliable data about employment and the average salary for each waste management option should be gathered from statistical services and the literature. Furthermore, the overall cost, comprised of the process cost and the fuel cost for transportation needs for each scenario is calculated. Next, DEA is carried out by applying the model presented in Section 3.2 and using the aforementioned indicators as inputs and outputs.

The results of the joint application of LCA and DEA would allow us to (i) evaluate the efficiency of the waste management alternatives, (ii) identify the efficient/sustainable EoL options, (iii) define targets and benchmarks for the inefficient ones to make them efficient/sustainable, and (iv) translate the targets for inefficient EoL alternatives to proposals for public strategies and policy measures towards sustainability.

5. Conclusion

The present work proposes the joint application of LCA and DEA methodologies in order to evaluate the sustainability performance of waste management alternatives of the main materials found in a typical decommissioned wind turbine in an integrated approach, considering the environmental, economic, and societal aspects of the problem. Results of the proposed methodology are expected to provide useful information to decision-makers and policymakers for developing appropriate sustainability-oriented, energy and environmental policies and measures that could encourage the implementation of valuable waste management alternatives. Furthermore, the joint application of LCA and DEA could establish a methodological framework for integrated, multi-aspect sustainability assessment and benchmark for wind turbine decommissioning, and in a more general scope for the sustainability evaluation of waste management alternatives.

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