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A new model for environmental and economic evaluation of renewable energy systems: The case of wind turbines

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HIGHLIGHTS

- We propose a model to join environmental and economic viability for wind turbines.
- Economic viability can be joint to the environmental one through carbon footprint.
- Configurations that appears economical viable may have high environmental impacts.
- *Carbon fibre* has lower emissions and shorter pay-back as regards to *glass fibre*.
- Changing the number of wind turbines does may worsen the joint evaluation.

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ABSTRACT

Both scientific community and political institutions frequently stress the crucial role of energy and renewable energy systems as a key asset for global sustainable future development. Wind energy is a relevant renewable source due to its high conversion performances, achieved particularly by large scale plants. Nevertheless, the production processes, rather than the installation one, may entail relevant energy consumption, as well as the release of CO_2 and other pollutants.

This study develops a model for concurrent environmental and economic viability of wind turbines under the framework of Life Cycle Assessment. A case study is developed to evaluate a set of different project alternatives for three types of wind turbines, for which different scenarios are analysed through a dedicated assessment tool. The research highlights the manufacturing phase of wind turbines as crucial in finding the concurrent economic and environmental feasibility.

1. Introduction

Nowadays, renewable energies are gaining more attraction in global energy market and in society. In recent years, these energy sources have become a concrete alternative to reduce the dependence on fossil fuels, giving both environmental and economic benefits [1,2]. Among renewables sources, while big wind power plants have reached a relative maturity, medium wind turbines (MWTs) still needs to be investigated, especially under profitability and environmental perspective. The recent literature shows a number of studies about the economic feasibility of MWTs [3]. Yet, a viability analysis as a stand-alone process may not be adequate for understanding the effective viability of this type of renewables.

Thus, to pursue a correct evaluation, the analysis should include both environmental and economic aspects. This may be especially true for small firms, for which offering a solution with low environmental impact that may not be feasible under the economic point of view could let them incur in financial problems [4].

Furthermore, although renewable energy sources are presented as clean energy systems, i.e. having zero environmental impact, this assertion is true only if we do not consider the release of pollutants in manufacturing and logistic processes [4–7].

The present study is intended to develop a model to join the environmental and economic evaluation of wind power plants under the framework of Life Cycle Assessment (LCA). The model developed is applied to evaluate a set of different project alternatives for three types of MWT, with a nameplate power of 600 kW. Since the analysis is carried out to evaluate wind turbines in Italy, the set of geographical factors influencing the results have been assumed accordingly [3].

The remainder of the paper is as follows. Section 2 presents a review of the recent literature. Section 3 gives the research objectives and framework, while in Section 4 the LCA analysis for wind turbines is developed.

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Section 5 outlines the evaluation of the economic drivers. Section 6 develops the proposed analysis and the case study. Then, after the discussion of Section 7, Section 8 ends the paper, drawing the final remarks.

2. Literature review

2.1. Renewable energy systems and wind turbines

Electricity generation produces a relevant amount of greenhouse gas (GHG) emissions [8–10].

Because nowadays the main sources for electricity production are based on fossil fuels, GHG emission is expected to increase in the next future. In addition, politic institutions frequently stress the crucial role of minimizing emissions because it involves many consequences on ecosystems [2,11]. Therefore, renewable energy sources are gaining more attraction. Among them, wind power has experienced a rapid growth worldwide over the last two decades and it is expected to grow even faster in future [8,12].

With reference to the European Wind Energy Association, in 2012 Italy was the third EU Country in terms of annual installations with 1273 MW produced [12]. In addition, the improvement over time of wind turbines manufacturing, and the reduced maintenance and operation requirements is pushing towards the development of large scale and more efficient machines [13]. The extant literature shows a relevant interest on this topic by a number of authors. To cite a few, Ahmed and Cameron [14] presented a review of wind power technologies, highlighting the trends of industry and the challenges that these technologies will face. Katsigiannis and Stavrakakis [15] examined a comparative technical and economic assessment of different wind turbine classes in Australia to estimate the best design for wind turbines. Fadai [16] investigated the feasibility of manufacturing wind turbines in Iran. To sum up, over the past 2 decades wind energy sector experienced a huge growth not only in terms of market share, but also in terms of technological developments [13].

The use of wind turbines (WTs) for electricity generation achieved its maturity and experienced the greatest growth worldwide in the 90s. The increasing trend of WT installations was also connected to significant legal incentives adopted by several countries. Nowadays, in most of these countries wind power is becoming a concrete competitor of the traditional fossil fuels [3,17].

WTs can be of two different types. The vertical axis wind turbine (VAWT) and the horizontal axis wind turbine (HAVT). The first ones have fixed blade and are controlled for tilt or yaw, while the second ones are often armed with control systems for pitch control [18]. In addition, the variation of wind direction has no negative effects for VAWTs because they do not need to be oriented against wind direction [19].

Under economic perspective, Small and Medium WTs need larger initial investments compared to their size, and they are less cost-effective compared to large turbine plants due to the fact that all the components of the system have lower costs [3].

Regarding the economic feasibility, many researches have worked to provide a reference for the decision making phase. An early approach for economic and energy evaluation can be the one of Costanza [20] regarding the embodied energy for good production joint with an economic evaluation.

Mohammadi and Mostafaeipour [21] evaluated the economic profitability of small wind turbines in Iran. Stockton [22] studied the economic feasibility of a wind power plant in the Hawaiian Islands, while Li et al. [23] addressed their study to the economic feasibility of micro-wind turbines for domestic applications in Ireland. These results show how these systems look promising if installed in places with relatively high wind speed (e.g. higher than 6 m/s). On this line, Kabir et al. [8] proposed a comparative life cycle energy, emission, and economic analysis of wind power generation in Canada. This comparison was done considering life cycle energy, environmental and economic aspects.

Another notably work is proposed by Ayodele et al. [24]. These authors present an economic analysis of wind turbines with different powers considering six geographical zone of Nigeria. As regards to MWTs, other works were related to energy production and carbon emissions, like the one of Rankine et al. [25] or sensitivity analysis in LCA [26,27].

3. Research objectives and framework

3.1. Research questions

Wind farms are usually optimised under economic criteria, in terms of fast payback periods or high net present values [3]. In this context, a joint optimisation regarding the economic and environmental impacts of a wind farm still needs to be explored. Instead of further exploring the *Triple Bottom line* approach in the field of wind renewable energy industry [28–30], we developed a user-friendly framework to aid practitioners and potential stakeholders (e.g. Municipalities) deciding on WTs projects over a life-cycle perspective that joins economic and environmental aspects.

This paper provides a comparative analysis between the environmental and economic impact of different MWTs. The research methodology resulted in a framework that may drive companies in selecting the best technical alternatives by addressing both economic and environmental issues.

Based on the literature reviewed, the first research question (RQ_1) investigates the problem on how it is possible to consider simultaneously both the impact that each turbine may cause to the environment and its economic viability.

RQ_1: Is it possible to conduct a joint evaluation of the economic and environmental impacts based on LCA

The objective of RQ_1 is to understand how the environmental assessment can be combined with the economic viability of wind farms. The correct evaluation of more than one alternative can be hard to achieve if the firm does not have an efficient evaluation method that includes both environmental and economic aspects.

Then, the problem of comparing different project alternatives is addressed by the second research question (RQ_2).

RQ_2: How technical choices may impact on the global evaluation?

Based on the evaluation method developed in the first part of the work, this portion of research is aimed to understand how different technical choices, like materials and/or plants' size, can impact both under environmental and economic perspective.

3.2. Research framework and methodology

Fig. 1 shows the research methodology adopted in this study. The research framework uses the LCA analysis to provide information about the environmental drivers and the related impact. Then, the economic analysis is assessed with the Pay Back Period (PBP).

Based on this framework, we may summarize this study with the following main steps:

– *Develop the LCA of wind turbines*
  In this step we identify which are the most relevant environmental criteria concerning the adoption of green practices. The LCA is aimed to (i) locate those components or sub-processes responsible of the highest environmental impacts, (ii) find suitable environmental indicators to quantify the envi-