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Carbon brainprint case study

Novel offshore vertical axis wind turbines

CARBON BRAINPRINT

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Novel offshore vertical axis wind turbines

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Contents

Summary

As part of the transition to a ‘low carbon economy’, renewable technologies are expected to play an increasing role in reducing dependence on fossil fuels for energy and electricity. Wind power in particular is likely to become a much larger contributor to the UK’s energy mix. The current dominant design for large, grid-connected wind turbines is a three blade rotor with a horizontal rotating axis. The concept of a vertical axis wind turbine (VAWT) is relatively new, but has several advantages over horizontal axis alternatives. It is able to capture the wind from any direction, and the vertical axis is such that the rotor equipment is located at base level, making it is simpler and less costly to install and maintain.

The Energy Technologies Institute (ETI) is a UK-based company formed from global industries and the UK government. One of three projects looking at new turbine design and concepts for offshore wind is the Novel Offshore Vertical Axis (NOVA) project, a UK-based consortium launched in January 2009 to look at the feasibility of a NOVA turbine.

This case study considered the potential reduction in greenhouse gases (GHGs) that could be achieved through the installation of NOVA wind turbines, in comparison to conventional horizontal axis wind turbines (HAWTs) for offshore power generation. The increased power rating of the NOVA turbines compared to current HAWTs is expected to provide considerable reductions in lifetime greenhouse gas emissions. It compared the emissions from 1 GW installations over 20 years, based on a life cycle analysis of construction, operation and disposal. The comparison used the popular Vestas V90 3 MW model and the proposed NOVA 10 MW units.

The estimated lifetime emissions were 521 kt CO_2e for the conventional design and 419 kt CO_2e for NOVA. Using budget share to attribute the reductions to the project partners, Cranfield’s brainprint was 34 kt CO_2e.

As there are no current NOVA units in operation, there were high uncertainties associated with the estimates. A Monte-Carlo simulation resulted in a mean difference in emissions between the two installations of 102 kt CO_2e, with a standard deviation of 108.

General description

As part of the transition to a 'low carbon economy', renewable technologies are expected to play an increasing role in reducing dependence on fossil fuels for energy and electricity. Wind power in particular is likely to become a much larger contributor to the UK's energy mix. The UK has the largest offshore wind capability in Europe (Renewables UK, 2010), and in 2009 overtook Denmark to become the leading country for installed offshore wind capacity (Renewables UK, 2009).

The current dominant design for large, grid-connected wind turbines is a three blade rotor with a horizontal rotating axis. The concept of a vertical axis wind turbine (VAWT) is relatively new, but has several advantages over horizontal axis alternatives. It is able to capture the wind from any direction, and the vertical axis is such that the rotor equipment is located at base level, making it is simpler and less costly to install and maintain (Katsaros, 2009). However earlier designs, such as the H-shape and Darrieus, were less efficient and suffered technical problems such as metal fatigue and issues with the transmission shaft, so the original designs had disappeared from the market and development had slowed until recently (EWEA, 2009a).

The Energy Technologies Institute (ETI) is a UK-based company formed from global industries and the UK government. One of three projects looking at new turbine design and concepts for offshore wind is the Novel Offshore Vertical Axis (NOVA) project, a UK-based consortium consisting of Wind Power Limited, OTM Consulting, Cranfield University, the University of Strathclyde, Sheffield University, James Ingram & Associates, CEFAS and QinetiQ. The project was launched by the ETI in January 2009 to look at the feasibility of a NOVA turbine (ETI, 2011).

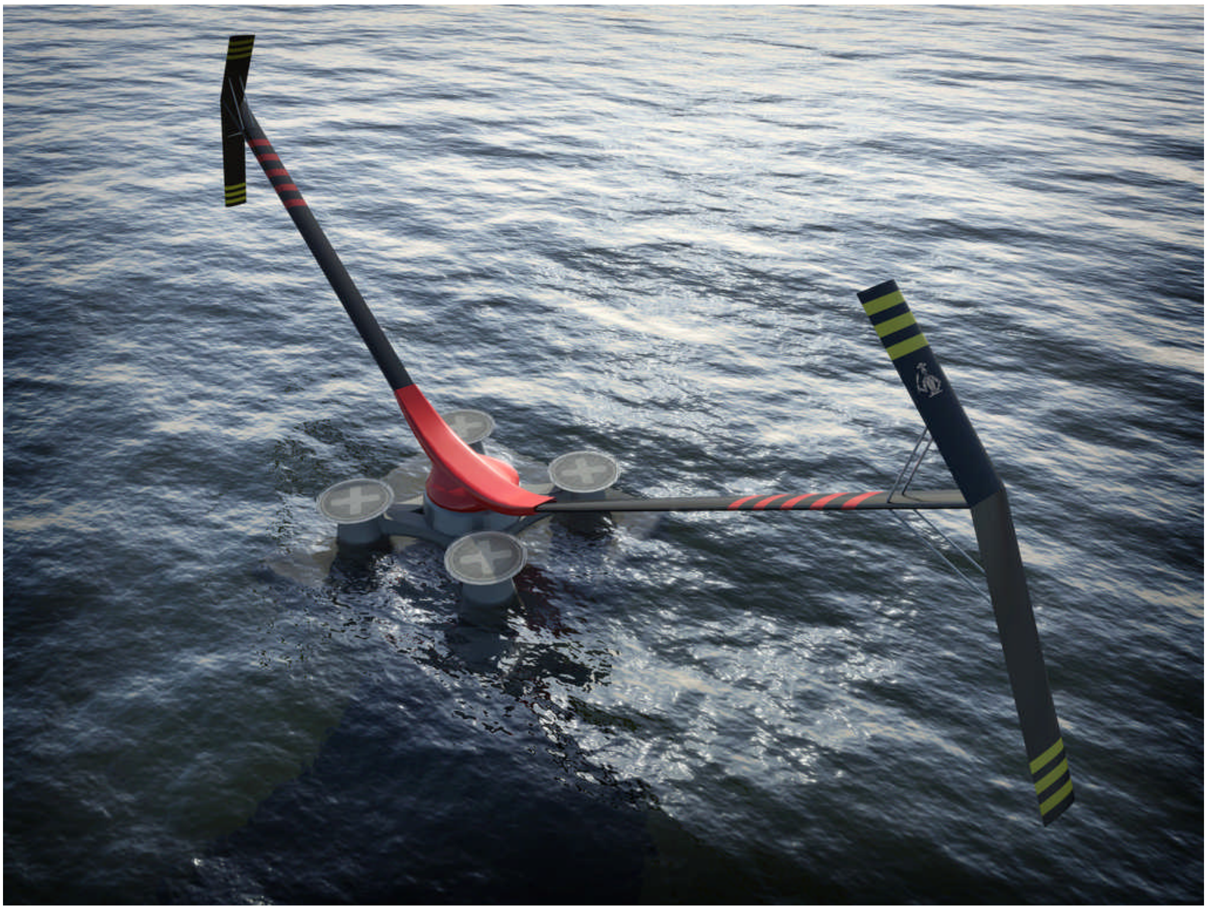

Figure 1 NOVA turbine (Copyright © 2010 WPL and Grimshaw)

This case study considered the potential reduction in greenhouse gases (GHGs) that could be achieved through the installation of NOVA wind turbines, in comparison to conventional horizontal axis wind turbines (HAWTs) for offshore power generation. The increased power rating of the NOVA turbines compared to current HAWTs is expected to provide considerable reductions in lifetime greenhouse gas emissions.

The vertical axis concept itself was not 'invented' at Cranfield, but Cranfield researchers have since made a considerable contribution to its development. This has mainly been through the 18 month intensive feasibility study for ETI, consisting of a detailed technological, economic and environmental assessment of the potential for the concept, compared with a baseline of conventional HAWTs. The aim of the project was to deliver a feasibility study to evaluate the design and commercial availability of a 5 MW or 10 MW VAWT.

The power output of conventional HAWTs is limited by the requirement for turbines blades to be larger and positioned higher. This also presents difficulties and additional emissions with respect to installation and maintenance. By comparison, the NOVA turbine was developed to be a low-stress design, with rotation ten times slower than a conventional HAWT (Brennan, 2010).

The NOVA project initially focused on a 5 MW vertical axis wind turbine (VAWT) design, but then moved to optimising the turbine configuration within certain constraints, the result being the 10 MW concept configuration (NOVA Consortium, 2010).

The fundamental design focus of the NOVA team was to minimise:

- *cost of electricity by reducing weight and height of components while increasing energy yield with ultra-high availability;*
- *technical risk by using proven, off-the-shelf components wherever possible; and*
- *environmental and social impact by material selection to minimise life cycle carbon emissions.*

(NOVA Consortium, 2010)

The long term vision of the NOVA project is to have installed 1 GW of 10 MW NOVA turbines offshore by 2020, via a large scale demonstrator installed offshore within 5 years (Wind Power Ltd, 2011). The UK government has a target of 20 GW of offshore wind generation installed by 2020, so the carbon brainprint of this study will be the reduction in greenhouse gas emissions associated with the installation of 1 GW of NOVA turbines as opposed to 1 GW of conventional HAWTs.

Vestas Wind Systems A/S (known as Vestas) has developed from a pioneer in the wind industry to become a global market leader (EWEA, 2009), and so its most successful offshore model, the V90-3.0 MW HAWT, was chosen as a baseline for comparison.

System boundaries

While the brainprint does not claim to be a full life cycle assessment, attempt is made to follow life cycle assessment (LCA) principles as closely as possible (Parsons & Chatterton, 2011a). In this case, because the innovation is an entirely new product (rather than an upgrade to existing technology), the brainprint required the comparison of complete life cycle emissions for the two independent turbines.

The life cycle of a wind turbine can be considered in terms of four main stages: manufacturing, transportation and installation, operation and maintenance, and decommissioning and end of life. In this case it was expected that emissions associated with manufacture and installation would dominate. The design of the NOVA turbine is such that the requirement for maintenance should also be reduced when compared with HAWTs, due to the hub being located at ground level (Katsaros, 2009).

Considering full life cycle emissions required the components of the turbines to be traced back to raw materials and greenhouse gas emissions associated with their extraction, processing and manufacture to be included. The manufacture of capital goods, e.g. machinery and vehicles, was not included.

Cranfield researchers were major, but not sole academic contributors to the NOVA project consortium, so the attributable proportion of the brainprint also needed to be estimated.

Data

The NOVA report used two methods of life cycle assessment to compare the lifecycle emissions of the NOVA turbine with those of the V90. ETI developed a simple Excel-based model using input data for component materials combined with additional emissions data relating to construction, operation and maintenance and decommissioning phases. The professional LCA software package Sima Pro (Pré Consultants, 2009) was also used to model detailed environmental impacts during each life cycle process.

Kolios & Brennan (2010) compared conventional offshore HAWT and NOVA wind installations, each with a total rating of 1 GW, assuming a capacity factor of 0.34. For wind power systems, the capacity factor provides an estimate of the amount of electricity generated by the turbines relative to the theoretical maximum output of the turbines under ideal wind conditions (Sinden, 2005).

In 2009 a Cranfield MSc student, Dmitris Katsaros, undertook a detailed LCA study to evaluate the environmental performance of various models of offshore and onshore wind turbines including the NOVA concept (Katsaros, 2009). The initial Sima Pro models constructed by Katsaros were developed and used for the NOVA project.

Data for the baseline HAWT, the offshore Vestas V90, were mainly derived from published sources. Vestas has been a pioneer in the field of LCA, and has been applying LCA techniques to measure the environmental performance of its turbines since 1999 (Vestas, 2011). The company has performed LCAs and produced environmental product declarations (EPDs) for several of its wind turbine models (e.g. Vestas, 2006, Vestas, 2009) and provided much of the data for the LCA models (Kolios & Brennan, 2010, Katsaros, 2009).

Brainprint

The NOVA project consortium proposed 'an ambitious but realistic vision' of 1GW of offshore vertical axis turbines installed in UK waters by 2020 (Kolios & Brennan, 2010). Thus the Carbon Brainprint will be the calculated emissions reduction achieved through the installation of 1 GW of NOVA turbines as opposed to a 1 GW installation of the leading offshore HAWT, the Vestas V90 3.0 MW.

The brainprint in this case will be entirely prospective as there are currently no installed NOVA turbines.

Prospective Brainprint

The rated capacity of a wind turbine is a theoretical value representing the maximum power it can produce under optimum wind conditions (Sinden, 2005). The Vestas offshore V90 has a power rating of 3 MW, while the aim for the NOVA turbine is rated at 10 MW following the optimisation phase of the original 5 MW design. An installation rated at 1 GW of NOVA turbines would therefore require 100 VAWTs, whilst 1 GW of conventional HAWTs, in this case V90 3.0 MW, would consist of 334 turbines.

Lifetime GHG emissions per turbine were obtained from the SimaPro model developed for the NOVA project and scaled to give total emissions for a 1 GW installation (Table 1). Two variations were modelled originally, with a single stage (SS) and a multi-stage (MS) gearbox. The feasibility study (NOVA Consortium, 2010) suggests that the single stage drive-train offered the most cost effective solution in terms of capita and operation costs and so data for this model was used. The total emissions reduction for a 1 GW installation over 20 years was approximately 102 kt CO_2e, representing a 20% reduction in GHG emissions. Using the assumed capacity factor of 0.34, this suggested that GHG emissions would be 8.72 g CO_2e/kWh for the V90 and 7.03 g CO_2e/kWh for NOVA.

Table 1 Estimate of lifetime power output and GHG emissions for NOVA and V90 turbines

	Vestas V90 3.0 MW	NOVA 10 MW	Reduction
Capacity factor	0.34	0.34	
Output per turbine, GWh/year	8.935	29.784	
Output per turbine over 20 years, GWh	179	596	
Output for 1GW installation over 20 years, TWh	59.7	59.6	
Lifetime GHG emissions for turbine, kt CO_2e	1.56	4.19	
Lifetime GHG emissions for 1GW installation, kt CO_2e	521	419	102

In the absence of other data by which to attribute the brainprint, the project budget share was used to attribute one-third to Cranfield's contribution (Brennan, 2010). The Cranfield share of the brainprint is therefore 34 kt CO_2e for a 1 GW installation.

The LCA conducted by Vestas for the offshore V90 3.0 MW turbine (Vestas, 2006) provides a point of comparison. This used different assumptions and data sources, including a capacity factor of 0.54 instead of 0.34. They reported LCA burdens using a functional unit of 1 kWh, resulting in emissions of 5.23 g CO_2e/kWh. Converting this to a 1 GW installation resulted in total emissions of 496 kt CO_2e over 20 years, which agrees well with the estimate above, despite the differences in the underlying assumptions.

Uncertainties

As the brainprint is entirely prospective, there is considerable uncertainty with respect to performance and rollout, and therefore scope for a variety of sensitivities.

Katsaros (2009) suggested that whilst NOVA turbines perform better than conventional HAWTs in absolute terms, the results are highly sensitive to the capacity factor of the turbines, when comparison is made in terms of emissions per kWh.

Since the emissions per turbine were obtained from the SimaPro models, the uncertainty surrounding the offshore capacity factor did not influence the result, because the estimated power output was not used in the brainprint calculation. With no NOVA turbines in operation there was no data available from which to estimate uncertainties. Therefore, following the guidance in Parsons & Chatterton (2011a), the emissions per turbine were allocated a normal distribution with coefficient of variation (CoV) of 25% representing the unfamiliarity with the circumstances. The SimaPro result for the V90 (Katsaros, 2009) was very similar to Vestas (2009), and is a well-established model, so was assumed to be normally distributed with a CoV of 5%.

A Monte Carlo simulation was performed using @Risk software (Palisade Corporation, 2007) with these uncertainties per turbine. The difference in emissions between the two 1 GW installations (the total brainprint) had mean 102 kt CO_2e and standard deviation 108 kt CO_2e. Therefore the probability that a 1 GW installation of NOVA turbines had lower GHG emissions than a 1 GW installation of V90s was 83%:

$$P(NOVA<V90) = 1 - \Phi((0-102)/108) = 0.8275.$$

It is expected that a NOVA turbine could operate for 40 years (Brennan, 2010), compared with 20 years for a conventional HAWT. This is mainly due to the low-stress design, with the rate of rotation being 10 times slower than HAWTs. However, for comparative purposes a 20 year lifespan was used for the NOVA study (Kolios & Brennan, 2010). Therefore, the brainprint estimate is likely to be highly conservative. However, owing to uncertainties over longer term maintenance for the NOVA turbine and potential advances in HAWT technology over this time period, no attempt has been made to estimate the change in brainprint attributable to the extended lifespan.

The NOVA report assumes that the mass of the wind turbine without the support structure is removed during the decommissioning phase and assumes that there is 'no disposal scenario in the life cycle' (Kolios & Brennan, 2010). However Katsaros (2009) suggested it is possible to decrease environmental burdens by approximately 8% if recycling of metal is included in the LCA. This is similar to the figure quoted by Vestas (2009), and so it was assumed that the 8% would apply to both designs. Therefore, without more detailed recycling data for the NOVA turbine, this uncertainty was not included.

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