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Net CO2 Reduction Analysis for A Wind Farm

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Abstract

The purpose of this study was to determine the net CO_2 reduction benefit that can be achieved by using wind instead of coal power. Coal power has a significantly higher rate of CO_2 emissions than wind generation, but wind power generation has a significant amount of embodied energy. The goal of this study is to determine the net carbon reduction benefit that can be achieved using wind power after accounting for factors such as embodied energy in materials and construction.

Introduction

There is a "green" movement that has taken root in American culture recently. While the majority of the developed world has been developing and investing in renewable energy technology, the United States is just starting to take such projects seriously. The federal stimulus package passed at the start of Obama's first term included money for projects such as better batteries for hybrid cars and photovoltaic plants, among other "green" technologies. Recently the protracted battle over approval for the Cape Wind project was finally settled, with the project ultimately being approved after many legal battles. However, many environmental issues do not have clear-cut answers, and often being "green" requires making a choice between the lesser of two evils. It can be argued that the development of some renewable energy technologies falls into this category, since some of these technologies use components that are toxic, despite the fact that those components are being used to generate "clean" energy. The goal of this paper is to analyze a specific renewable technology, wind power, and to determine what, if any, the overall benefit is to the environment with regard to net CO_2 emissions.

It is a well known fact that wind turbines emit significantly lower quantities of CO_2 during operation than a fossil fuel powered plant, and so one might wonder why such an analysis as this would be necessary. While it is true that the operating emissions from wind turbines are significantly lower, this is not the only factor that one must consider when performing an environmental impact assessment. There is also the concept of embodied energy and CO_2 that must be taken into consideration. Embodied energy is a term for the energy embodied, or contained, in the materials used to construct something. For example, the embodied energy for a ton of steel is 32 MJ/kg (Victoria University, 2011.) This value represents the amount of energy that it took to create that ton of steel. That embodied energy translates into CO_2 emissions, as in most cases the energy necessary to create the steel came from fossil fuels. Because wind turbines in general, and offshore turbines especially, require a significant amount of materials with high embodied energies, it is important to consider the amount of CO_2 emitted producing the construction materials and during the construction process. In order for the turbine to have a net carbon reduction benefit, it must generate more energy and CO_2 savings than it took to produce it. Not only do the materials required to construct the turbines, e.g. fiberglass, steel, and concrete have a high embodied energy, they are also produced from valuable natural resources. If the net reduction in CO_2 emissions from the turbines is not significant, it does not make sense from an environmental perspective to use large amounts of valuable natural resources to build the turbines in the first place.

The reason that wind turbines require such a large amount of resources to build is their size. The trend in wind energy has been to build bigger and bigger turbines. Currently the largest operational turbines have a capacity of 5 MW and a correspondingly large blade length of 61.5 meters. Many of these turbines are designed to be installed in water up to 45 meters deep (Washington, GPO, 2010.) The trend has also been to design turbines that can operate in deeper and deeper water, as there is more potential for wind energy development offshore where the average wind speed is higher, and there are fewer aesthetic and zoning restrictions to impede development. (Washington, GPO, 2010.) For example, in Britain the average wind speed on land is 7.8 m/s, but the average wind speed offshore is 8.8 m/s, meaning that the potential for generating electricity is 30% higher offshore. This provides a strong incentive to pursue offshore projects, since even if construction costs for an offshore project are higher, the extra electricity generated due to the higher wind speeds will ultimately make the offshore installation more lucrative (Swift-Hook, 165.) This is why the study will focus on the embodied energy costs of an offshore installation.

Methodology

In order to conduct a carbon benefit analysis, there need to be some assumptions made regarding the size and location of the turbines, among other factors. Due to the controversy surrounding the Cape Wind project and the national attention that came with such controversy, it will serve as the model for this study. The plan for the Cape Wind project calls for the installation of one hundred thirty 3.6 MW turbines in a part of Nantucket Sound called Horseshoe Shoal. Each turbine will be 258 feet tall, from the surface of the water, with a 16 foot diameter base. The turbines will be anchored into the sea floor by a monopole foundation consisting of 80 feet of hollow steel tubing (Cape Wind, 2010). A project of such size will require a significant amount of raw materials, which is why this embedded energy study is necessary.

The first step in performing the carbon reduction analysis is to determine the embodied energy of the model wind farm. This study intends to follow the methodology of previous studies as closely as possible. While a previous study by Rule et al, 2009 was able to use computer software to assist with the calculations, the calculations in this study will be performed by hand. To determine the embodied energy of the wind farm two pieces of information are required: how much steel, aluminum, and concrete are required to construct a turbine, and what are the embodied energies of those materials. While those are not the only components of a wind turbine, they are the most energy intensive components and it would be highly impractical to start factoring in the embodied energies of components such as paint or lubricants (Rule et al, 2009.) Multiplying the amount of material required by the embodied energy of the material will yield an approximation of the amount of energy embodied in a wind turbine (Kreith, Norton, Brown, 1990.) The next step in the analysis will be to estimate the amount of energy expended during the construction process, which although probably small compared to the embodied energy of the materials, should not be ignored because construction offshore is most likely energy intensive. For the coal powered plant, an embodied energy calculation has already been performed by Kreith, Norton, and Brown, 1990. They determined that 97% of a coal plant's CO_2 emissions come from the combustion of coal, meaning that construction and maintenance only account of 3% of CO_2 emissions from a coal plant. This three percent will be taken into consideration after the emissions from coal combustion have been calculated.

After performing the embodied energy analysis the next step in the evaluation is to determine how much CO_2 each plant will emit during its operational lifetime. These values will be obtained by multiplying the CO_2 emission rates for each power generation method by a time factor of 30 years. For the case of wind farms, the operational life will be considered 30 years. Although coal plants have an operational lifespan greater than 30 years, for the purposes of this study 30 years of emissions data will be used so that an even comparison can be made. The CO_2 emissions from the wind farm are minimal and are significantly smaller than the coal plant's, as is shown in Table 2. For the purposes of this study, the amount of energy required to decommission each plant will not be considered, especially since many of the materials used in wind farm construction can be recycled. Again, the magnitude of the coal plant's emissions would dwarf any CO_2 emitted during the decommissioning process.

Results

The embodied energy analysis was performed by breaking down the wind turbine into five major components: the tower, the blade, the nacelle, wiring, and the base. The embodied energy of each component was determined by multiplying the embodied energy of its materials by the mass of the materials. For example each of the turbine towers contained approximately 26,000 kg of steel (Montgomery, 2011.) That mass was multiplied by the embodied energy of steel, which is 32 MJ/kg to determine the total embodied energy of the tower (Victoria University, 2011.) This was then multiplied by the 136 turbines in Cape Wind to determine the embodied energy of all the towers in the wind farm. This process was repeated for all of the 5 major components, and after the embodied energy of each component was added together, the resulting value was 213.85 MW hours. The primary component of the tower was steel, which has an embodied energy of 32 MJ/kg (Victoria University, 2011.) Turbine blades are typically constructed of fiberglass because of its relatively light weight. Each turbine blade contains about 1,100 kg of fiberglass, which has an embodied energy of 30.3 MJ/kg (Victoria University, 2011.) The nacelle is also typically made of fiberglass and weighs 10,000 kg. The primary component of the wiring is copper, which has a high embodied energy of over 70 MJ/kg (Victoria University, 2011.) Each tower has about 3,600 kg of copper in its wiring (International Mining, 2010.) The base contains about 10,000 kg of steel and also contains 240m^3 of concrete, which has an embodied energy of 15,000 MJ/m^3 (Victoria University, 2011.) The embodied energy of each component is shown in table 1, and each embodied energy calculation is contained in Appendix A. After the embodied energy of each component was totaled, that value had 5% added to account for the energy required for construction. The construction of the wind farm accounts for 5% of the total energy cost (Rule, Worth, Boyle, 2009.)

Turbine Component	Embodied Energy (MW hours)
Tower	32
Blades	1
Nacelle	11.42
Wiring	9.85
Base Steel	11.3
Base Cement	138
Total	213.9

Table 1. A breakdown by component of the embodied energy of a wind turbine. The base contained significant quantities of both steel and cement. The final total reflects the energy required for the construction process as well.

After determining the embodied energy of the wind farm, the next part of the analysis is to estimate how much power the wind farm will produce over the course of its lifetime. Cape Wind has a nameplate capacity of 468 MW, but the turbines only generate electricity when the windspeed is within a certain range, and even then will only produce all 468 MW of power at certain wind speeds. Wind turbines can only generate electricity when the wind speed is above a certain threshold, which varies depending on the turbine model. And, even when the wind is blowing strongly enough to generate electricity, the turbines can only produce a maximum output within a narrow range of operational wind speeds. Thus even if a turbine has a nameplate capacity of 3.6 MW, it cannot produce that 3.6 MW under all operating conditions. Additionally, the turbine must be taken offline to perform maintenance and repairs. To compensate for this, a loading factor of 45% will be used, meaning that the turbines will be assumed to generate electricity 55% of the time (Rule, Worth, Boyle, 2009.)It is necessary to take this factor into account to accurately estimate the energy production for Cape Wind; failure to do so would result in an artificially high power generation calculation. Taking this factor into account, the actual average capacity of Cape Wind would be 257.4 MW. Assuming that the turbines are able to generate this every day that amounts to a lifetime production of 2.82 million MW over a 30 year span. When the embodied energy is subtracted from this value, this leaves a net gain of 2.8 million MW meaning that Cape Wind will produce more energy than it took to build.

The next part of the carbon reduction analysis is to determine how much CO_2 the wind farm will emit over the course of a 30 year period. In order to estimate the emissions from each power plant, a table of emissions data was compiled from multiple sources, then those values were averaged and the averages were used in the emissions calculations.

Source	Coal CO2 Emissions (kg/MWh)	Wind CO2 Emissions (kg/MWh)
Committee on Environmental Impacts of Wind Energy Projects, 2007	632.72	
Barnthouse et al, 1994	Benchmark Plants: 1035.45	
	Combined Cycle: 749.09	
Kreith et al, 1990	1037.88	7.01
Ackerman, 20	754.54	

Rule et al, 2009		3.60

Table 2: Various values for CO_2 emissions from coal fired power plants and wind farms.

Using the average values obtained from table 2, I determined that over a 30 year period the wind farm will generate 653,190,000 kg of CO_2 compared to the coal plant, which will generate 81,818,000,000 kg over the same time period. Including the 3% of emissions from construction, the coal plant's total emissions are 8.43×10^{10} kg. However, the embodied energy in the wind farm needs to be taken into consideration as well. Assuming that the 213.85 MW of embodied energy come from a coal fired power plant this is an additional 160,500 kg of CO_2, bringing the grand total of CO_2 emitted by the wind farm over the course of its life to be 653,350,000 kg. Thus using a wind farm instead of a coal power plant has the potential to save over 81 billion kg of CO_2 from being emitted into the atmosphere.

Conclusion

The goal of this study was to determine the net carbon reduction benefit, if any, of an offshore wind farm vs. a coal fired power plant. After performing the embodied energy analysis and calculating CO_2 emissions for the life of the wind farm, the data clearly shows an enormous net carbon reduction benefit. From an environmental perspective, wind turbines are an answer to the problem of CO_2 emissions from fossil fuels and can provide a clean source of electricity. However, wind turbines cannot produce power on a consistent basis, and thus are part of the solution to lowering CO_2 emissions, not the entire solution. Nevertheless, this report concludes that wind turbines have the potential to significantly reduce CO_2 emissions and that the construction of offshore wind farms is a viable, environmentally sound option.

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Appendix A: Calculations

$$Tower: \frac{26,308\ kg}{turbine}\ x\ \frac{136\ turbines}{1}\ x\ \frac{32\ MJ}{kg}\ x\ \frac{1\ MWh}{3600\ MJ} = 31.8\ MWh$$

$$Blades: \frac{1,134\ kg}{turbine}\ x\ \frac{136\ turbines}{1}\ x\ \frac{30.3\ MJ}{kg}\ x\ \frac{1\ MWh}{3600\ MJ} = 1.3\ MWh$$

$$Nacelle: \frac{9,979\ kg}{turbine}\ x\ \frac{136\ turbines}{1}\ x\ \frac{30.3\ MJ}{kg}\ x\ \frac{1\ MWh}{3600\ MJ} = 11.42\ MWh$$

$$Wiring: \frac{3,629\ kg}{turbine}\ x\ \frac{136\ turbines}{1}\ x\ \frac{70.6\ MJ}{kg}\ x\ \frac{1\ MWh}{3600\ MJ} = 9.85\ MWh$$

$$Base\ (steel): \frac{10,000\ kg}{turbine}\ x\ \frac{136\ turbines}{1}\ x\ \frac{32\ MJ}{kg}\ x\ \frac{1\ MWh}{3600\ MJ} = 11.3\ MWh$$

$$Base\ (cement): \frac{240\ m3}{turbine}\ x\ \frac{136\ turbines}{1}\ x\ \frac{15,210\ MJ}{m3}\ x\ \frac{1\ MWh}{3600\ MJ} = 138\ MWh$$