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GHG emissions and energy performance of offshore wind power

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ABSTRACT

This paper presents specific life cycle GHG emissions from wind power generation from six different 5 MW offshore wind turbine conceptual designs. In addition, the energy performance, expressed by the energy indicators Energy Payback Ratio (EPR) Energy Payback Time (EPT), is calculated for each of the concepts.

There are currently few LCA studies in existence which analyse offshore wind turbines with rated power as great as 5 MW. The results, therefore, give valuable additional environmental information concerning large offshore wind power. The resulting GHG emissions vary between 18 and 31.4 g CO_2-equivalents per kWh while the energy performance, assessed as EPR and EPT, varies between 7.5 and 12.9, and 1.6 and 2.7 years, respectively. The relatively large ranges in GHG emissions and energy performance are chiefly the result of the differing steel masses required for the analysed platforms. One major conclusion from this study is that specific platform/foundation steel masses are important for the overall GHG emissions relating to offshore wind power. Other parameters of importance when comparing the environmental performance of offshore wind concepts are the lifetime of the turbines, wind conditions, distance to shore, and installation and decommissioning activities.

Even though the GHG emissions from wind power vary to a relatively large degree, wind power can fully compete with other low GHG emission electricity technologies, such as nuclear, photovoltaic and hydro power.

1. Introduction

All electricity generation technologies consume energy and emit greenhouse gases (GHGs) to a greater or lesser degree. When assessing the environmental performance of electricity generation it is important to take a Life Cycle Assessment (LCA) approach. This enables assessment of both the investment and the operating impacts relating to the generation process, and means that the entire life cycle of the investigated power plant, including upstream and downstream processes, should be taken into consideration. Upstream processes include, for example, mining and transport activities relating to the extraction of fuel, as well as extracting and processing activities relating to the materials used for building the power plant. Typical downstream processes include activities related to building and operating the grid, as well as the management of waste from the power generation processes. For most renewable electricity technologies and nuclear power, upstream and downstream GHG emissions account for over 90% of the cumulative GHG emissions. For conventional fossil fuel technology, however, the upstream GHG emissions also impact on the total picture, as they can represent up to 25% of the direct emissions from the power generation [1].

According to the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [2], wind energy offers significant potential for the reduction of near-term (2020) and long-term (2050) greenhouse gas (GHG) emissions. This is achieved by generating electricity from larger, grid-connected wind farms, deployed either on- or offshore. At the end of 2009, the total installed wind power capacity of 160 GW, of which 2.1 GW comprised offshore capacity, was capable of meeting roughly 1.8% of worldwide electricity demand. This contribution could increase to about 20% by 2050 if ambitious efforts were made to reduce GHG emissions and to address the other limiting factors for large-scale wind energy development [2].

Wind turbines with a rated power of 5–6 MW are now being designed and installed, mostly for offshore operation [3]. There seem, however, to be few available studies concerning the environmental assessment of these ratings in relation to offshore turbines. Weinzettel et al. [4] have analysed the environmental performance of a floating 5 MW offshore wind turbine (Sway

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concept), and Tveten [5] has analysed wind power generation based on 5 MW offshore turbines in Scandinavia. Schleisner [6], Voorspools et al. [7], DONG Energy [8], Jungbluth et al. [9], Bauer et al. [10], Chataignere and Le Boult [11] and Vestas ([12] and [13]) have all assessed offshore wind power LCAs with turbine ratings from 0.5 MW to 3 MW. In the case of onshore wind power, however, there are several existing studies [14–21].

The aim of this paper is to present LCA GHG emissions and energy performance of six different offshore 5 MW wind power conceptual designs. The paper focuses on exploring the variations of the concepts rather than making a detailed ranking of the various different concepts. In addition, comparisons with relevant wind power LCA data are presented. The work has been carried out as a part of the research project Energy Trading & Environment 2020 [22].

The paper is organised as follows: Section 2 gives a short presentation of the Life Cycle Assessment methodology and the investigated energy indicators. Section 3 describes the offshore conceptual designs which have been investigated, while the resulting GHG emissions and energy performance are presented in Section 4. The results are compared with relevant literature data in Section 5, while Section 6 presents the conclusions.

2. Life Cycle Assessment (LCA) methodology

Life Cycle Assessment (LCA) represents a structured, comprehensive and internationally standardised (ISO 14044:2006 [23]) method for quantifying environmental and health impacts, resources consumed and resource depletion associated with any goods or services. In accordance with the International Reference Life Cycle Data System (ILCD) Handbook [24], Life Cycle Thinking and LCA create the scientific approaches behind modern environmental policies and business decision support relating to sustainable production and consumption.

Every electricity technology has an outage probability, whether it consists of a system of geographically dispersed wind farms, a hydro power station with a reservoir, or a fossil-fuelled power plant. The effect of adding new capacity can be quantified by the capacity credit. This is the capacity of conventional plants displaced by the new capacity, with an unchanged probability of failure to meet the reliability criteria of the system [25]. With high penetration levels of renewable energy, the capacity credit of different technologies such as wind energy, solar energy and bio energy could differ significantly. These differences have been ignored in this study. This simplification does not affect the comparison between the various different offshore wind turbine conceptual designs, but should be taken into account when comparing wind, solar and conventional energy technologies.

2.1. Analysed environmental indicators

This paper presents the environmental indicators GHG emissions and energy performance related to wind power generation. The GHG emissions have been calculated as Global Warming Potential (GWP), presented as g CO_2-equivalents. With regard to energy performance, two of the most common energy indictors for renewable electricity generation have been calculated: Energy Payback Ratio (EPR) and Energy Payback Time (EPT). A short description of these indicators is given below.

Energy Payback Ratio (*EPR*) expresses the amount of delivered energy during the power plant's lifetime, per energy unit invested in infrastructure and extraction/transport processes. It should be noted that the literature uses various different expressions for the EPR indicator. Examples of these are 'energy ratio', 'external energy ratio' and 'energy return on investment (EROI)', all of which refer to the same basic calculation as EPR [26]. In accordance with Hall [27], the EPR indicator refers to the amount of energy returned from one unit of energy invested in an energy-producing activity. A high EPR value means high energy efficiency. It should be mentioned that the energy being included in the fuel which represents the energy source (such as coal or gas) for thermal power plants is not included as invested energy in EPR calculations. This makes comparisons difficult between thermal and non-thermal electricity technologies due to the relatively high losses in the electricity conversion step for thermal power generation.

Energy Payback Time (*EPT*) expresses the amount of time in months or years, taken to "pay back" the energy invested in infrastructure and extraction/transport processes. A low EPT value means high energy efficiency. As in calculations for EPR, the energy being included in the fuel which represents the energy source is not included as invested energy in the calculation of EPT.

EPR represents a good energy indicator for assessing whether a wind turbine actually produces more energy than it consumes during its life cycle. EPT, on the other hand, measures the amount of electricity-producing months or years, which are required in order to pay back the energy invested in the wind power plant. It should be emphasised that EPR is dependent on the lifetime assumed for the power plant while EPT is independent of this parameter. The relationship between the parameters is expressed using the following equation:

$$\mathrm{EPR} = \mathrm{Lifetime}/\mathrm{EPT} \quad (1)$$

Raadal et al. [28] present a detailed investigation and discussion of different energy indicators for electricity generation.

3. The investigated offshore wind power concepts

Table 1 shows the analysed six offshore wind turbine concepts, comprising five floating and one bottom-fixed.

All concepts use the NREL 5 MW offshore reference wind turbine Rotor-Nacelle-Assembly (RNA), based on Jonkman et al. [33]. The hub height is 90 m and the rotor diameter is 126 m. The water depth is 200 m for the floating concepts and 50 m for the bottom-fixed concept. The wind farm (bottom-fixed or floating) is assumed to be located 200 km off the British Coast, at Doggerbank (independent of the real water depth), and consists of 100 wind turbines installed in a square layout (10*10 turbines). Fig. 1 illustrates the different concepts.

The Sway Tension-Leg Spar (TLS) is a single spar with excess buoyancy, one vertical tendon and a downwind turbine. The tower structure utilises external axial stiffening rods. More information can be found in Ref. [29].

The UMaine Semi-Submersible concept was developed in the DeepCwind project at the University of Maine. The concept consists

Table 1
Overview of the analysed concepts.

Concept	Name	General description	Reference
Floating	SWAY	Tension-Leg-Spar (TLS) similar to the SWAY concept	Borgen [29]
	UMaine Semi-S	UMaine Semi-Submersible	Robertson and Jonkman [30]
	UMaine Spar	UMaine Spar-Buoy (same as OC3-Hywind, at water depth of 200 m)	
	UMaine TLP	Tension-Leg-Platform with vertical tendons	
	MIT TLB	MIT Tension-Leg-Buoy (TLB),	Sclavounos et al. [31]
Bottom-fixed	OC4 Jacket	IEA OC4 Jacket	Vorpahl et al. [32]