NATIONAL ENERGY TECHNOLOGY LABORATORY

Role of Alternative Energy Sources: Wind Technology Assessment

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Acronyms and Abbreviations

AEO	Annual Energy Outlook
ASTM	American Society for Testing and Materials
AWEA	American Wind Energy Association
CA ISO	California Independent System Operator
CCS	Carbon capture and sequestration
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COE	Cost of electricity
CTG	Combustion turbines/generators
ECF	Energy conversion facility
EERE	Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
GHG	Greenhouse gas
GTSC	Gas turbine simple cycle
GWP	Global warming potential
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
km	kilometer
LC	Life cycle
LCA	Life cycle assessment
LCC	Life cycle cost
LCOE	Levelized cost of electricity
MACRS	Modified accelerated cost recovery system
MISO	Midwest Independent System Operator
MMS	Mineral Management Services
MW	Megawatt
MWh	Megawatt-hour
N_2O	Nitrous oxide
NEPA	National Environmental Policy Act
NETL	National Energy Technology Laboratory
NGCC	Natural gas combined cycle
NO_X	Nitrogen oxides
NREL	National Renewable Energy Laboratory
O&M	Operating and maintenance
PJM ISO	Pennsylvania New Jersey Maryland Independent System Operator
PSFM	Power Systems Financial Model
PT	Product Transport
RFS2	Renewable Fuel Standards 2
RMA	Raw material acquisition
RMT	Raw material transport
SF_6	Sulfur hexafluoride
SO_2	Sulfur dioxide
T&D	Transmission and distribution
TWh	Terawatt-hour
U.S.	United States
USDA	United States Department of Agriculture
USACE	U.S. Army Corps of Engineers

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Executive Summary

This report discusses the role of wind power in meeting the energy needs of the United States (U.S.). This includes an analysis of key issues related to wind power and, where applicable, the modeling of the environmental and cost aspects of wind power.

A wind farm is a collection of wind turbines. Horizontal turbines, wherein three rotor blades are mounted on a horizontally-oriented axis, are the preferred technology for wind power. A conventional onshore wind turbine has an average capacity of 1.5 MW. As the onshore wind power industry matures, the capacities of advanced wind turbines will reach 6 MW. The U.S. does not have any offshore wind farms, but the Cape Wind project, off the coast of Massachusetts, is in the planning stage and will use 3.6 MW turbines. The rated capacity of a wind turbine is a function of its rotor diameter, which can range from 63 meters for a conventional wind turbine up to 125 meters for an advanced wind turbine. A key difference between onshore and offshore wind power is the availability of wind, which affects the capacity factor of a wind farm. The average capacity factor for onshore wind power is 30 percent, and the estimated capacity factor for offshore wind power in the U.S. is 39 percent.

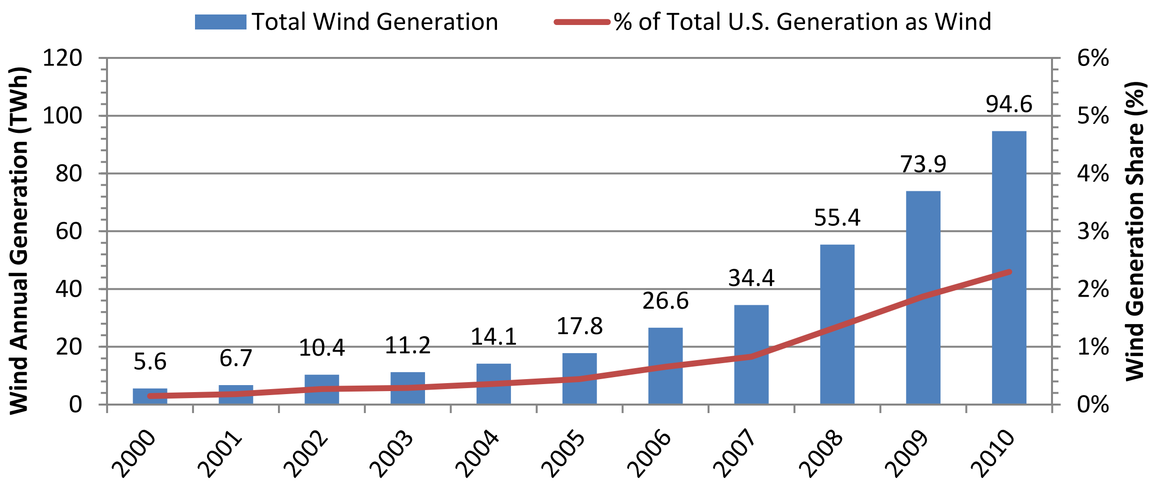
The resource base of onshore wind power can supply approximately 10,400 GW of wind power capacity (AWEA, 2011a), with the strongest onshore wind resources in the southern, central, and northern plain states, across the lake states, and in southern Texas (AWS Truepower & NREL, 2011). The U.S. does not have any offshore wind farms, but U.S. offshore wind resources are estimated to be sufficient to support approximately 4,150 GW of power production (Schwartz, Heimiller, Haymes, & Musial, 2010). The strongest offshore wind resources are available off the coast of the U.S. Northeast, the Great Lakes, California and Oregon, and Hawaii.

From 2000 to 2010, the contribution of wind power to total U.S. electricity production increased from 0.2 to 2.3 percent. In terms of total electricity produced, wind power has grown from 5.6 TWh in 2000 to 95 TWh in 2010 (EIA, 2011c), which is equivalent to a 32.7 percent annual growth rate. While this is a high growth rate, a large wind resource base remains unused. As of 2010, the U.S. had 40.2 GW of installed wind power capacity, which is equivalent to 0.39 percent of the estimated onshore wind resource base.

It is important to distinguish between total and viable resource base. The AWEA estimates 14,550 TW of potential wind capacity in the U. S., 29 percent of which is offshore potential (AWEA, 2011a). The total resource base for wind (and other renewable energy sources) is not economically accessible, so it would be too optimistic to expect full use of the total resource base. There is a large amount of uncertainty about what percent of the possible capacity will be installed and, further, what amount of electricity will be generated from that installed capacity (e.g. capacity factor).

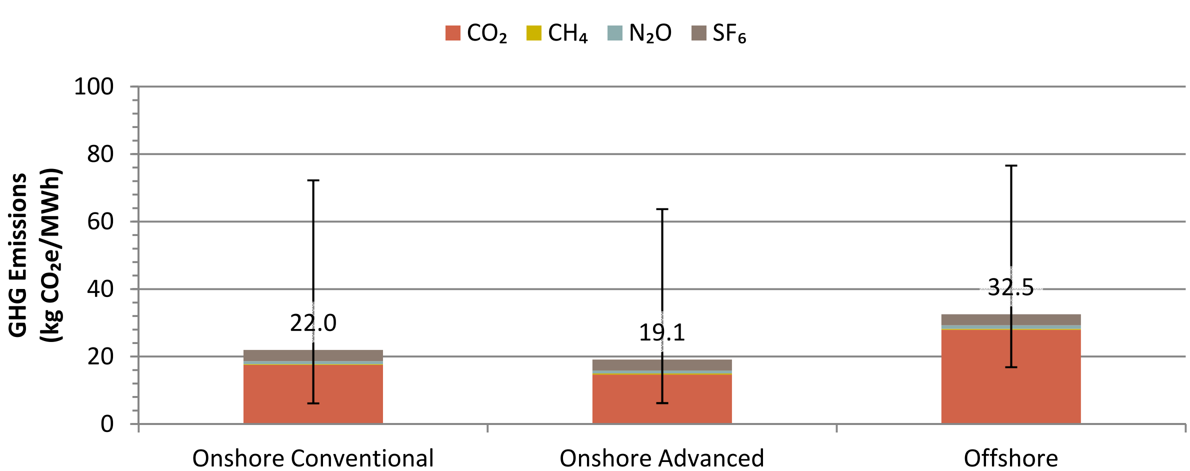
Current U.S. wind power generation capacities are predominantly provided by independently owned power producers. As of May 2011, 87 percent of wind power was provided by independently owned producers. This share is anticipated to continue in the near term, as private investors and other sources of private capital continue to drive the U.S. wind market. The growth in total generation and its contribution to the U.S. electricity supply are shown in **Figure ES-1**.

Figure ES-1: Annual Wind Generation and Share (EIA, 2011c)



The environmental profile of this analysis is based on the life cycle analysis (LCA) method that accounts for the cradle-to-grave energy and material flows for wind power and, when applicable, backup power. The life cycle (LC) greenhouse gas (GHG) emissions for wind power from conventional and advanced onshore wind power are 22.0 and 19.1 kg CO_2e per MWh and are 32.5 kg CO_2e per MWh for offshore wind power. The advanced onshore system has lower GHG emissions than the conventional system. This is due to the higher economy of scale between turbine materials and turbine rating (MW) for the advanced systems. The turbine manufacturing processes account for 90 percent of the LC GHG emissions for conventional onshore and 93 percent for advanced onshore. Offshore wind power has higher LC GHG emissions than both onshore scenarios due to added complexity of installing, maintaining, and connecting wind turbines 20 km from the shoreline. In particular, the operation of a marine vessel for personnel and material transport, as well as the idling of a marine vessel during construction and maintenance, account for 42 percent of the LC GHG burdens of offshore wind power. The LC GHG emissions from wind power (expressed in Intergovernmental Panel on Climate Change [IPCC] 2007 100-year global warming potentials [GWP]) are shown in **Figure ES-2**.

Figure ES-2: Life Cycle GHG Profile for Wind Power



When the reliability of power generation is considered, the need for backup power increases the LC GHG emissions of wind power. When a gas turbine simple cycle (GTSC) power plant provides backup power to an *onshore* wind farm, the LC GHG emissions are 502 kg CO_2e per MWh. Similarly, when a GTSC power plant provides backup power to an *offshore* wind farm, the LC GHG emissions are 429 kg CO_2e per MWh. For comparison, an advanced fossil combustion technology such as an integrated gasification combined cycle (IGCC) plant with a carbon capture and sequestration (CCS) system has LC GHG emissions of 218 kg of CO_2e/MWh (NETL, 2010b).

The above results do not account for the GHG emissions from land use change. The area of transformed land for wind power systems was assessed using reported land use areas, satellite imagery, aerial photographs, and other available data for each of the facilities considered within this study. The original use of changed land (e.g., agriculture, forest, or grassland) was also determined. GHG emissions due to land use change were evaluated based upon the U.S. Environmental Protection Agency's (EPA) method for the quantification of GHG emissions, in support of Renewable Fuel Standards 2 (RFS2) (EPA, 2010a). The offshore wind farm results in the smallest transformed land area of all the reported profiles, at approximately 0.034 m^2/MWh, followed by the onshore conventional and onshore advanced wind farms at 0.253 m^2/MWh and 0.256 m^2/MWh, respectively. The associated GHG emissions from direct and indirect land use for the three wind power scenarios follow the same sequence and range from 0.73 to 2.72 kg CO_2e/MWh. When considering land use GHG emissions in addition to the other GHG emissions, the land use GHG emissions increase total LC GHG by 12 percent (22.0 to 24.7 kg CO_2e/MWh) for onshore conventional wind power, by 14 percent for onshore advanced wind power (19.1 to 21.8 kg CO_2e/MWh), and by 2 percent for offshore wind power (32.5 to 33.2 kg CO_2e/MWh). Systems with backup power also have GHG emissions from land use change, but they are dominated by combustion emissions, making land use change a smaller share of total GHG emissions.

The cost profile of wind power was based on a discounted cash flow analysis. Compared to offshore wind power, onshore wind power has lower capital and operating and maintenance (O&M) costs per kilowatt of power. However, offshore wind power has a higher average capacity factor than onshore wind power, which helps reduce its costs in comparison to onshore wind power. The cost results are dominated by capital costs. When the same financial assumptions are applied to onshore and offshore wind power technologies, the cost of electricity (COE) is $115/MWh for onshore conventional, $113/MWh for onshore advanced, and $259/MWh for offshore. The expected cost results show that onshore wind power has a lower COE than offshore wind power, but the overlapping uncertainties of these results indicate that if offshore wind power has better-than-expected performance, or a financing structure with low expected returns, it can be cost competitive with onshore wind power.

The electricity production tax credit (PTC) is a federal tax credit that was originally enacted by the Energy Policy Act of 1992 and was most recently renewed as a part of the American Recovery and Reinvestment Act (ARRA) of 2009 (EPA, 2011). The PTC gives producers of wind power 2.2 cents for every kWh of electricity produced during first 10 years of operation (EPA, 2011). The PTC is scheduled to expire at the end of 2012 (Wiser & Bolinger, 2011). The ARRA also includes provisions that allow wind energy producers to forgo the PTC and claim an investment tax credit (ITC) or cash grant that is 30 percent of the total project cost (Wiser & Bolinger, 2011). In addition to these tax credits and grants, wind projects installed between September 2010 and the end of 2011 can depreciate 100 percent of their assets in the first year (Wiser & Bolinger, 2011). As these tax credits and other financial incentives expire, it is likely that investments in new wind power projects will slow down significantly, and with no long-term federal policies for renewable energy investments, it is difficult for producers to secure power purchase agreements.

The barriers to implementation include uncertainties in construction schedules, especially for offshore wind projects. Onshore wind farms have enjoyed much shorter planning and construction horizons, as compared to fossil fueled power plants, with a typical planning cycle of approximately 3-4 years (EIA, 2011b). The offshore wind industry, in contrast, lags behind the onshore wind industry in these aspects. For instance, the first major offshore wind project in the U.S. was approved after about a decade of planning and compliance procedures, in April, 2010 (Cape Wind, 2010). Availability of power transmission capacity, combined with the difficulty of constructing long distance power transmission lines, is another barrier to the implementation of wind power.

The risks of implementation include various environmental impacts that are unique to wind power, including increases in bird and bat strikes from wind turbines. In the case of offshore wind power, interference with marine navigation, loss of benthic biota, and interference with cultural and visual resources (USACE, 2006) are further risks of implementation.

The opinions of wind power experts include the outlooks of wind developers and industry associations. Fearful of entering into a serial boom-bust scenario, many wind developers are currently calling for additional federal policies to support continued wind development. Onshore wind development has, in some cases, reached cost competitiveness with natural gas-based power production on a per kWh basis. However, according to a representative of the American Wind Energy Association (AWEA), wind power lacks predictable federal policies needed to drive consistent wind power growth. Some analysts are predicting that wind growth may shift towards offshore installations in the near to midterm. Based largely on the recent release of the Obama Administration's *A National Offshore Wind Strategy* (EERE, 2011), economists are anticipating a surge in offshore wind installations (Reuters, 2010).

1 Introduction

The role of an energy source in the national energy supply is determined by a combination of factors, including technical considerations, resource availability, environmental characteristics, economics, and other issues that may pose risks or barriers. The objective of this analysis is to conduct a broad assessment of wind power using the list of seven criteria as summarized in **Table 1-1**.

Table 1-1: Criteria for Evaluating Roles of Energy Sources

Criteria	Description
Resource Base	Availability and accessibility of natural resources for the production of energy feedstocks
Growth	Current market direction of the energy system. This could mean emerging, mature, increasing, or declining growth scenarios
Environmental Profile	Life cycle (LC) resource consumption (including raw material and water), emissions to air and water, solid waste burdens, and land use
Cost Profile	Capital costs of new infrastructure and equipment, operating and maintenance (O&M) costs, and cost of electricity (COE)
Barriers	Technical barriers that could prevent the successful implementation of a technology
Risks of Implementation	Financial, environmental, regulatory, and/or public perception concerns that are obstacles to implementation. Non-technical barriers
Expert Opinion	Opinions of stakeholders in industry, academia, and government

Wind power involves the conversion of wind energy to electrical energy. The most common type of technology for utility-scale wind power is a three-blade rotor mounted on a horizontally-oriented shaft. The shaft is connected to a gearbox or direct-drive system that drives an electric generator. The rotor, shaft, and generator assembly is mounted on top of a tall tower. Wind power facilities, known as “wind farms”, have multiple wind turbines as well as transformers and other electrical equipment that allow transmission of power to the electricity grid.

The average capacity of wind turbines in the United States (U.S.) has increased steadily from 0.7 MW in 1998 to 1.8 MW in 2010. One of the most common wind turbines is GE’s 1.5 MW turbine, which accounted for half of new wind turbine installations in 2010 (Wiser & Bolinger, 2011).

In 2011, wind power accounted for 2.3 percent of total U.S. electricity production (Wiser & Bolinger, 2011). As of 2010, 20 states have at least 400 MW of installed wind power capacity (Wiser & Bolinger, 2011). Seven states have more than 2,000 MW of installed wind power capacity (Texas, Iowa, California, Minnesota, Washington, Oregon, and Illinois) (Wiser & Bolinger, 2011). It is also possible to install wind turbines offshore. Offshore installations have been implemented in Europe, and are currently in proposal or planning phases in the U.S.

The reliability of wind power is a function of the reliability of wind itself. Wind is an intermittent resource, making the generation of wind power intermittent. Most wind power plants generate 25 to 40 percent of the time (Wiser & Bolinger, 2011), so it is necessary to back up wind power with other power technologies.

This remainder of this report focuses on the environmental, cost, and other issues associated with wind power in the U.S.

2 Wind Power Technology Performance

The onshore wind farm of this analysis has a total capacity of 200 MW. A conventional, onshore wind turbine has a capacity of 1.50 MW. The average capacity factor for onshore wind power is 30.0 percent (Wiser & Bolinger, 2011). The capacity factor for onshore wind power ranges from 25.0 percent to 33.0 percent. A 100-mile trunkline is necessary to connect onshore wind power to the electricity grid.

The offshore wind project is representative of the Cape Wind project, which has a total capacity of 468 MW. A single offshore wind turbine has a capacity of 3.6 MW. The expected capacity factor for the Cape Wind project is 39.0 percent (MMS, 2009). This analysis assumes that the capacity factor for offshore wind power ranges from 95.0 percent to 105 percent of the expected value capacity factor (i.e., 36.2 percent to 40.0 percent). A 12-mile submarine cable is required to connect the offshore wind project with an onshore electrical connection (MMS, 2009), which is then connected to a 100-mile trunkline to the electricity grid.

The key cost and performance parameters for onshore conventional, onshore advanced, and offshore wind power are shown in **Table 2-1**, **Table 2-2**, and **Table 2-3**, respectively. The parameters shown in these tables are based on historic performance data for onshore wind farms (Wiser & Bolinger, 2011), offshore performance data specified by the environmental impact statement EIS for the Cape Wind project (MMS, 2009), and cost data provided by other authors (Haughton, 2004; Parsons, Milligan, Kirby, Dragoon, & Caldwell, 2003; Wiser & Bolinger, 2011). The method for calculating the cost data shown in the following tables is explained in more detail in **Section 5.2**.

Table 2-1: Performance and Cost Parameters for Onshore Conventional Wind Power

Parameter	Low	Expected Value	High	Reference
Total Project Capacity (MW)		200		Study Assumption
Single Turbine Capacity (MW)		1.5		Wiser & Bolinger, 2011
Total Number of Turbines (Count)		133		Calculated
Capacity Factor (%)	25%	30%	33%	Wiser & Bolinger, 2011
Project Life (Years)	20	20	30	DOE, 2008
Capital Cost (Total Project Cost) (2007$/kW)	1,190	1,970	3,200	Wiser & Bolinger, 2011
Decommissioning (2007$/kW)	119	197	320	Study Assumption
Variable O&M (Grid Integration) (2007$/MWh)		2.62		Parsons & Milligan, 2003
Fixed O&M (Annual) (2007$/MW-yr.)		24,050		Wiser & Bolinger, 2011

Table 2-2: Performance and Cost Parameters for Onshore Advanced Wind Power

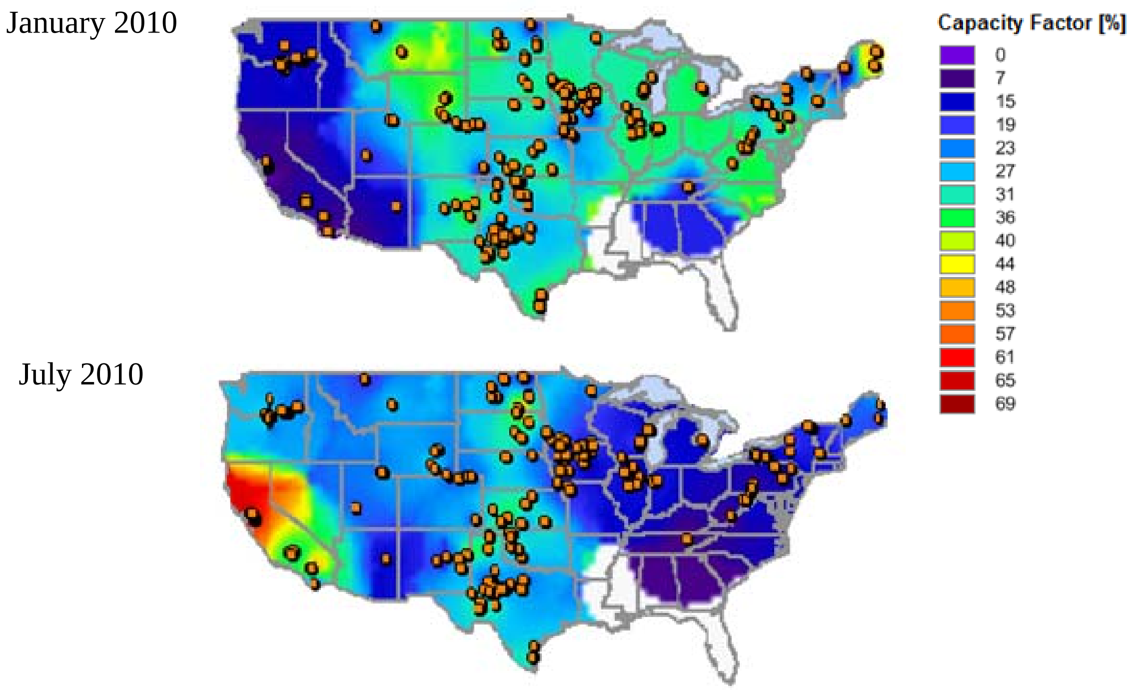
Parameter	Low	Expected Value	High	Reference
Total Project Capacity (MW)		200		Study Assumption
Single Turbine Capacity (MW)		6		Wiser & Bolinger, 2011
Total Number of Turbines (Count)		33		Calculated
Capacity Factor (%)	25%	30%	33%	Wiser & Bolinger, 2011
Project Life (Years)	20	20	30	Study Assumption
Capital Cost (Total Project Cost) (2007$/kW)	1,370	1,920	2,380	Wiser & Bolinger, 2011
Decommissioning (2007$/kW)	137	192	238	Study Assumption
Variable O&M (Grid Integration) (2007$/MWh)		2.62		Parsons & Milligan, 2003
Fixed O&M (Annual) (2007$/MW-yr.)		24,050		Wiser & Bolinger, 2011

Table 2-3: Performance and Cost Parameters for Offshore Wind Power

Parameter	Low	Expected Value	High	Reference
Total Project Capacity (MW)		468		MMS, 2009; Haughton et. al., 2004
Single Turbine Capacity (MW)		3.60		MMS, 2009; Haughton et. al., 2004
Total Number of Turbines (Count)		130		Calculated
Capacity Factor (%)	37.1	39.0%	41.0%	MMS, 2009
Project Life (Years)	20	20	30	Study Assumption
Capital Cost (Total Project Cost) (2007$/kW)	4,370	5,470	6,560	Haughton et. al., 2004
Decommissioning (2007$/kW)	238	875	1,090	Study Assumption
Variable O&M (Grid Integration) (2007$/MWh)		2.62		Parsons & Milligan, 2003
Fixed O&M (Annual) (2007$/MW-yr.)		34,188		Haughton et. al., 2004

Available wind power is defined by installed capacity and capacity factor. The installed capacity is the maximum power at the optimal wind speed. The capacity factor of a wind farm is the ratio of electrical energy produced over a period of time and electrical energy that could be produced at the full capacity during the same period. Capacity factor may be calculated for a single turbine, a wind farm with a group of turbines, or across a region, representing hundreds to thousands of individual turbines. The capacity factor of wind units is location and time dependent, and is subject to high variability. It is also affected by weather and grid conditions. **Figure 2-1** illustrates average monthly capacity factors of wind power plants across the United States (U.S.) for January and July of 2010. During these two months, the capacity factors ranged between 7 and 70 percent. However, under typical conditions on an annualized basis, most wind power plants operate at a capacity factor ranging from 25 to 40 percent (EPA, 2008; Wiser & Bolinger, 2011). During 2010, average capacity factor for all wind power in the U.S. was approximately 30 percent (Wiser & Bolinger, 2011).

Figure 2-1: Average Capacity Factor of Wind Power Plants in Winter and Summer



In general, standby power should be used to back up intermittent resources (Hittinger, Whitacre, & Apt, 2010). Depending on the pattern of resource intermittency for a given technology or location, it might have to be backed up by spinning, non-spinning, or fast ramping firm generators. High level greenhouse gas (GHG) emissions analysis can even use back-up energy instead of power. However, for detailed cost-benefit and stability and reliability analysis, it is more appropriate to use backup capacity (power) instead of backup energy because of generation temporal and spatial characteristics. Since a wind generator is not dispatched with its full capacity, it does not require 100 percent backup (DOE, 2008).

This analysis uses a simple cycle gas turbine (GTSC) to represent the environmental burdens of backup power. GTSC power plants are already in use as load-following power plants and can ramp up quickly to respond to demand fluctuations, making them a suitable technology for backing up wind power. (Other technologies that can quickly respond to demand fluctuations include hydropower, batteries, fuel cells, and micro-turbines (EAC, 2008)). The GTSC power plant consists of two parallel, advanced F-Class natural gas-fired combustion turbines/generators (CTG). The performance profile for the GTSC plant was adapted from the NETL baseline (NETL, 2010a) for Natural Gas Combined Cycle (NGCC) power by considering only the streams that enter and exit the combustion turbines/generators and not accounting for any process streams related to the heat recovery systems used by combined cycles. (More details on the development of GTSC data are provided in **Appendix C**.) The performance characteristics for a GTSC power plant are summarized in **Table 2-4**.

Table 2-4: GTSC Properties

GTSC Operating Parameters		
Fuel Input (Natural Gas)	75,900	kg/hr.
Net Output	360	MW
Capacity Factor	Variable	%
Life Cycle Greenhouse Gas Emissions		
CO_2	658	kg/MWh
N_2O	1.74E-01	kg CO_2e/MWh
CH_4	54.3	kg CO_2e/MWh
SF_6	3.26	kg CO_2e/MWh
CO_2e	715	kg CO_2e/MWh

The average U.S. electricity mix is one of two power backup scenarios used in this analysis. The various paths to electricity production (which include bituminous coal, natural gas, other fossil fuels, nuclear, and renewable energy sources) are assembled by NETL's model according to the composite fuel mix of U.S. power production. Environmental Protection Agency's (EPA) eGRID database was used for determining the contribution of each pathway to average U.S. electricity generation (EPA, 2008). The fuels and GHG emissions of the average U.S. electricity mix in 2005 are shown in **Table 2-5**.

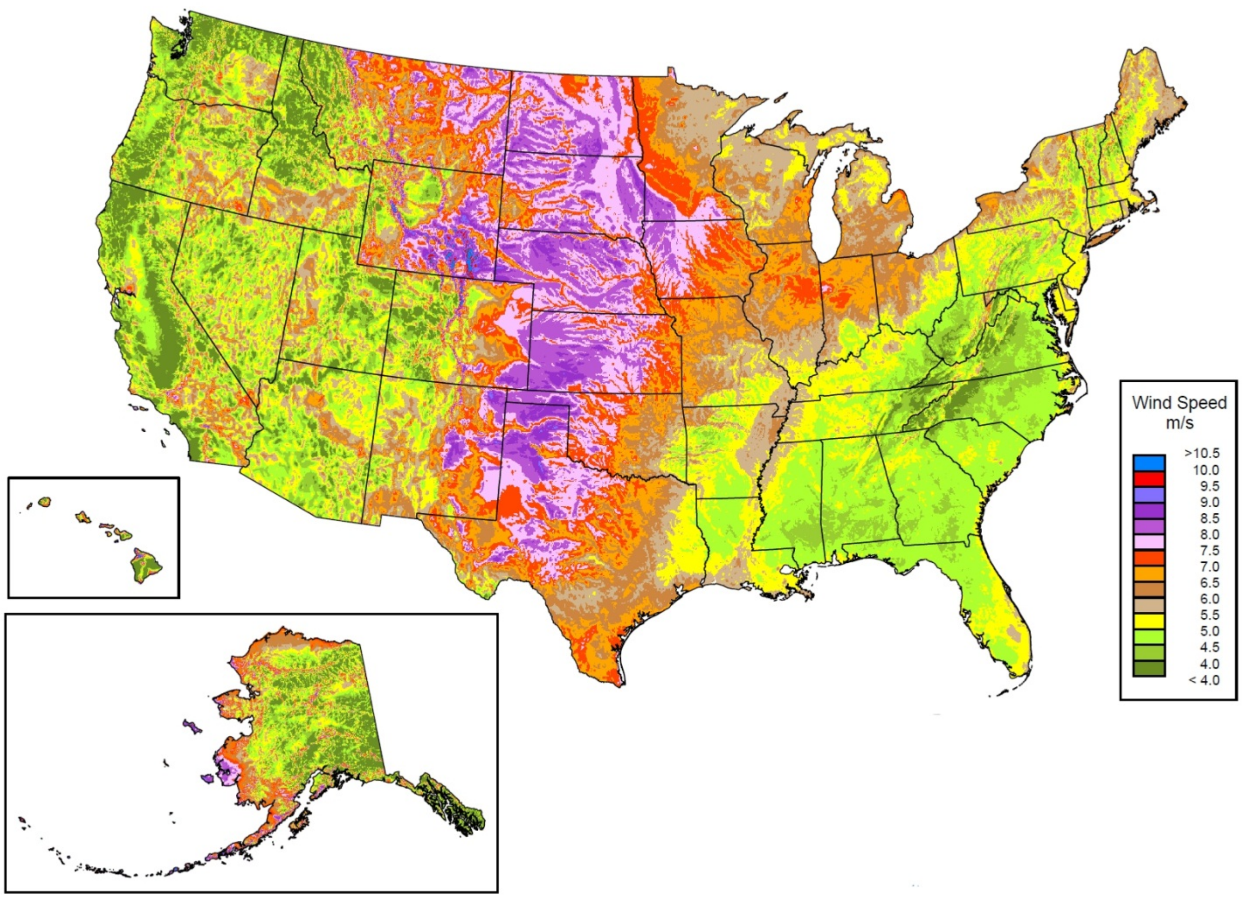
Table 2-5: U.S. Electricity Grid Fuel Profile

Fuel	MJ/MWh	%
Bituminous Coal	1,940	50.1%
Natural Gas	735	19.0%
Nuclear	755	19.5%
Hydropower	255	6.6%
Heavy Fuel Oil	120	3.1%
Wind Power	16	0.4%
Biomass	50	1.3%
Greenhouse Gas Emissions		
CO_2	683	kg/MWh
N_2O	3.22	kg CO_2e/MWh
CH_4	51.6	kg CO_2e/MWh
SF_6	3.27	kg CO_2e/MWh
CO_2e	741	kg CO_2e/MWh

3 Wind Power Resource, Capacity, and Growth

The resource base for wind in the U.S. has been studied extensively by the U.S. government, as well as industry groups, individual companies involved in the wind industry, and various partnerships among these groups. As a result, national level wind resource availability data are available across the U.S. As shown in **Figure 3-1**, high wind speeds are abundant within the southern, central, and northern plain states, across the lake states, and in southern Texas. Consistent winds sufficient to drive turbines are also available at regional and local areas across the mountain states and the West, and within portions of the Northeast. Sufficient wind resources are also available across much of the western fringe of Alaska and, to a lesser extent, Hawaii. Wind resources are generally lacking in the south. Onshore wind resources in the U.S. are estimated to be sufficient to supply approximately 10,400,000 MW of wind power capacity with a capacity factor of 30 percent; this estimate excludes areas that are not feasible for development, such as wilderness or urban areas (NREL, 2010b).

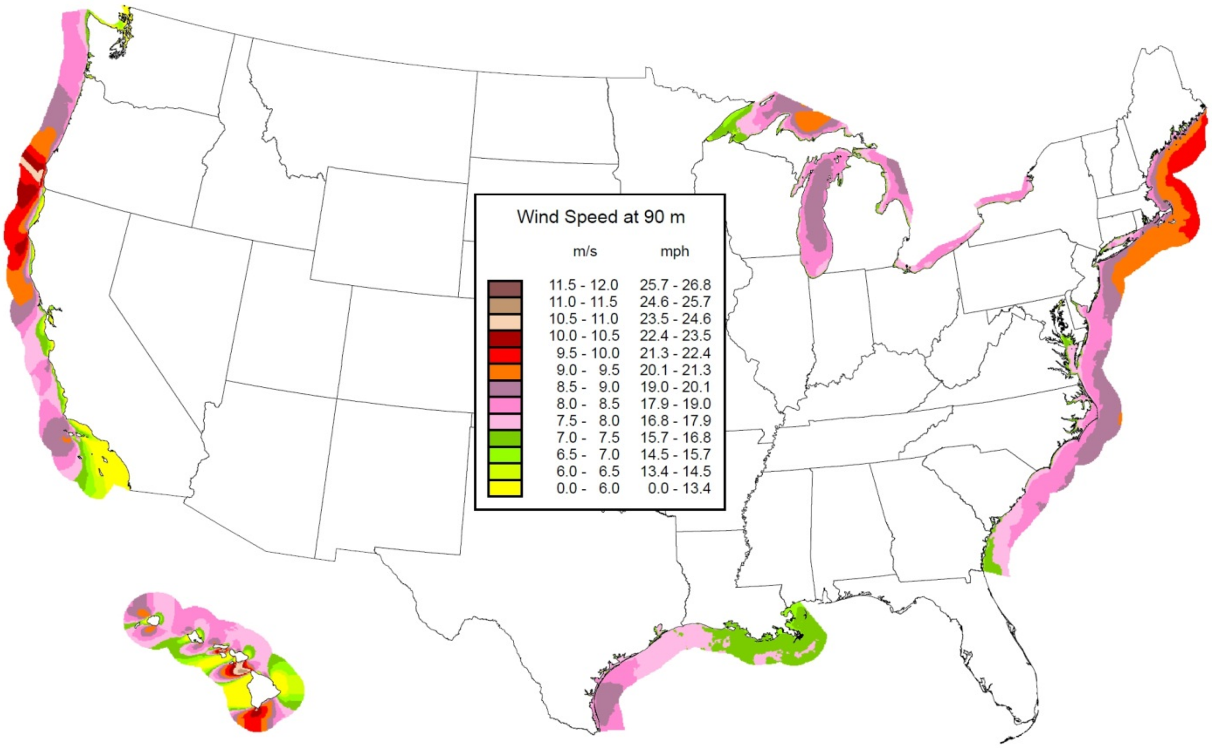
Figure 3-1: U.S. Distribution of Wind Speeds at 80 Meters (AWS Truepower & NREL, 2011)



In general, offshore wind speeds reach higher persistent velocities as compared to onshore wind resources. A compilation of U.S. offshore wind speeds is provided in **Figure 3-2.** As shown, the strongest offshore wind resources are available off the coast of the U.S. Northeast, the Great Lakes, California and Oregon, and Hawaii. Significant offshore wind resources are also available off the eastern seaboards or New Jersey, Maryland, Virginia, and North Carolina, as well as Texas, southern

California, and central to northern Oregon. In total, U.S. offshore wind resources are estimated to be sufficient to support approximately 4,150,000 MW of power production (Schwartz, et al., 2010).

Figure 3-2: U.S. Average Offshore Wind Speed at 90 Meters (NREL, 2011)



The fraction of total U.S. power generation from wind power has increased from approximately 0.1 percent in 2000, to approximately 2.3 percent in 2010. As shown in **Figure 3-3**, wind power production represents the second highest category of renewable power production, behind conventional hydroelectric. Additionally, total wind power production is greater than all other renewables (including solar photovoltaic, solar thermal, geothermal, biomass, etc.) combined. In terms of power production trends over time, **Figure 3-4** provides a summary of U.S. wind generation from 2000 through 2010, indicating consistent and near exponential growth during that period. Overall, wind power generation has increased from 5.6 TWh in 2000 to 95 TWh in 2010 (EIA, 2011c), equivalent to a compound annual growth rate of 32.7 percent.

Figure 3-3: 2009 U.S. Power Production by Fuel (EIA, 2011b)

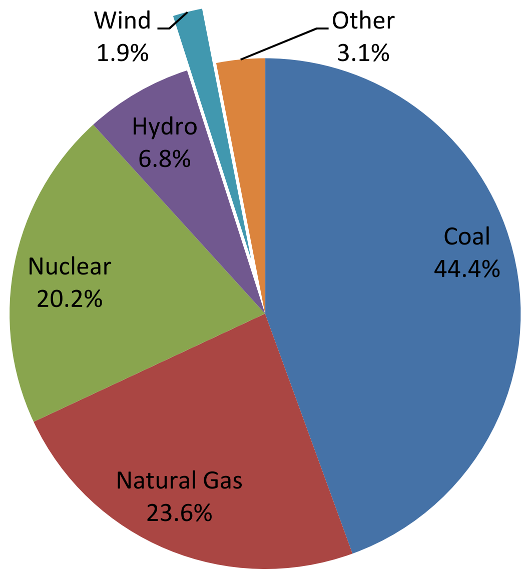
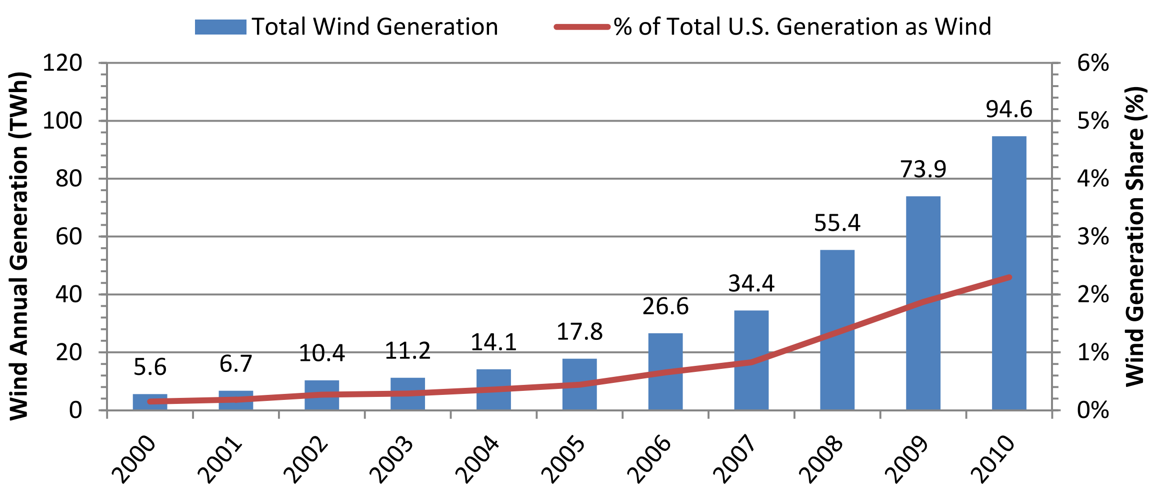
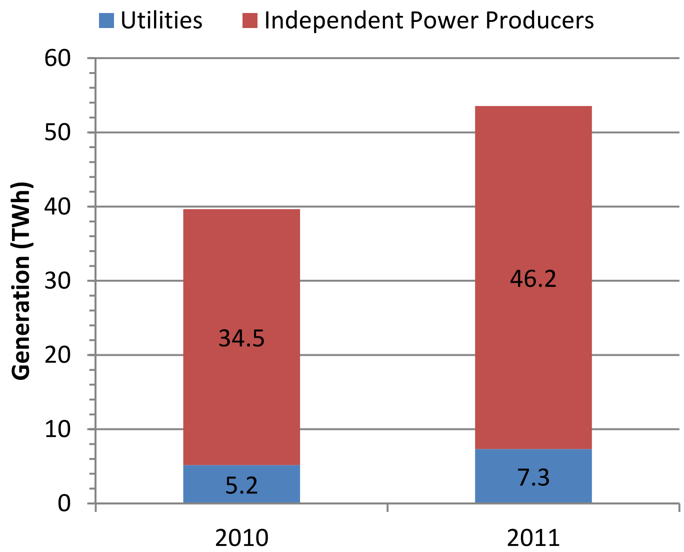


Figure 3-4: Annual Wind Generation and Share (EIA, 2011c)



Reflecting onshore wind power's relatively recent commercial scale emergence and rapid development in the U.S., current U.S. wind power generation capacities are predominantly provided by independently owned power producers. As shown in **Figure 3-5**, during January through May of 2010 and 2011, produced wind power was generated primarily by facilities owned by independent power developers/producers (86 to 87 percent), and only minimally by utilities (13 to 14 percent). Based on anticipated wind power projects (see additional discussion below), this trend is anticipated to continue in the near term, as private investors and other sources of private capital continue to drive the U.S. wind market.

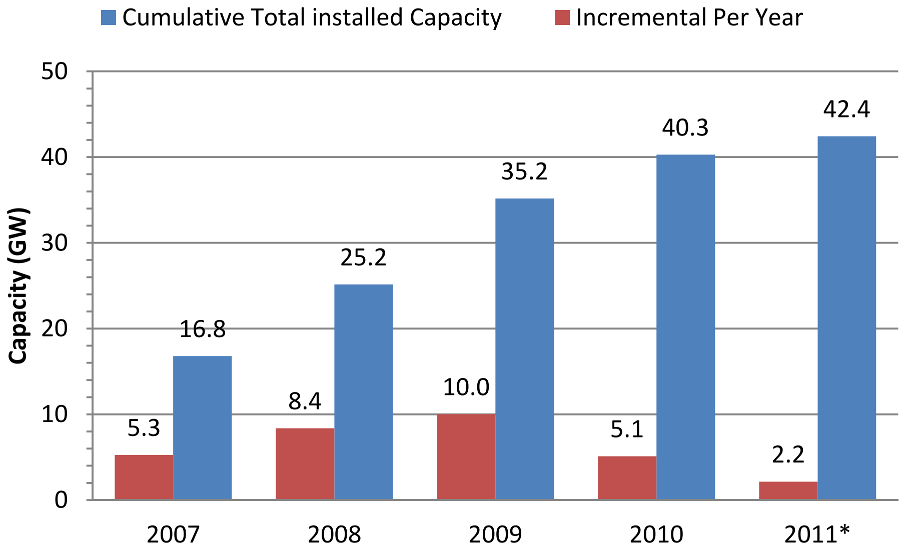
Figure 3-5: Comparison of 2010 and 2011 U.S. Wind Generation (EIA, 2011c)



As shown in **Figure 3-6**, incremental annual wind power installations reduced by approximately 50 percent between 2009 and 2010, from 10 GW in 2009, to 5.1 GW in 2010, or slightly less than 2007 levels (i.e., 5.3 GW). Although capacity growth has slowed, total wind capacity is still increasing, and many additional wind power projects are in the early to middle phases of development. This growth in wind power has been stimulated by tax credits, cash grants, and aggressive depreciation schedules. The electricity production tax credit (PTC) is a federal tax credit that was originally enacted by the Energy Policy Act of 1992 and was most recently renewed as a part of the American Recovery and Reinvestment Act (ARRA) of 2009 (EPA, 2011). The PTC gives producers of wind power 2.2 cents for every kWh of electricity produced during first 10 years of operation(EPA, 2011). The PTC is scheduled to expire at the end of 2012 (Wiser & Bolinger, 2011). The ARRA also includes provisions that allow wind energy producers to forgo the PTC and claim an investment tax credit (ITC) or cash grant that is 30 percent of the total project cost (Wiser & Bolinger, 2011). To qualify for these incentives, a wind farm must have started construction by the end of 2011 and be in operation by the end of 2012 (Wiser & Bolinger, 2011). In addition to these tax credits and grants, wind projects installed between September 2010 and the end of 2011 can depreciate 100 percent of their assets in the first year (Wiser & Bolinger, 2011). As these tax credits and other financial incentives expire, it is likely that investments in new wind power projects will slow down significantly, and with no long-term federal policies for renewable energy investments, it is difficult for producers to secure power purchase agreements.

As of 2010, Texas had the highest wind power production gross capacity in the U.S., at 10.1 GW, followed by Iowa (3.68 GW), and California (3.25 GW) (Wiser & Bolinger, 2011). As of May 2011, 7 GW of domestic wind power projects were under construction or in site preparation (Wiser & Bolinger, 2011). Of these, the highest projected capacity of new wind projects was located in the state of Washington (735 MW). Other leaders included plains and lake states (Oklahoma at 709 MW, Minnesota at 677 MW, Illinois at 587 MW, Ohio at 304 MW, Nebraska at 265 MW, and South Dakota at 210 MW), as well as Colorado (552 MW), California (443 MW), and Texas (350 MW) (AWEA, 2011a). The Northeast as a whole is scheduled to add 554 MW of wind capacity, while the South is expected to add 158 MW (AWEA, 2011a). These projections are based on data collected by the American Wind Energy Association; unexpected shifts in financing, permitting, or grid integration barriers could easily hinder such growth in wind power capacity.

Figure 3-6: Incremental and Cumulative Installed Wind Capacity (AWEA, 2011a)

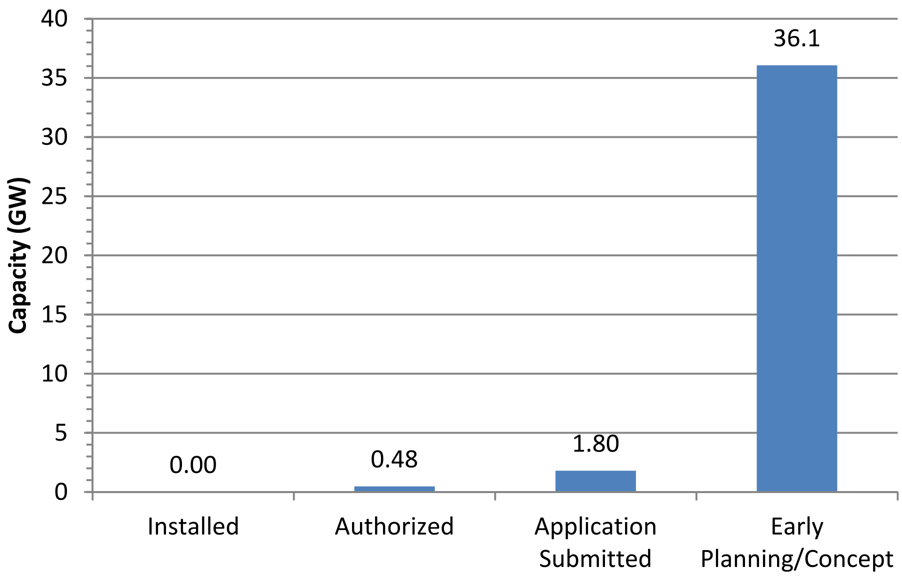


**2011 figures are for 1st and 2nd quarters only*

Offshore wind market futures are characterized by a high degree of uncertainty, but have been bolstered by recent federal announcements in support of offshore wind power. These include a new *National Offshore Wind Strategy* (EERE, 2011), as well as the recent promulgation of the Bureau of Ocean Energy management, Regulation, and Enforcement's *Renewable Energy and Alternate Uses of Existing Facilities on the Outer Continental Shelf* rule, and the Energy Policy Act of 2005, which authorized the granting of offshore leases for alternative energy projects, including wind. As discussed previously, only one domestic project, Cape Wind, has successfully navigated the permitting process for offshore wind power. At a start to finish time of nearly a decade, the permitting process for Cape Wind was neither streamlined nor rapid, and underscores significant challenges faced by the industry both in terms of cost and implementation timeframe.

However, industry outlook for offshore wind remains sufficiently positive, at least with respect to a 5- to 10-year timeframe, to drive new project starts. As shown in **Figure 3-7**, although no offshore wind power has yet been installed, 475 MW have been authorized (representing Cape Wind and a small trial installation in Texas), 1.8 GW are moving forward with relevant applications and environmental review, and 36.1 GW (representing 68 individual projects) are currently in early planning and concept stage (4C Offshore, 2011). Additional projects are also being considered, but have not yet announced anticipated or potential capacities (4C Offshore, 2011).

Figure 3-7: Installed and Potential Offshore Wind Power Projects (4C Offshore, 2011)



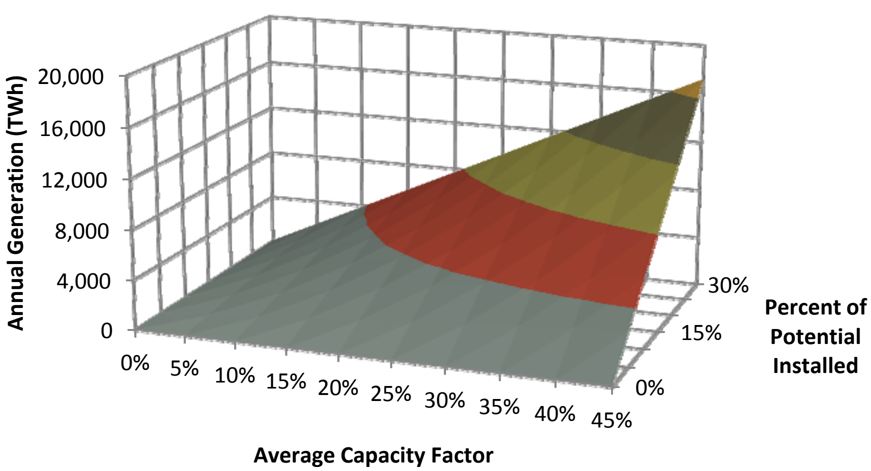
The AWEA estimates 14,550 TW of potential wind capacity in the U.S., 29 percent of which is offshore potential (AWEA, 2011a). This estimate, like similar estimates for tidal, solar, and geothermal potential energy, is misleading because not all of that resource is economically accessible. There is a large amount of uncertainty about what percent of the capacity will be installed and, further, what amount of electricity will be generated from that installed capacity (e.g. capacity factor). **Table 3-1** shows the amount of electricity generated in various combinations of potential installed capacities and capacity factors as percentage of 2010 U.S. total power generation of 3,950 TWh. For example, if 1 percent of potential wind power is developed and the associated wind farms have a 30 percent capacity factor, then the resulting wind power will supply 10 percent of the U.S. electricity supply. Or if 15 percent of potential wind power is developed and the associated wind farms have a 20 percent capacity factor, then the resulting wind power will supply 97 percent of the U.S. electricity supply. The bolded values in **Table 3-1** are those which are greater than 100 percent, i.e. those which exceed the total annual U.S. electricity generation in 2010 of 3,950 TWh. The results in this table are not meant to imply that all demand for electricity could be supplied by wind generation, since there are many factors, such as cost, grid stability, and transmission constraints, which limit penetration. The Energy Information Administration's (EIA) Annual Energy Outlook (AEO) 2011 reference case predicts less than a GW of new wind installations between 2013 and 2021, so assessment of potential wind power must be weighed against the reality of what will be installed.

Table 3-1: Potential Wind Generation

Potential Capacity (GW)	Percent of Potential Installed	Capacity Factor							
		10%	15%	20%	25%	30%	35%	40%	45%
36	0.25%	0.8%	1.2%	1.6%	2.0%	2.4%	2.8%	3.2%	3.6%
73	0.50%	1.6%	2.4%	3.2%	4.0%	4.8%	5.6%	6.5%	7.3%
146	1%	3.2%	4.8%	6.5%	8.1%	10%	11%	13%	15%
291	2%	6.5%	10%	13%	16%	19%	23%	26%	29%
437	3%	10%	15%	19%	24%	29%	34%	39%	44%
582	4%	13%	19%	26%	32%	39%	45%	52%	58%
728	5%	16%	24%	32%	40%	48%	56%	65%	73%
1,455	10%	32%	48%	65%	81%	97%	**113%**	**129%**	**145%**
2,183	15%	48%	73%	97%	**121%**	**145%**	**169%**	**194%**	**218%**
2,910	20%	65%	97%	**129%**	**161%**	**194%**	**226%**	**258%**	**290%**
3,638	25%	81%	**121%**	**161%**	**202%**	**242%**	**282%**	**323%**	**363%**
4,365	30%	97%	**145%**	**194%**	**242%**	**290%**	**339%**	**387%**	**436%**

Figure 3-8 shows the potential generation from wind power given the estimates of potential capacity and assumptions about average capacity factor. The conclusion is that even with poorly performing turbines (at capacity factors lower than 20), and with very low utilization of the potential resource, (below 10 percent), large amounts of electricity can be generated relative to the demand in the U.S. Again, this should not be taken to mean that this can be done cheaply or reliably, but rather as an important context for the amount of wind resource.

Figure 3-8: Potential Wind Generation



4 Environmental Analysis of Wind Power

The operation of a wind farm (onshore or offshore) does not result in direct emissions of GHGs or other environmental emissions. However, energy is expended during the manufacture, transport, installation, and maintenance of wind turbines and other equipment used for wind power. Further, the construction of a trunkline that connects a wind project to the electricity grid also incurs environmental burdens. LCA is necessary to evaluate the indirect emissions and other environmental burdens of onshore and offshore wind power.

4.1 LCA Scope and Boundaries

The boundaries of the LCA account for the cradle-to-grave energy and material flows for wind power and, when applicable, backup power. The boundaries include five life cycle (LC) stages:

LC Stage #1, Raw Material Acquisition (RMA): Accounts for acquisition of fuels from the earth or forest. RMA is not relevant to wind power because wind is a primary energy source that does not require anthropogenic inputs prior to power generation. In scenarios for GTSC backup of wind power, RMA accounts for the extraction of natural gas. The supply mix of domestic natural gas include conventional and unconventional sources of natural gas, which are based on the 2009 industry profiles published in the AEO (EIA, 2011a) and as used by NETL's LC profile of natural gas (NETL, 2011).

LC Stage #2, Raw Material Transport (RMT): Accounts for the transport of fuel. RMT is not relevant to wind power because wind is a primary energy source that does not require anthropogenic inputs prior to power generation. In scenarios for GTSC backup of wind power, RMT accounts for the pipeline transport of natural gas to the GTSC power plant.

LC Stage #3, Energy Conversion Facility (ECF): Includes all construction and operation activities at a wind power project, including site preparation, equipment manufacture and installation, and facility operation. In the case of an offshore wind project, it also includes the use of marine vessels used for construction and crew transport, and the construction of a submarine cable that connects the offshore wind project with an onshore grid. The output of this stage is electricity that is ready for transmission. In scenarios for backup of wind power, this stage accounts for the combustion of natural gas by a GTSC power plant or the LC emissions of electricity supplied by the national power grid. This stage is also referred to as the energy conversion facility (ECF).

LC Stage #4, Product Transport (PT): Accounts for the transmission of electricity from the point of generation to the final consumer. There is a seven percent loss associated with transmission and distribution (T&D) of electricity (representative of the U.S. average electricity grid). The only emission associated with this stage is the sulfur hexafluoride (SF_6) that is released by transmission and distribution electrical equipment. This stage is also referred to as product transport (PT).

LC Stage #5, End Use (EU): Accounts for the consumption of electricity (this stage does not have any energy or material flows and thus serves as a placeholder in the model).

4.2 Basis of Comparison

The use of a consistent functional unit is another convention that enforces comparability between LCAs. The functional unit of this analysis is the delivery of 1 MWh of electricity to the consumer.

4.3 Greenhouse Gas Metrics

GHGs in this inventory are reported on a common mass basis of carbon dioxide equivalents (CO_2e) using the global warming potentials (GWP) of each gas from the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (Forster et al., 2007). The default GWP used is the 100-year time frame. For comparison, **Table 4-1** shows the IPCC 2007 GWPs for 20-year, 100-year, and 500-year time frames.

Table 4-1: IPCC 2007 Global Warming Potentials (Forster, et al., 2007)

GHG	20-year	100-year (Default)	500-year
CO_2	1	1	1
CH_4	72	25	7.6
N_2O	289	298	153
SF_6	16,300	22,800	32,600

The results of this analysis also include an inventory of non-GHG emissions, effluents related to water quality, resource consumption, and water withdrawal and discharge. Equivalency factors are not applied to these metrics.

4.4 Scenarios

This analysis has scenarios for three wind farm technologies as well as scenarios for backup power.

The onshore wind farms of this analysis have total capacities of 200 MW and use conventional or advanced horizontal axis wind turbines. The key difference, for the purpose of this study, between conventional and advanced turbines is their rotor diameters. Onshore conventional turbines have a rotor diameter of 63 meters, while onshore advanced wind turbines have a rotor of 125 meters. The power output of a wind turbine is highly dependent on its rotor diameter; the conventional onshore wind turbine in this analysis has a capacity of 1.5 MW, and the advanced onshore wind turbine has a capacity of 6.0 MW.

The characteristics of the offshore wind farm in this analysis are based on the design of the Cape Wind energy project, an offshore wind farm that has been approved off the coast of Massachusetts. It has a total capacity of 468 MW. Each turbine has a rotor diameter of 98 meters and a capacity of 3.6 MW.

The three wind farm projects are summarized in **Table 4-2**.

Table 4-2: Wind Farm Scenarios

Property	Scenario		
	Onshore Conventional	Onshore Advanced	Offshore
Total Project Capacity, MW	200	200	468
Single Turbine Capacity, MW	1.5	6.0	3.6
Turbine Rotor Diameter, m	1.5	125	98

This analysis also models backup power in addition to the three wind power technology scenarios. Two backup scenarios are modeled: (1) a load-following simple cycle gas turbine (GTSC) that uses the domestic mix of natural gas and (2) a power mix representative of the average U.S. electricity grid.

Detailed data on wind turbine manufacture, wind farm construction, and wind farm operation are provided in **Appendix B**. More details on GTSC and average grid backup power are provided in **Section 2**, Wind Power Technology Performance. Details on GTSC and the natural gas LC are also provided in NETL's technology assessment of natural gas power (NETL, 2012).

4.5 Model Structure

An LCA model is an interconnected network of unit processes. The throughput of one unit process is dependent on the throughputs of upstream and downstream unit processes. These processes were assembled using the GaBi 4.0 software tool. **Figure 4-1** shows NETL's total LC approach to modeling wind power, and **Figure 4-2** shows the detailed modeling approach for the wind farm (LC Stage #3) only.

Figure 4-1: LCA Modeling Framework for Wind Power

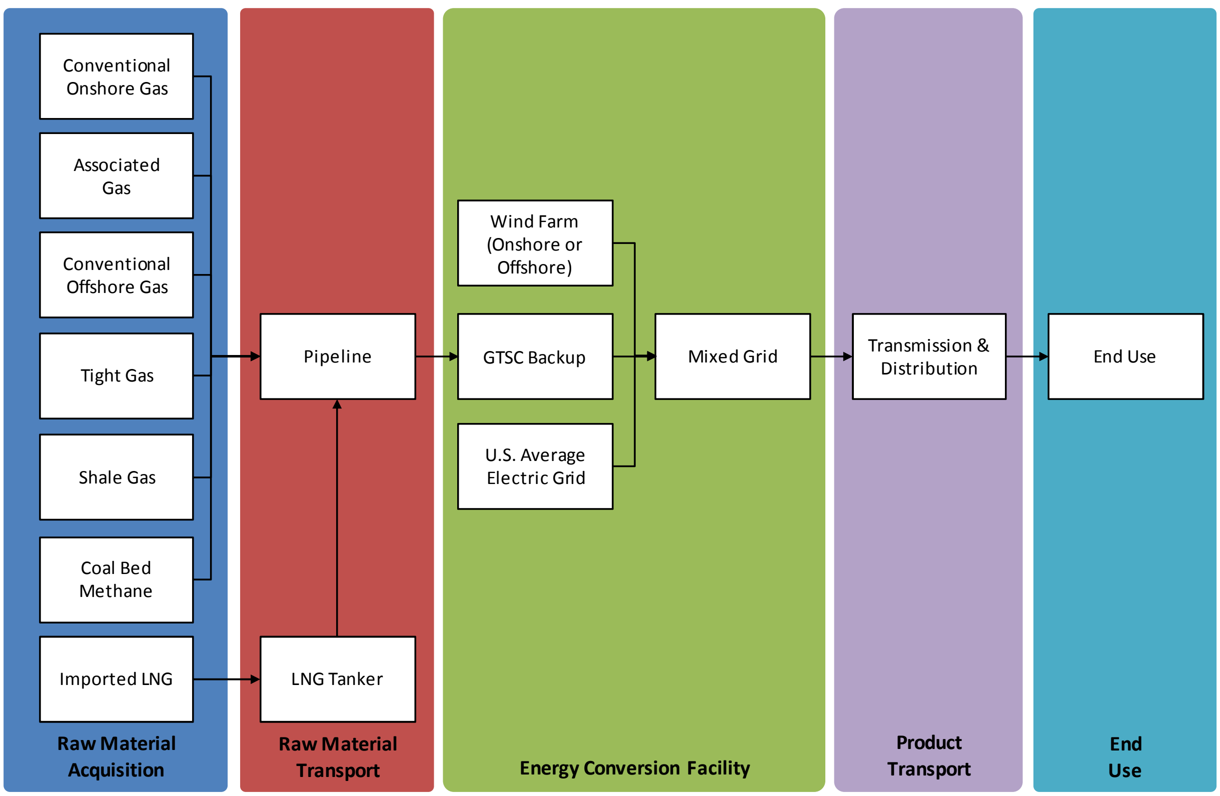
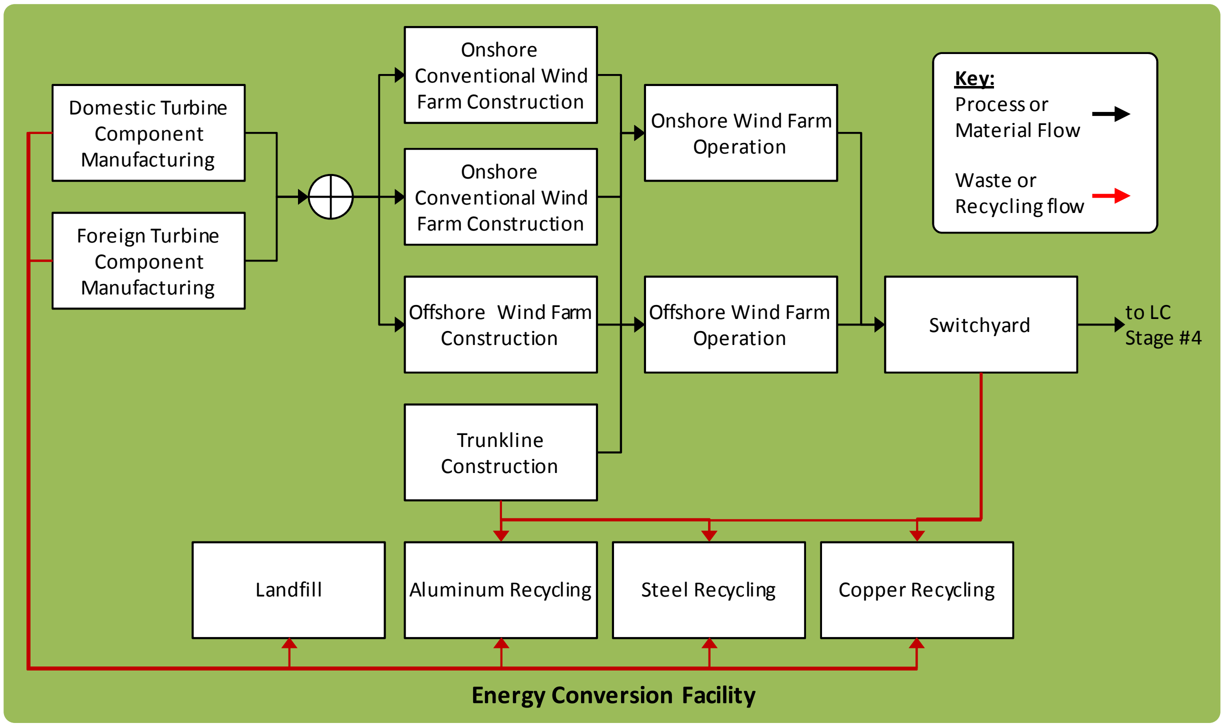


Figure 4-2: Detailed Modeling Structure of Life Cycle Stage #3 for Wind Power



4.6 Key Modeling Parameters

The key modeling parameters include engineering specifications, wind characteristics, and wind farm performance.

4.6.1 Rotor Diameter

This analysis uses a 1.5 MW wind turbine to model onshore conventional wind power. The turbine scaling equations used by this analysis demonstrate that a turbine with a rotor diameter of 63 meters is capable of generating 1.5 MW at typical wind speeds. General Electric's technical specifications for 1.5 MW wind turbines show rotor diameters ranging from 77 to 83 meters (GE, 2010a). Another data source, EERE's 2010 technology profile of wind power (Wiser & Bolinger, 2011), shows that the average wind turbine capacity between 2004 and 2007 had a capacity of 1.43 to 1.60 MW (a capacity range that includes 1.5 MW turbines); the average rotor diameter during the same time period ranged from 68 to 79 meters (Wiser & Bolinger, 2011). To capture the variability exhibited by these data sources, this analysis assigns an uncertainty of +/- 10 percent around the expected value for the rotor diameter; this percent range is consistent with the variability described by the average rotor diameters reported in literature (GE, 2010a; Wiser & Bolinger, 2011). For the rotor diameter of 1.5 MW onshore wind turbines, the low value is 57 meters, the expected value is 63 meters, and the high value is 69 meters.

Advanced onshore wind turbines, as modeled in this analysis, have a capacity of 6 MW and a rotor diameter of 125 meters. Advanced onshore wind turbines have not been installed, so there is no data on the variability of their rotor diameters. The expected value for this parameter is 125 meters; the range of uncertainty for this parameter is 100 to 125 meters.

The environmental impact statement for the Cape Wind project specifies a rotor diameter of 111 meters for offshore, 3.6 MW wind turbines (MMS, 2009). A range of 107 to 113 meters is used to account for the uncertainty in rotor diameters for offshore wind turbines; this uncertainty range is based on manufacturer specifications for offshore wind turbines (GE, 2012; Siemens, 2011).

4.6.2 Wind Speed

The average onshore wind speed at an 80 meter height ranges from 4 to 10 meters per second (m/s); this range is for the entire U.S. and does not account for the locations of wind farms. In the leading states for installed onshore wind power (Texas, Iowa, California, Minnesota, Washington, Oregon, and Illinois), the average wind speed at an 80 meter height is approximately 6.5 m/s to 9.5 m/s, with an expected value of 8.0 m/s (AWS Truepower & NREL, 2011; NREL, 2011). These average wind speeds include periods of low wind availability when wind turbines are not operating. Since the environmental model of this analysis includes parameters for both capacity factor and wind speed, the values for these parameters should be representative of the same operating regime – the parameter for capacity factor describes the share of time that a wind farm is producing power, so the parameter for wind speed should also be representative of the period of time during which a wind farm is producing power.

The relationship between wind speed and wind power production are described by the power curve for a wind turbine. As described by a typical power curve for onshore wind power, a wind turbine starts producing power when wind speeds exceed 5 m/s, reaches a maximum power output at 12 to 13 m/s, and shuts down to prevent equipment damage when wind speeds exceed 22 m/s (DOE, 2008; IPCC, 2012). This analysis uses a wind speed of 12 m/s for the expected value of onshore wind speed; this value does not represent the average wind speed of the wind farm, but falls in the middle of the power curve and represents the average wind speed for wind power generation. To account for the variability of this parameter, a range of 8 to 18 m/s is used to calculate the uncertainty in GHG emissions from onshore wind power.

The environmental impact statement for the Cape Wind project specifies a wind speed operating range of 3 to 25 m/s (MMS, 2009); these are extreme wind speeds, not average wind speeds, so they are not an appropriate range for calculating LC environmental burdens. This analysis uses a wind speed of 12 m/s for the expected value of offshore wind speed. This is the same value used for onshore wind power because offshore wind turbines have similar power curves as onshore wind turbines. To account for the variability of this parameter, a range of 8 to 18 m/s is used to calculate the uncertainty in GHG emissions from offshore wind power.

4.6.3 Capacity Factor

The capacity factor describes the share of time that a power plant is producing power. The capacity factors for wind farms are dependent on the availability of wind and vary regionally. The average capacity factor for onshore conventional wind power in the U.S. is 30 percent (Wiser & Bolinger, 2011). No data are available for the actual performance of onshore advanced wind power, so this analysis uses the same capacity factor (30 percent) for onshore conventional and onshore advanced wind power. The projected capacity factor for the Cape Wind offshore wind project is 39 percent (MMS, 2009).

4.6.4 Other Parameters

The import rate, recycling rate, and life span of wind turbines are also parameterized in the LCA model. The import rate accounts for the fraction of turbine component manufactured overseas compared to domestically produced components. The recycling rate specifies the portion of recoverable scrap (from turbine manufacturing or wind farm decommissioning) that is recycled. The turbine life is used to scale the expected life of a turbine to the total projection life of the wind farm.

Table 4-3 shows the expected values for key parameters used by the LCA model of wind power.

Table 4-3: Onshore and Offshore Wind Power Modeling Parameters

Parameter	Onshore Conventional	Onshore Advanced	Offshore	Reference
Rotor Diameter (m)	63	125	111	Wiser & Bolinger, 2011; GE, 2010a
Wind Speed (m/s)	12	12	12	AWS Truepower & NREL, 2011
Capacity Factor (%)	30	30	39	Wiser & Bolinger, 2011; MMS, 2009
Percent Imported (%)	55	55	55	Wiser & Bolinger, 2011
Percent Recycled (%)	90	90	90	DOE, 2008
Turbine Life (Years)	20	20	20	DOE, 2008

4.7 Wind Turbine Component Replacement Rates

Over the life of the wind farm, some turbine components will need to be replaced. Wind farms are a relatively new technology, so actual data on failure rates over a 30-year period are not available. Based on cost contingencies for wind farm operations, the EERE developed ranges of anticipated failure rates for key wind farm components (DOE, 2008). These failure rates are highly variable. Turbine blades are expected to fail within 18 to 22 years; if all three blades on a rotor fail within this time frame, a wind turbine with a 30-year project life will use 1.4 to 1.7 rotors[1]. Similarly, a gearbox has an expected life of 10 to 20 years, so a wind farm with a 30-year project life will use 1.5 to 3 gearboxes[2]. No data are available on the distribution of failure rates within these ranges, so the model of this analysis uses the midpoint of each range as the expected value. **Table 4-4** shows the expected lives of key wind turbine components and how many pieces are used during a 30-year project. As shown in **Table 4-4**, this analysis models the replacement of the rotor, nacelle, generator, and gearbox.

[1] 30 years divided by a 22 year life expectancy is equivalent to 1.4 pieces per project life. 30 years divided by an 18 year life expectancy is equivalent to 1.7 pieces per project life.

[2] 30 years divided by a 20 year life expectancy is equivalent to 1.5 pieces per project life. 30 years divided by a 10 year life expectancy is equivalent to 3.0 pieces per project life.

Table 4-4: Wind Farm Component Replacement Rates

Component	Part Life (yrs.)			Pieces per Wind Farm Life (pieces/30 yrs.)		
	Low	Expected Value	High	Low	Expected Value	High
Rotor	18	20	22	1.4	1.5	1.7
Nacelle (Bearing, Shafts, Motors, Frames, etc.)	12	16	20	1.5	1.9	2.5
Generator	15	17.5	20	1.5	1.7	2.0
Gearbox	10	15	20	1.5	2.0	3.0

This LCA applies the same replacement rates to all types of wind projects (onshore conventional, onshore advanced, and offshore). These rates are also tested by the sensitivity analysis presented later in this report.

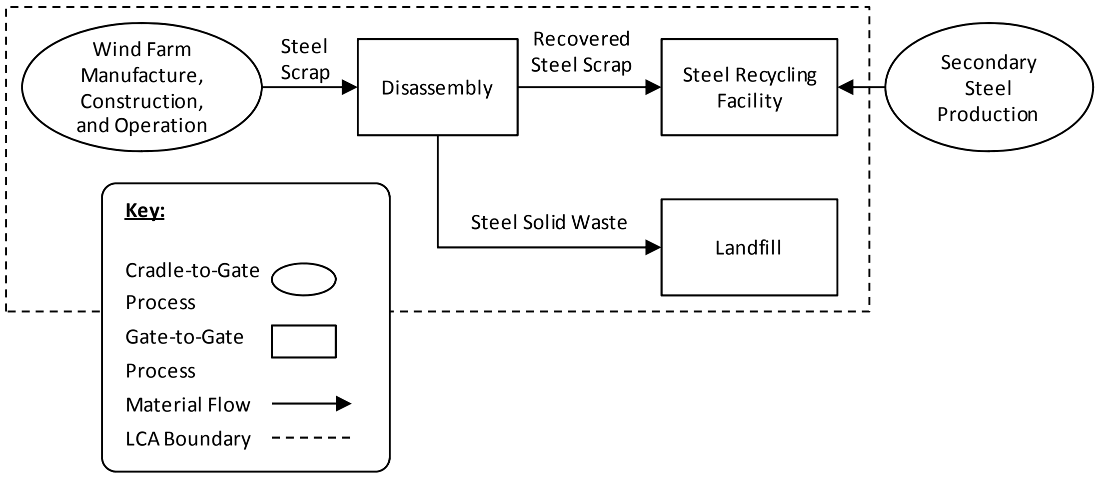
4.8 Management of Recyclable Materials

Recyclable materials are generated during the manufacture of wind farm components. All non-recyclable materials, such as concrete or metal/fiber composites, are landfilled. Scrap is produced during the manufacture of all wind turbine components. One percent of all materials that enter the turbine manufacturing process end up as scrap, and 90 percent of metallic scrap is recovered for recycling. Non-metallic, composite scrap is not recyclable and is thus landfilled. The model includes parameters that allow the adjustment of these manufacturing scrap rates.

Recyclable materials are also generated during the decommissioning of wind farms. It is assumed that 90 percent of metallic scrap is recovered for recycling. Non-metallic, composite scrap is not recyclable, so it is landfilled.

System expansion is used to model the interaction between the recycled materials of wind power and the material streams of other supply chains. The boundaries of the system expansion used for modeling the end-of-life management of wind turbines are shown in **Figure 4-3**.

Figure 4-3: Example of System Expansion for Material Recycling



Due to the high value of some wind turbine components, remanufacture or refurbishment is more likely than recycling of materials. However, lack of data prevented the modeling of refurbishment scenarios. The lower environmental benefits of recycling relative to reuse mean manufacturing impacts are likely overestimated.

4.9 Land Use Change

Analysis of land use effects is considered a central component of an LCA under both the International Standards Organization (ISO) 14044 and the American Society for Testing and Materials (ASTM) standards. Additionally, the EPA's Renewable Fuel Standard Program (RFS) (EPA, 2010b) includes a method for assessing land use change and associated GHG emissions. The land use model of this analysis is consistent with this method. It quantifies both the area of land changed, as well as the GHG emissions associated with that change, for direct and select indirect land use impacts.

4.9.1 Definition of Direct and Indirect Impacts

Land use effects can be roughly divided into direct and indirect. In the context of this study, direct land use effects occur as a direct result of the LC processes needed to produce electricity via onshore or offshore wind turbines, with or without GTSC backup. Direct land use change is determined by tracking the change from an existing land use type (native vegetation or agricultural lands) to a new land use that supports production; examples include wind farms, biomass feedstock cropping, coal mines, and energy conversion facilities.

Indirect land use effects are changes in land use that occur as a result of the direct land use effects. For instance, if the direct effect is the conversion of agricultural land to land used for energy production or conversion, an indirect effect might be the conversion of native vegetation to new farmland, but at a remote location, in order to meet ongoing food supply/demand. This specific case of indirect land use change has been studied in detail by the EPA (EPA, 2010a) and other investigators, and sufficient data are available to enable its consideration within this study. There are also many other types of indirect land use change that could result from installation and operation of new energy production and conversion facilities. For instance, the installation of a new wind farm in a rural location could result in the migration of employees closer to the site, causing increased urbanization in surrounding areas. However, due to high uncertainty in predicting and quantifying this and other less-studied indirect effects, such phenomena were not considered in this analysis.

4.9.2 Land Use Metrics

A variety of land use metrics that seek to numerically quantify changes in land use, have been devised in support of LCAs. Two common metrics in support of a process-oriented LCA are transformed land area (square meters of land transformed) and GHG emissions (kg CO_2e). The transformed land area metric estimates the area of land that is altered from a reference state, while the GHG metric quantifies the amount of carbon emitted in association with that change. **Table 4-5** summarizes the land use metrics included in this study.

Table 4-5: Primary Land Use Change Metrics Considered in this Study

Metric Title	Description	Units	Type of Impact
Transformed Land Area	Area of land that is altered from its original state to a transformed state during construction and operation of wind farms	Square Meters	Direct and Indirect
Greenhouse Gas Emissions	Emissions of GHGs associated with land clearing/transformation, including emissions from above-ground biomass, below-ground biomass, soil organic matter, and lost forest sequestration	kg CO_2e	Direct and Indirect

For this analysis, the assessment of GHG emissions from land use includes those emissions that result from the following:

- Quantity of GHGs due to biomass clearing during construction of each facility
- Quantity of GHGs due to oxidation of soil carbon and underground biomass following land transformation
- Evaluation of ongoing carbon sequestration that would have occurred under existing conditions, but did not occur, under study/transformed land use conditions

Additional land use metrics, such as potential damage to ecosystems or species, water quality changes, changes in human population densities, quantification of land quality (e.g. farmland quality), and many other land use metrics may conceivably be included in the land use analysis of an LCA. However, data needed to support accurate analysis of these metrics are severely limited in availability (Canals et al., 2007; Koellner & Scholz, 2007) or otherwise outside the scope of this study. Therefore, only transformed land area and GHG emissions are quantified for this study.

4.9.3 Land Use Calculation Method

As previously discussed, the land use metrics used for this analysis quantify the land area that is transformed from its original state due to construction and operation of the facilities, including agricultural production, required for the wind power cases of this study.

4.9.3.1 Transformed Land Area

The transformed land area metric was assessed using reported land use areas, satellite imagery, aerial photographs, and other available data for each of the facilities considered within this study, in order to assess and quantify the area of original state land use for agriculture, forest, or grassland. Urban, residential, and other land uses were assumed to be avoided during the siting of each facility. Assumed facility locations and sizes are shown in **Table 4-6**. The facility sizes, natural gas feed rates for GTSC production, wind farm capacities, and locations used elsewhere in this LCA were incorporated into the transformed land area metric for consistency. It is assumed that the U.S. power grid system was pre-existing, and no construction or other changes that would be relevant to land use would occur under LC Stage #5. The supply mix of domestic natural gas include conventional and unconventional sources of natural gas, which are based on the 2009 industry profiles published in the AEO (EIA, 2011a) and used by NETL's LCAs of natural gas.

Table 4-6: Wind or Wind-GTSC Backup Facility Locations

Profile or LC Stage No.	Facility	Location
Wind Facilities		
Onshore Wind		
LC Stage #3	Onshore Wind Farm	U.S. Average
LC Stage #4	Wind Farm Trunkline	U.S. Average
Offshore Wind		
LC Stage #3	Offshore Wind Farm	Not Considered[1]
LC Stage #4	Wind Farm Trunkline	U.S. Average
GTSC Facilities		
Conventional Offshore (Domestic)		
LC Stage #1	Conventional Domestic Offshore Platform	U.S. Offshore
LC Stage #2	Conventional Domestic Offshore Pipelines	U.S. Offshore
Conventional Onshore (Domestic)		
LC Stage #1	Conventional Domestic Onshore Wellfields	Contiguous 48 States
LC Stage #2	Conventional Domestic Onshore Pipelines	Contiguous 48 States
Conventional Onshore Associated (Domestic)		
LC Stage #1	Conventional Domestic Onshore Wellfields	Contiguous 48 States
LC Stage #2	Conventional Domestic Onshore Pipelines	Contiguous 48 States
Barnett Shale (Domestic)		
LC Stage #1	Barnett Shale Gas Wellfields	Texas/Permian Basin
LC Stage #2	Barnett Shale Gas Pipeline	Texas, Louisiana, Mississippi
Coal Bed Methane (Domestic)		
LC Stage #1	Coal Bed Methane Wellfields	Montana, Wyoming, New Mexico, Colorado, Oklahoma, Illinois
LC Stage #2	Coal Bed Methane Pipeline	Wyoming, Nebraska, Kansas, Oklahoma, Arkansas, Mississippi
Facilities Common to All Natural Gas Sources		
LC Stage #3	GTSC	Southern MS

Transformed land area for onshore wind facilities was evaluated based on U.S. average land use values for wind farms (Denholm, Hand, Jackson, & Ong, 2009). Transformed land area for all other facilities, existing land use types, were evaluated based on facility sizes found in the literature, combined with statewide or regional average land uses as identified by the U.S. Department of Agriculture (USDA) (USDA, 2005).

For indirect land use change, consistent with EPA's RFS2 analysis, it was assumed that 30 percent of all agricultural land that was lost as a result of the installation of facilities within the study resulted in the creation of new agricultural land at a remote location within the U.S. The creation of new agricultural land, in turn, was assumed to result in the conversion of either forest or grassland/pasture to farmland, according to regional land use characteristics identified in USDA (2005).

[1] The offshore wind farm is not considered for land use impacts because it would be installed in water, and therefore would not result in any land use impact.

4.9.3.2 Greenhouse Gas Emissions

GHG emissions due to land use change were evaluated based on the EPA's method for the quantification of GHG emissions, in support of RFS2 (EPA, 2010a). EPA's analysis quantifies GHG emissions that are expected to result from land use changes from forest, grassland, savanna, shrubland, wetland, perennial, or mixed land use types to agricultural cropland, grassland, savanna, or perennial land use types. Relying on an evaluation of historic land use change completed by Winrock, EPA calculated a series of GHG emission factors for the following criteria: change in biomass carbon stocks, lost forest sequestration, annual soil carbon flux, methane emissions, nitrous oxide emissions, annual peat emissions, and fire emissions, all of which would result from land conversion over a range of timeframes. EPA's analysis also includes calculated reversion factors, for the reversion of land use from agricultural cropland, grassland, savanna, and perennial, to forest, grassland, savanna, shrub, wetland, perennial, or mixed land uses. Emission factors considered for reversion were change in biomass carbon stocks, change in soil carbon stocks, and annual soil carbon uptake over a variety of timeframes. Each of these emission factors, for land conversion and reversion, was included for a total of 756 global countries and regions within countries, including the 48 contiguous states. Based on the land use categories (forest, grassland, and agriculture/cropland) that were affected by study facilities, EPA's emission factors were applied on a statewide or regional basis.

As discussed in **Section 4.9.1**, GHG emissions from indirect land use were quantified only for the displacement of agriculture and not for the displacement of other land uses. Indirect land use GHG emissions were calculated based on estimated indirect land transformation values, as discussed previously. Then, EPA's GHG emission factors for land use conversion were applied to the indirect land transformation values, according to transformed land type and region, and total indirect land use GHG emissions were calculated.

4.10 Environmental Results

The LCA model of this analysis accounted for the GHG emissions of the wind power LC, including emissions from the manufacture and installation of wind turbines and ancillary equipment, fuel consumed during the O&M of the wind power facility, and the emissions from the transmission and distribution of electricity. All results are expressed on the basis of 1 MWh of electricity delivered to the consumer. The GHG results are discussed below.

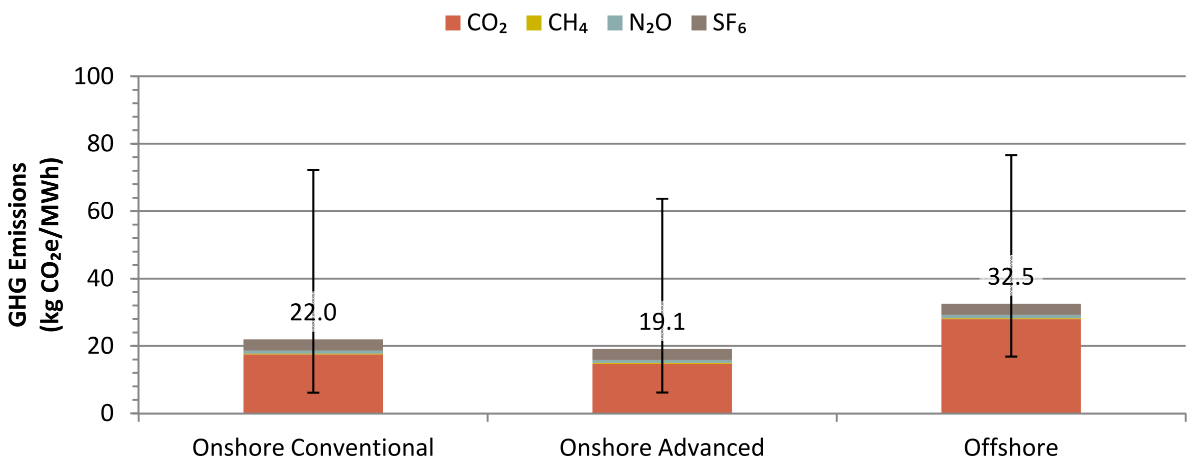
4.10.1 Onshore and Offshore Wind Power

The LC GHG emissions for wind power from conventional and advanced onshore wind power are 22.0 and 19.1 kg CO_2e per MWh, respectively, and are 32.5 kg CO_2e per MWh for offshore wind power. The advanced onshore system has lower GHG emissions than the conventional system; this is due to the higher economy of scale between turbine materials and turbine rating (MW) for the advanced systems. Offshore wind power has higher LC GHG emissions than both onshore scenarios due to added complexity of installing, maintaining, and connecting wind turbines 20 km from the shoreline.

The LC GHG emissions for wind power are shown in **Figure 4-4**. The GHG profile for wind power is dominated by carbon dioxide, which is attributable to material and installation requirements for wind farms. Carbon dioxide is 80 percent of the GHG profile for onshore conventional, 77 percent for onshore advanced, and 86 percent for offshore wind power.

SF_6 also contributes significantly to the GHG profile for wind power. Significant SF_6 emissions are not released directly by wind farms, but SF_6 is released by the electrical equipment used for the transmission and distribution of electricity (LC Stage #4). SF_6 is 15 percent of the GHG profile for onshore conventional, 17 percent for onshore advanced, and 10 percent for offshore wind power.

Figure 4-4: Life Cycle GHG Profile for Wind Power



Detailed GHG results for conventional onshore, advanced onshore, and offshore wind power are shown in **Table 4-9**, **Table 4-7**, and **Table 4-8**, respectively. All values are expressed in kg of carbon dioxide equivalents (CO_2e) per MWh of delivered electricity. The CO_2e values are calculated from the GHG inventory results using global warming potentials (GWP) of 25 for CH_4, 298 for N_2O, and 22,800 for SF_6.

Table 4-7: Life Cycle GHG Emissions for Onshore Conventional Wind Power

Stages and Substages		CO_2	CH_4	N_2O	SF_6	Total
ECF	Switchyard	6.00E-02	2.45E-03	3.78E-04	3.92E-05	6.29E-02
	Trunkline	8.80E-01	3.12E-02	3.54E-03	2.96E-04	9.15E-01
	Recycling - Aluminum	-1.59E-01	-1.68E-02	-7.33E-05	0.00E+00	-1.76E-01
	Recycling - Copper	-6.37E-01	-2.19E-02	-8.30E-03	-7.23E-07	-6.67E-01
	Recycling - Steel	-1.62E+00	-1.71E-02	-4.97E-04	0.00E+00	-1.64E+00
	Domestic Turbine MFG	4.47E+00	2.74E-01	7.41E-02	1.09E-02	4.83E+00
	Foreign Turbine MFG	1.41E+01	5.79E-01	1.54E-01	1.34E-02	1.49E+01
	Wind Farm Operation	1.44E-01	8.07E-02	1.84E-02	2.12E-06	2.43E-01
	Wind Farm Construction	2.16E-01	9.93E-03	8.23E-03	1.68E-05	2.34E-01
	Landfill Waste	1.06E-02	7.78E-03	2.61E-05	6.00E-11	1.84E-02
PT	Transmission and Distribution	0.00E+00	0.00E+00	0.00E+00	3.27E+00	3.27E+00
Total		1.75E+01	9.29E-01	2.50E-01	3.29E+00	2.20E+01

Table 4-8: Life Cycle GHG Emissions for Onshore Advanced Wind Power

Stages and Substages		CO_2	CH_4	N_2O	SF_6	Total
ECF	Switchyard	6.00E-02	2.45E-03	3.78E-04	3.92E-05	6.29E-02
	Trunkline	8.80E-01	3.12E-02	3.54E-03	2.96E-04	9.15E-01
	Recycling - Aluminum	-1.39E-01	-1.47E-02	-6.40E-05	0.00E+00	-1.54E-01
	Recycling - Copper	-3.66E-01	-1.26E-02	-4.77E-03	-4.15E-07	-3.83E-01
	Recycling - Steel	-2.59E+00	-2.73E-02	-7.94E-04	0.00E+00	-2.61E+00
	Domestic Turbine MFG	5.50E+00	3.09E-01	1.18E-01	8.81E-03	5.94E+00
	Foreign Turbine MFG	1.11E+01	5.01E-01	1.76E-01	1.08E-02	1.18E+01
	Wind Farm Operation	4.74E-02	7.70E-02	1.76E-02	1.90E-06	1.42E-01
	Wind Farm Construction	1.55E-01	5.56E-03	2.79E-03	1.68E-05	1.64E-01
	Landfill Waste	1.40E-02	1.03E-02	3.46E-05	7.95E-11	2.44E-02
PT	Transmission and Distribution	0.00E+00	0.00E+00	0.00E+00	3.27E+00	3.27E+00
Total		1.47E+01	8.83E-01	3.12E-01	3.29E+00	1.91E+01

Table 4-9: Life Cycle GHG Emissions for Offshore Wind Power

Stages and Substages		CO_2	CH_4	N_2O	SF_6	Total
ECF	Switchyard	6.00E-02	3.78E-04	2.45E-03	3.92E-05	6.29E-02
	Trunkline	8.80E-01	3.54E-03	3.12E-02	2.96E-04	9.15E-01
	Recycling - Aluminum	-1.25E-01	-5.77E-05	-1.32E-02	0.00E+00	-1.38E-01
	Recycling - Copper	-2.80E-01	-3.64E-03	-9.59E-03	-3.17E-07	-2.93E-01
	Recycling - Steel	-1.73E+00	-5.32E-04	-1.83E-02	0.00E+00	-1.75E+00
	Domestic Turbine MFG	4.04E+00	8.35E-02	2.29E-01	6.85E-03	4.36E+00
	Foreign Turbine MFG	8.71E+00	1.30E-01	3.87E-01	8.37E-03	9.24E+00
	Wind Farm Operation	1.31E+01	2.21E-02	3.73E-01	1.32E-06	1.35E+01
	Wind Farm Construction	3.24E+00	4.96E-02	6.19E-02	8.63E-07	3.35E+00
	Landfill Waste	1.11E-02	2.73E-05	8.16E-03	6.28E-11	1.93E-02
PT	Transmission and Distribution	0.00E+00	0.00E+00	0.00E+00	3.27E+00	3.27E+00
Total		2.79E+01	2.85E-01	1.05E+00	3.28E+00	3.25E+01

Detailed results for wind power are also shown in **Figure 4-5**, **Figure 4-6**, and **Figure 4-7**. These figures also include an uncertainty range for the GHG emissions from key processes and show the possible GHG emissions for best and worst case scenarios. For example, the expected value for the total GHG emissions from conventional onshore wind power is 22.0 kg CO_2e/MWh and is representative of expected values for the parameters discussed in **Section 4.6**. But if all parameters are set at their highest performance, the GHG emissions are as low as 6 kg CO_2e/MWh. Conversely, if all parameters are set at their lowest performance, the GHG emissions are as high as 72 kg CO_2e/MWh. The underlying math of the environmental model uses these parameters to apportion turbine manufacturing, transport, and construction burdens per unit of electricity produced, so a change in a parameter will affect the GHG contributions of all manufacturing, transport, and construction processes. (Sections **4.10.2** and **4.10.3** identify the parameters that introduce the most uncertainty to the GHG results for wind power).

Figure 4-5: Detailed GHG Emissions for Onshore Conventional Wind Power

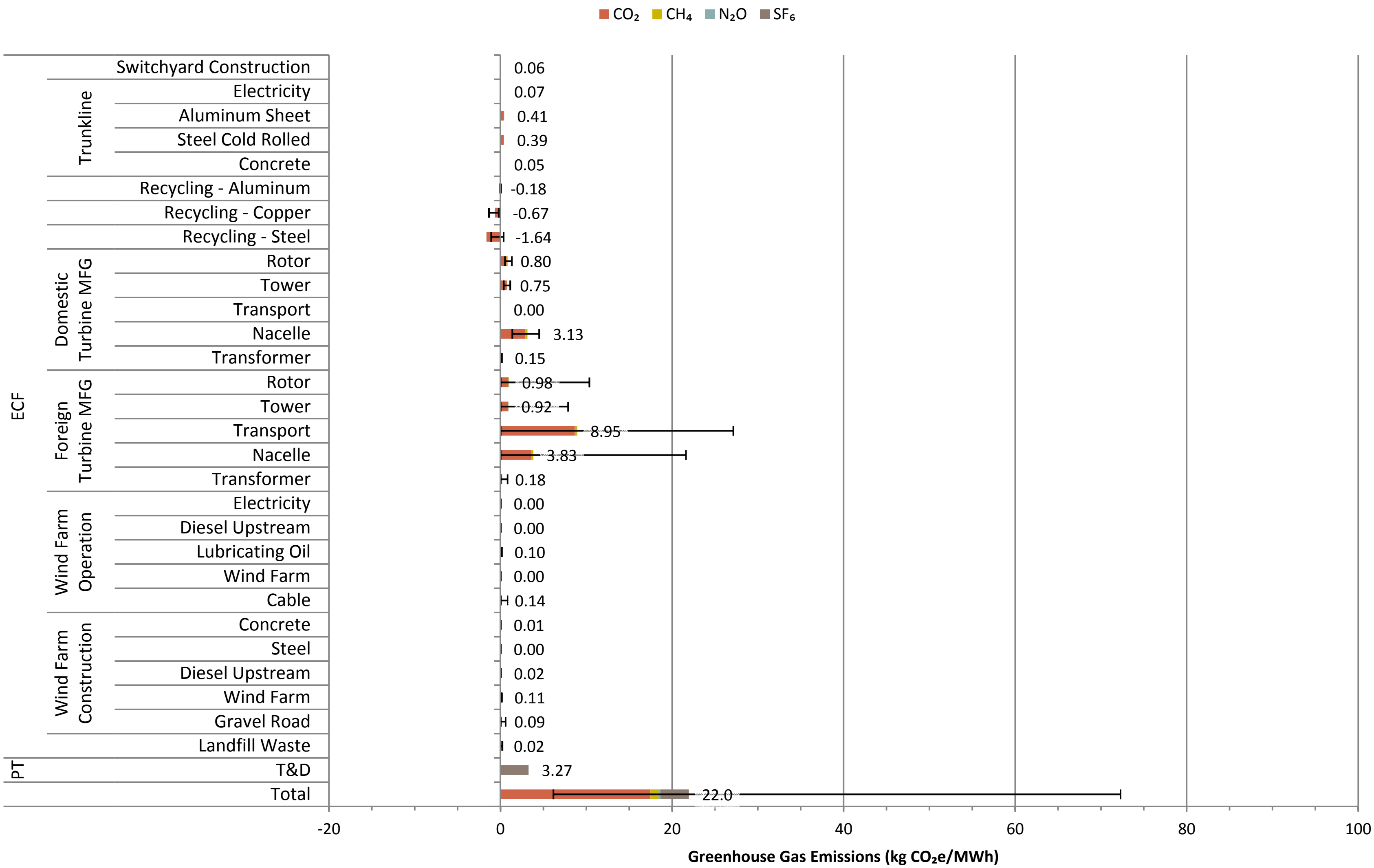


Figure 4-6: Detailed GHG Emissions for Onshore Advanced Wind Power

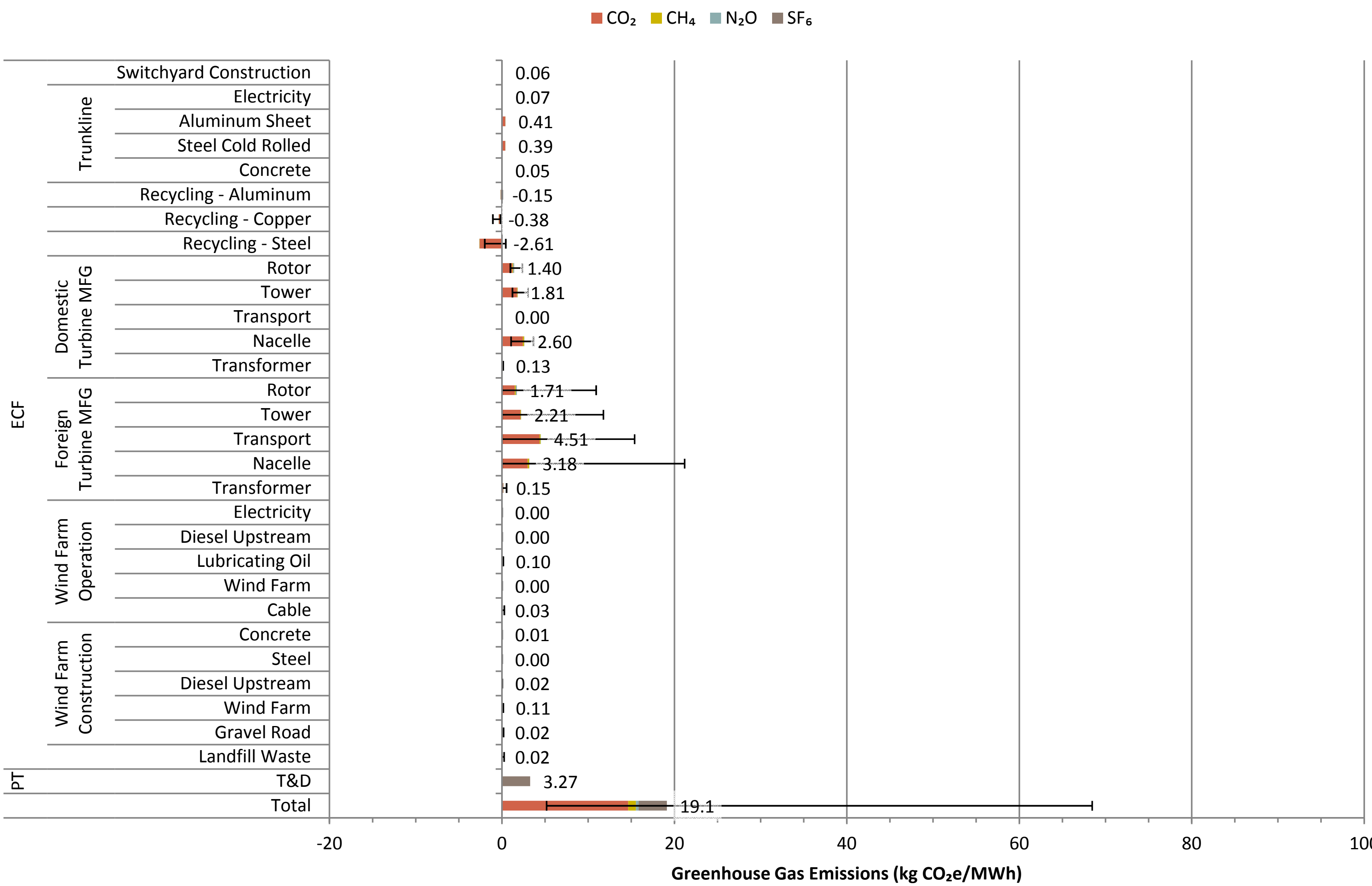
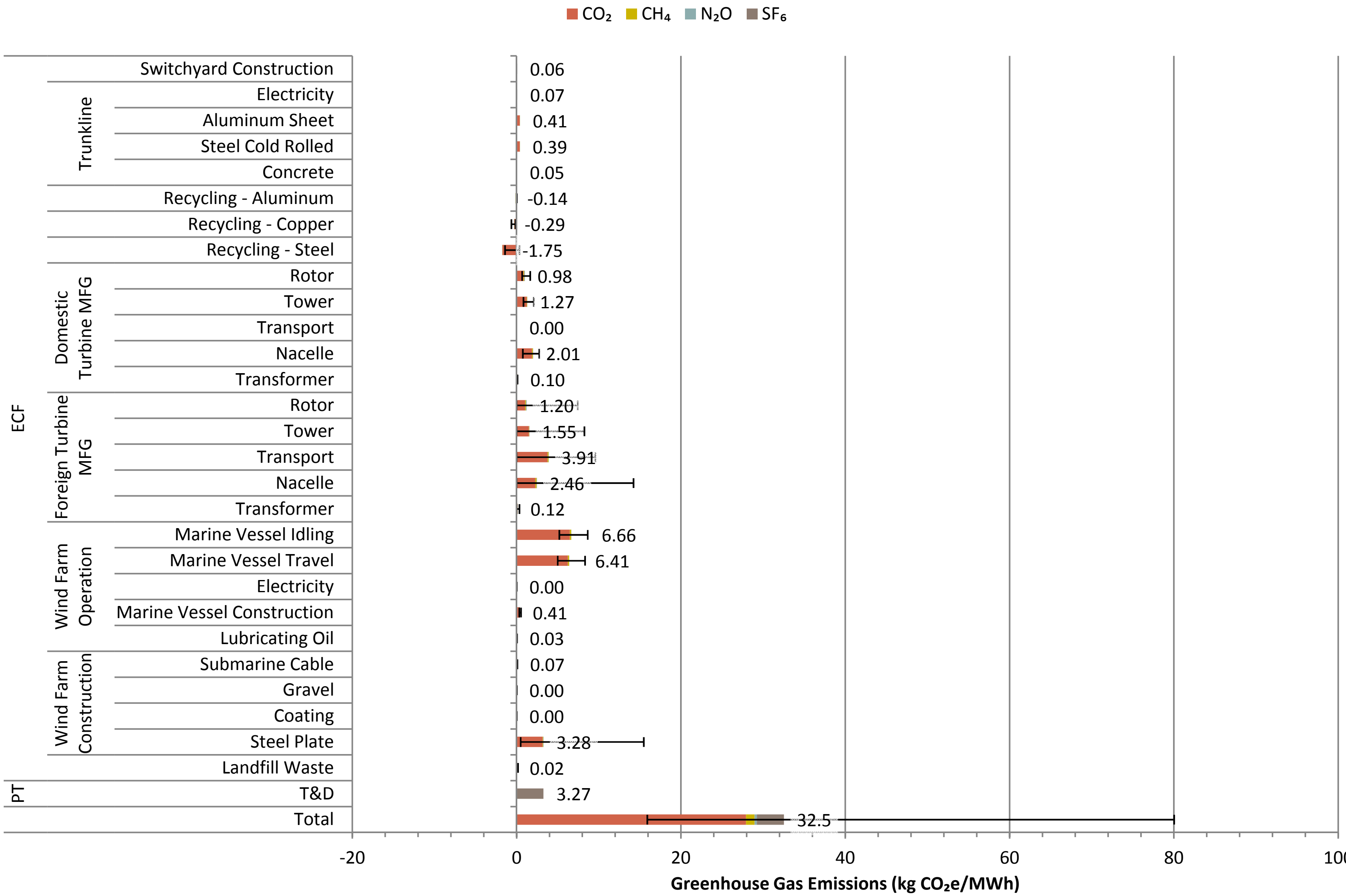


Figure 4-7: Detailed GHG Emissions for Offshore Wind Power



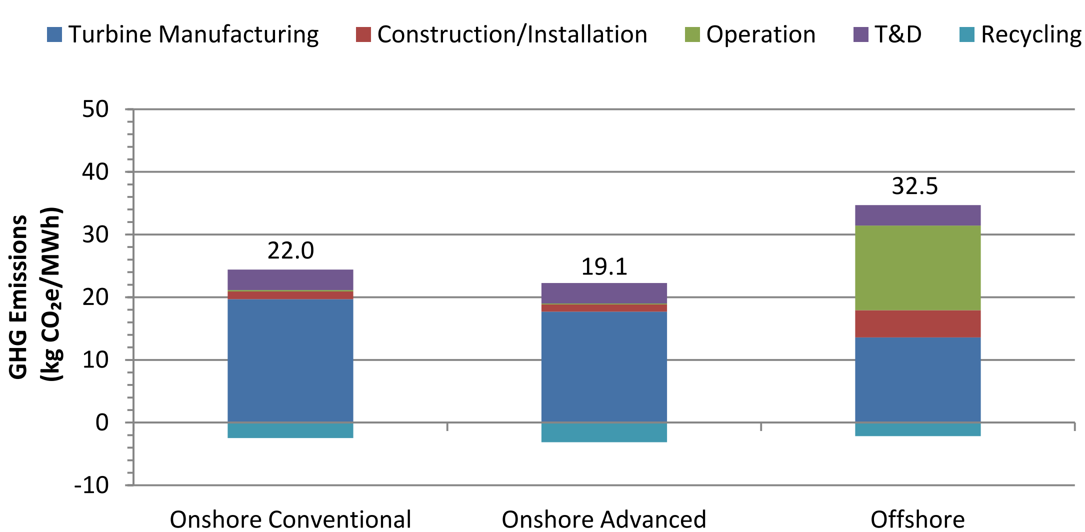
A comparison of the GHG profile for the three wind power technologies is provided in **Figure 4-8**.

For onshore wind power, the manufacturing of imported turbine components represents the largest contribution to GHG emissions, followed by domestic manufacturing of turbine components. Together, the turbine manufacturing processes account for 90 percent of the LC GHG emissions for conventional onshore and 93 percent for advanced onshore. The release of SF_6 during the transmission and distribution of electricity is also a significant source of GHG emissions from wind power, accounting for 10 to 17 percent of LC GHG emissions, depending on the scenario. Other activities, such as the construction of the wind farm and associated infrastructure, are not key contributors to the onshore wind power LC GHG profile.

The turbine manufacturing processes are still significant to the LC GHG profile for offshore wind power at an overall contribution of 42 percent. Operation activities also represent a 42 share of the GHG emissions from offshore wind power. Construction activities for offshore wind include the fabrication and installation of the steel monopile foundation that anchors the turbine into the seabed, as well as the fabrication and installation of the submarine cable that transmits power from the offshore turbine back to the shore where it is then connected to the trunkline. Diesel combustion emissions from marine vessels that are utilized during the construction phase are also included in the LC GHG profile. The wind farm operation GHG emissions are primarily from diesel combustion in the marine vessels that are utilized to transport crew and equipment for routine and unplanned turbine maintenance. The GHG emissions from the manufacturing of marine vessels used during construction and maintenance are also accounted for under construction activities.

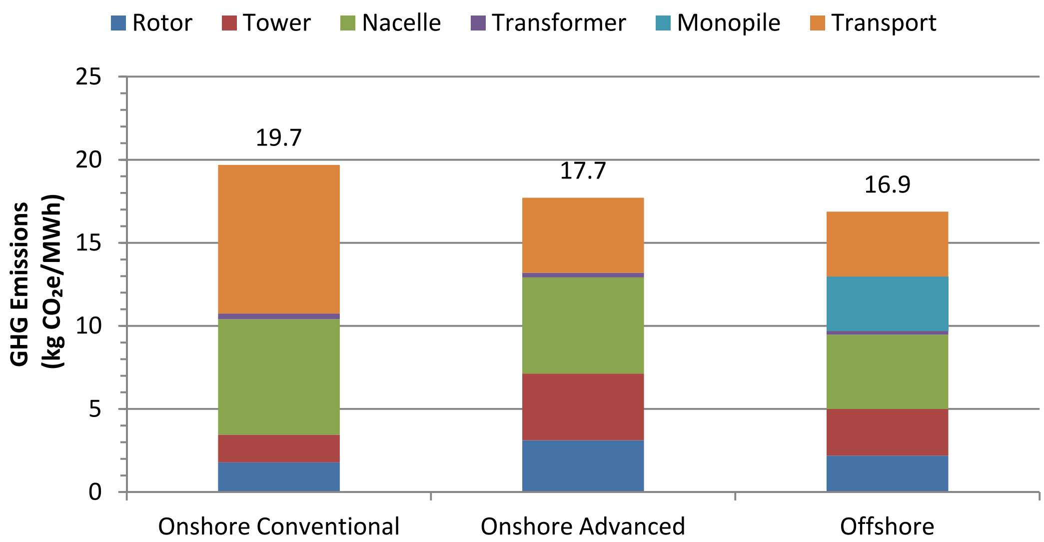
The recycling of aluminum, copper, and steel from manufacturing scrap and during the end-of-life disposition of wind turbines results in a reduction in LC GHG emissions. The recovery of these metals and their subsequent displacement of competing sources of metals reduces the LC GHG emissions of onshore conventional by 11 percent, onshore advanced wind power by 16 percent, and offshore wind power by 7 percent.

Figure 4-8: Life Cycle GHG Contributions of Wind Power Processes



As shown in **Figure 4-8**, manufacturing of turbines is a significant contributor to LC GHG emissions for both onshore and offshore wind power so it is worthwhile to focus on the manufacturing of the specific turbine components. Key turbine components are shown in **Figure 4-9**. The three main components of wind turbines are the nacelle, tower, and rotors. A transformer is located at the base of each turbine. Offshore wind power also requires a foundation for the wind turbine, which was modeled as a monopile. This analysis also includes turbine transport as a manufacturing activity to capture the impact of foreign and domestic sourcing of the components.

Figure 4-9: Life Cycle GHG Contributions of Turbine Components



The transport of turbines from the manufacturer to the wind farm accounts for the majority of GHG emissions for imported conventional onshore turbines; due to the efficiency of scale of the offshore and advanced onshore turbines, transportation requirements are not as large. The transportation requirements of domestic turbines are insignificant in comparison to other LC activities.

An efficiency of scale is also demonstrated by the GHG emissions of the nacelle components. The nacelle includes a gear box and generator, which do not need to be scaled up significantly when increasing the rating of a turbine. In fact, the GHG emissions of the nacelles (per MWh of delivered electricity) are lower for offshore and advanced onshore turbines than for conventional onshore turbines.

The overall contribution of manufacturing impacts for the offshore wind power case are driven down because the system has a higher capacity factor compared to onshore wind power (39 percent versus 30 percent). Regardless of size, the increase in the capacity factor of an offshore turbine results in an increase in the lifetime power generation from that turbine and, as a result, a reduction in component manufacturing contribution to LC GHG emissions.

A comprehensive list of metrics (GHG emissions, criteria and other air pollutants of concern, water use, water quality, and land) are presented in **Appendix C.**

4.10.2 Sensitivity and Uncertainty for Onshore Wind Power

Table 4-10 shows the parameters and values that were evaluated to understand the sensitivity and uncertainty in the LCA model for conventional and advanced onshore wind power. Parameters include physical characteristics of the turbine, the supply and magnitude of the wind source, as well as measures of the sourcing of turbine materials, either domestically or internationally, and the proportion of material from the turbine that is recycled during wind farm decommissioning.

Table 4-10: Onshore Wind LCA Modeling Parameters

Parameter	Onshore Conventional			Onshore Advanced			Units
	Low	Expected Value	High	Low	Expected Value	High	
Rotor Diameter	57	63	69	100	125	125	m
Wind Speed	8	12	18	8	12	18	m/s
Percent Imported	0	55	100	0	55	100	%
Percent Recycled	0	90	100	0	90	100	%
Turbine Life	20	20	30	20	20	30	Years
Capacity Factor	20	30	40	20	30	40	%

Figure 4-10 and **Figure 4-11** show the range of LC GHG emissions for conventional and advanced onshore wind power as a function of the range of values for the model input parameters shown in **Table 4-10**. In these figures, the slope of a line represents the sensitivity of GHG emissions to a change in the associated parameter. For example, the slope of the wind speed line is steeper than other lines in **Figure 4-10** and **Figure 4-11**, which indicates that the GHG emissions are more sensitive to wind speed than other parameters. The vertical distance traversed by a line between its low and high parameter values represents the total uncertainty for the associated parameter. For example, the line for wind speed in **Figure 4-10** represents the most uncertainty for onshore conventional wind power -- it represents a total uncertainty range of 12 to 32 kg CO_2e/MWh, which envelops the individual uncertainty ranges caused by the other parameters. These figures represent only the uncertainty for individual parameters when all other parameters are held constant at their expected values, not the total study uncertainty caused by the aggregation of all parameter uncertainty.

The expected base case results of 22.0 and 19.1 kg CO_2e per MWh for conventional and advanced onshore wind power are shown for reference as dashed lines in the figures. **Figure 4-10** and **Figure 4-11** indicate the possible range of GHG results is 12 to 32 kg CO_2e per MWh for conventional onshore wind power and 14 to 36 kg CO_2e per MWh for advanced onshore wind power, depending on the value of the parameters. Both figures also indicate where in the range of parameter values the expected input is located at the point where the parameter line crosses the base case line. Only one parameter is varied at a time, with the other parameters remaining at the expected value used in the model. Therefore, the figures do not show any interaction between certain parameters.

The figures show that the most important parameters with respect to the LC GHG profile for conventional and advanced onshore wind are wind speed and rotor diameter. Both of these parameters directly affect the amount of power that can be generated from a turbine, so it is intuitive that they would be the most sensitive in the model. The infrastructure and construction burdens for wind power are nearly the same regardless of the size of the rotor diameter. Therefore, the same amount of GHG emissions are apportioned to a much smaller power output. Similar to the effect of the wind speed and rotor diameter parameters, the capacity factor also determines how much electricity is generated during the lifetime of the turbine. At higher capacity factors, the infrastructure, construction, and turbine manufacturing contributions to LC GHG emissions are lower because of higher power output. The opposite behavior is true as well.

Parameters that are not directly associated with the power output of the onshore wind turbine, for example percentage of imports, recycling percentage, and turbine life, are not as sensitive in the model. These figures also illustrate that there is nonlinearity in the results with respect to the wind speed and rotor diameter parameters. In the conversion of wind to power there is a cubic relationship for wind speed and a squared relationship for rotor diameter based on the fundamental equations that are used to calculated power production potential.

Figure 4-10: Sensitivity and Uncertainty of Conventional Onshore Wind Power GHG Emissions

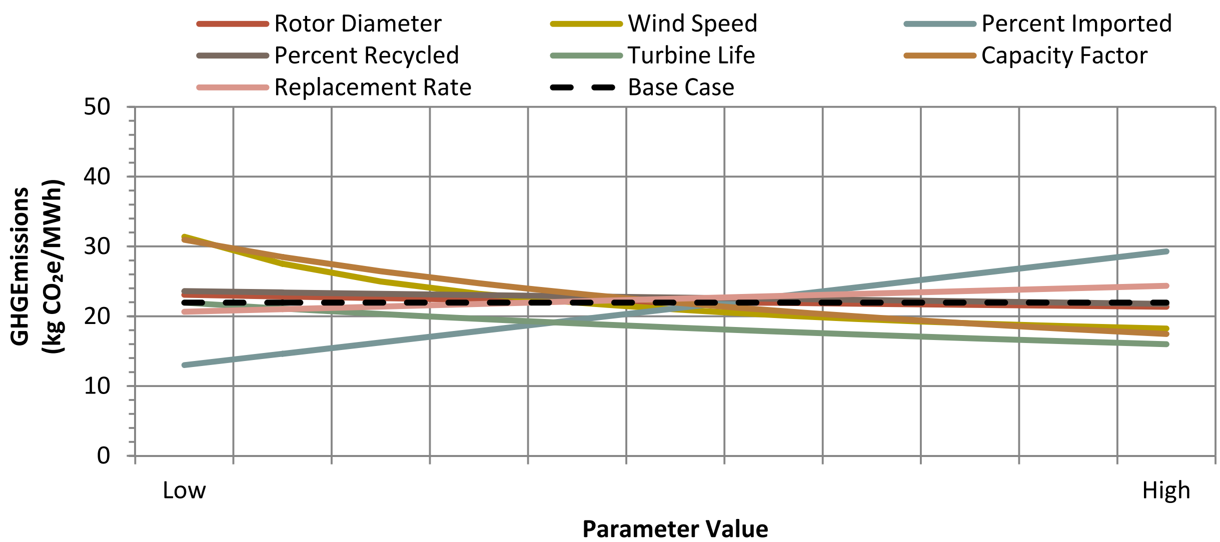
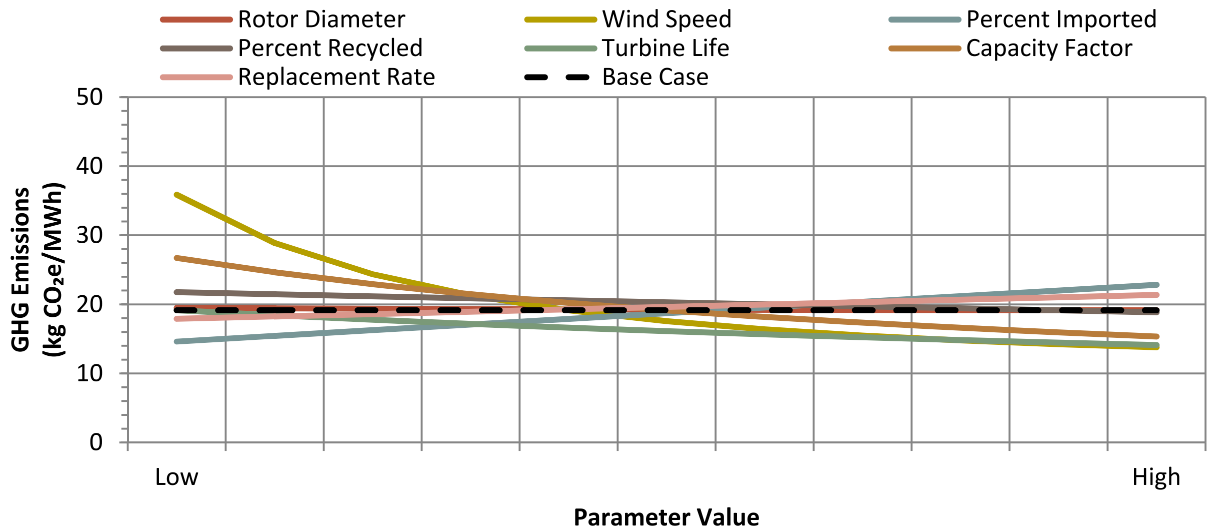


Figure 4-11: Sensitivity and Uncertainty of Onshore Advanced Wind Power GHG Emissions



4.10.3 Sensitivity and Uncertainty for Offshore Wind Power

A similar sensitivity and uncertainty analysis was performed for offshore wind power. **Table 4-11** shows the parameters and values that were evaluated to understand the sensitivity and uncertainty in the LCA model for offshore wind power. The parameters are the same as those modeled for the sensitivity and uncertainty of onshore wind power.

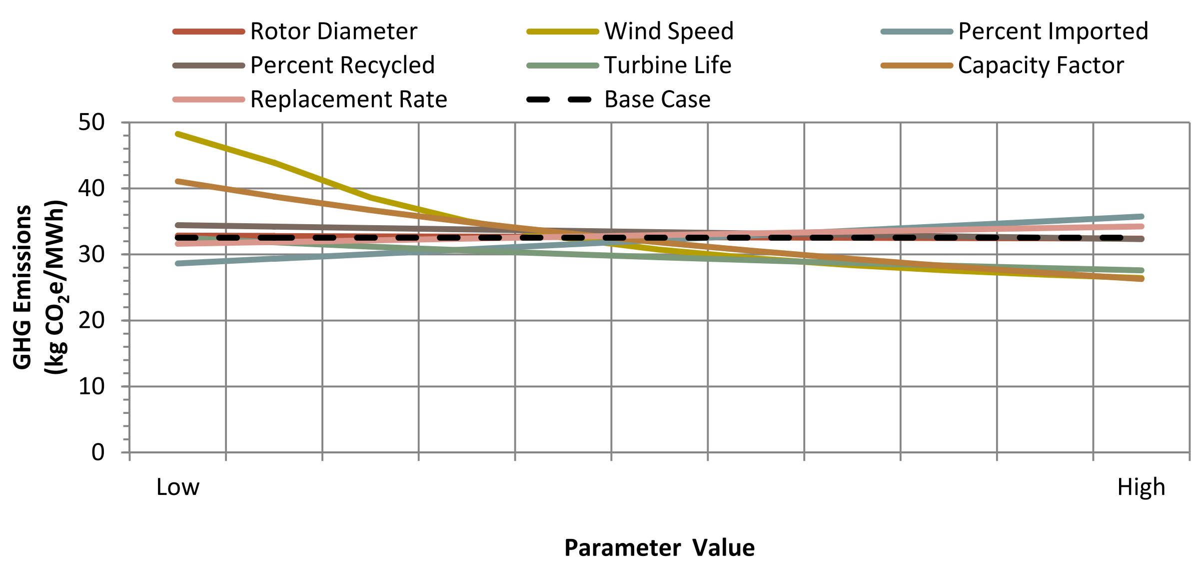
Table 4-11: Offshore Wind LCA Modeling Parameters

Parameter	Low	Expected Value	High	Units
Rotor Diameter	107	111	113	m
Wind Speed	8	12	18	m/s
Percent Imported	0	55	100	%
Percent Recycled	0	90	100	%
Turbine Life	20	20	30	Years
Capacity Factor	30	39	50	%

Figure 4-12 shows the range of LC GHG emissions for offshore wind power as a function of the range of values for the model input parameters shown in **Table 4-11**.The expected base case result of 32.5 kg CO_2e per MWh is shown for reference as a dashed line. This figure indicates the possible range of GHG results for offshore wind power as 27 to 48 kg CO_2e per MWh depending on the value of the parameters.

Similar to both of the onshore technologies, **Figure 4-12** shows that the most important parameters with respect to the LC GHG profile for offshore wind are wind speed, rotor diameter, and capacity factor. As expected, **Figure 4-12** illustrates some nonlinearity in the results with respect to the wind speed and rotor diameter parameters.

Figure 4-12: Uncertainty and Sensitivity of Offshore Wind Power GHG Emissions



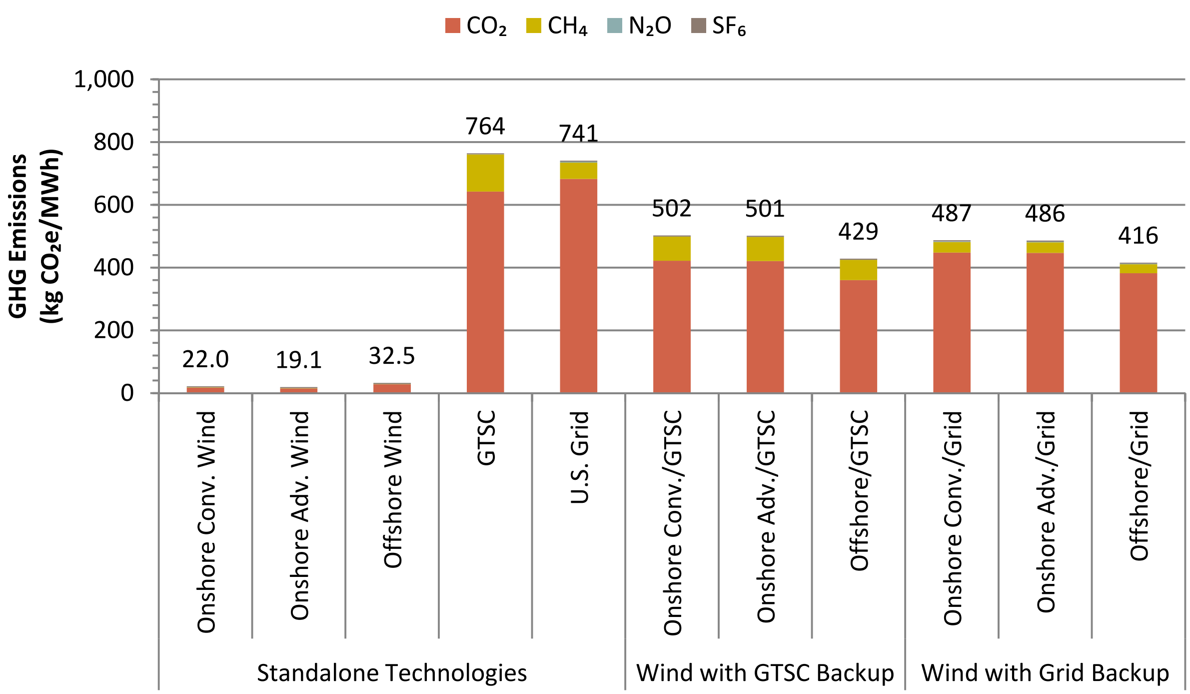
4.10.4 Combined Wind and Backup Power

Wind farms have relatively low capacity factors, which are due to intermittent wind availability. The default capacity factors for onshore wind power are 30 and 39 percent, respectively (MMS, 2009; Wiser & Bolinger, 2011). (No data are available to suggest that the capacity factors are different for onshore conventional and onshore advanced wind power.) Two backup power sources for balancing the intermittent output of wind farms are modeled: (1) a load-following GTSC plant and (2) the average U.S. power mix.

It is not necessary to back up the wind farm to a combined capacity factor of 100 percent. This analysis uses a combined capacity factor of 85 percent, which is comparable to the average capacity factor of other baseload technologies. At a combined capacity factor of 85 percent, an onshore wind farm with an expected capacity factor of 30 percent represents a 35.3 percent contribution to the mix of wind and backup power, and the GTSC power plant represents a 64.7 percent contribution to the mix of wind and backup power. Similarly, at a combined capacity factor of 85 percent, an offshore wind farm with an expected capacity factor of 39 percent represents a 45.9 percent contribution to the mix of wind and backup power, and the GTSC power plant represents a 54.1 percent contribution to the mix of wind and backup power.

The LC GHG emissions (in CO_2e per delivered MWh) for the stand-alone and backup scenarios are shown in **Figure 4-13** for onshore conventional, onshore advanced and offshore wind power.

Figure 4-13: LC GHG Emissions for Wind with Backup Scenarios



The LC GHG emissions of conventional wind farms are 22.0 kg of CO_2e per MWh, but, when the reliability of power generation is considered, the need for backup power increases the LC GHG emissions of wind power. When a GTSC power plant provides backup power to an onshore conventional wind farm, the LC GHG emissions are 502 kg CO_2e per MWh; when the average U.S.

power mix is used to balance an onshore wind farm, the LC GHG emissions are 487 kg CO_2e per MWh. As shown in **Figure 4-13** the conclusions for backing up onshore *advanced* wind power are similar to those for onshore *conventional* wind power.

The capacity factor of offshore wind power is higher than onshore wind power (39 percent vs. 30 percent) so the backup scenarios for offshore wind power have lower GHG emissions than the backup scenarios for onshore wind power. The LC GHG emissions of offshore wind farms are 32.5 kg of CO_2e per MWh, but, when the reliability of power generation is considered, the need for backup power increases the LC GHG emissions of wind power. When a GTSC power plant provides backup power to an offshore wind farm, the LC GHG emissions are 429 kg CO_2e per MWh; when the average U.S. power mix is used to balance an offshore wind farm, the LC GHG emissions are 416 kg CO_2e per MWh.

4.10.5 Greenhouse Gas Emissions from Land Use Change

Results from the analysis of transformed land area are illustrated in **Figure 4-14**. The offshore wind farm has 0.034 m^2/MWh of transformed land area, the lowest area of the three wind power scenarios. The scenario for onshore advanced wind power with GTSC backup has the highest transformed land area of this analysis (0.555 m^2/MWh); however, the results for both onshore technologies are essentially the same. The only difference in the land use characteristics of conventional and advanced onshore wind power is the footprint of the wind turbines. Onshore advanced wind turbines use approximately six percent more land per MWh of production than onshore conventional wind turbines.

Offshore wind's comparatively low land use results primarily from the wind farm itself being installed offshore, where no land use effects would occur. However, offshore wind power also has a higher capacity factor (39 percent) than onshore wind power (30 percent), which also contributes to lower transformed land areas for both offshore wind cases. Adding GTSC backup approximately doubled transformed land area for the onshore wind case and increased offshore wind transformed land area by a factor of approximately ten. Substantial transformed land areas associated with GTSC backup are contributed largely by natural gas extraction and transport facilities, under LC Stages #1 and #2.

Figure 4-14: Direct Land Use, Transformed Land Area

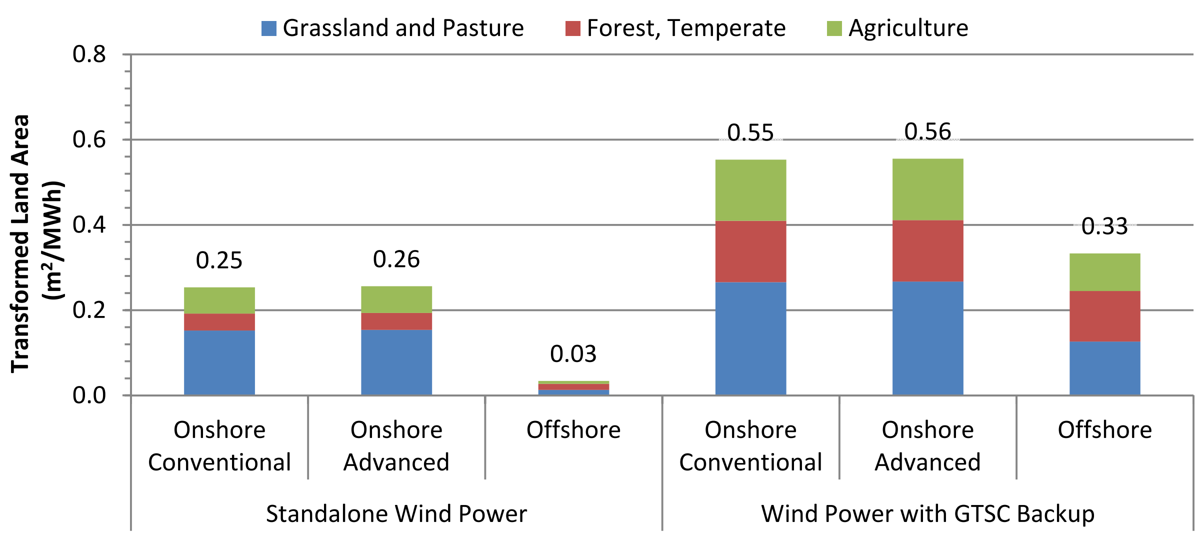
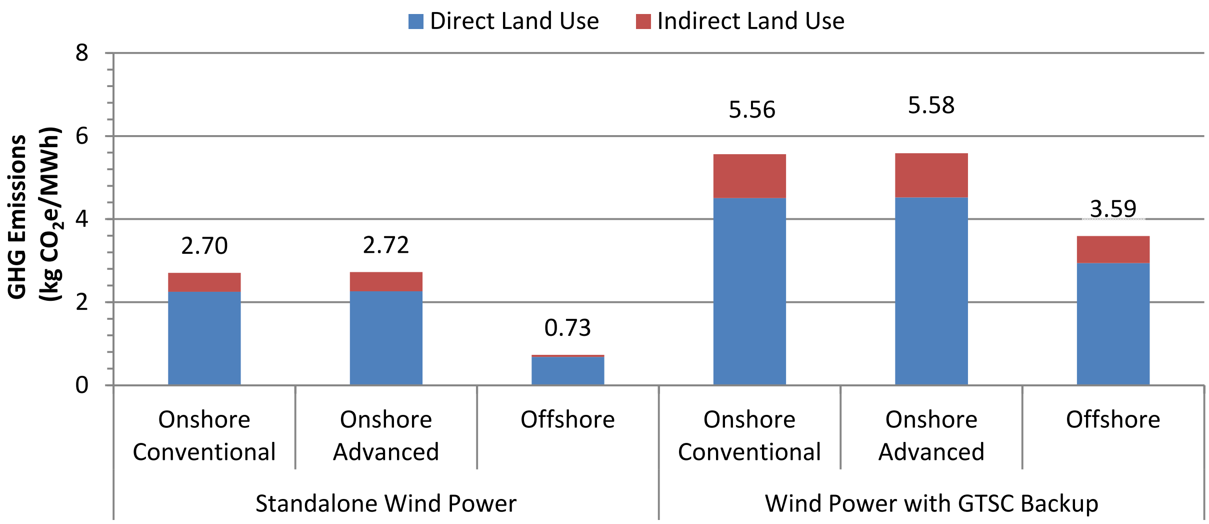


Figure 4-15 shows results from the analysis of GHG emissions from direct and indirect land use. In comparison to GHG emissions from other activities in the natural gas lifecycle, land use GHG emissions are minor and account for about 0.73 (offshore wind farm) to 5.58 kg CO_2e/MWh (onshore advanced wind farm with GTSC backup). Direct land use emissions comprise most of total land use GHG emissions – from 81 percent 93 percent of total land use GHG emissions. Direct land use emissions are high in comparison to indirect land use emissions because displaced agriculture comprised a relatively small proportion of the total transformed land area (see **Figure 4-14**). As noted above, loss of agricultural land was the only factor tied to indirect land use effects. For direct land use emissions, loss of forest land resulted in larger net land use GHG emissions than other land use types, because existing standing stock forest biomass was presumed to be cleared/oxidized as a result of installation of study facilities.

Figure 4-15: Direct and Indirect Land Use GHG Emissions



The GHG emissions from direct and indirect land use are a significant portion of total LC GHG emissions for onshore wind power. As shown in **Figure 4-15**, the land use (direct and indirect) GHG emissions from an onshore conventional wind farm are 2.70 kg/MWh. For the same scenario, the GHG emissions from other LC processes are 22.0 kg CO_2e/MWh. Thus, the total LC GHG emissions are 24.7 kg CO_2e/MWh, of which land use GHG emissions are an 11 percent share.

Similarly, for onshore advanced wind power, the land use GHG and other LC GHG emissions are 2.72 and 19.1 kg CO_2e/MWh, respectively. The total LC GHG emissions for onshore advanced wind power are 21.8 kg CO_2e/MWh, of which land use GHG emissions are a 14 percent share.

Offshore wind power does not disturb as much land as onshore wind power, so the GHG emissions from land use are not as significant for offshore wind power. As shown in **Figure 4-15**, the land use (direct and indirect) GHG emissions from an offshore wind farm are 0.73 kg/MWh. For the same scenario, the GHG emissions from other LC processes are 32.5 kg CO_2e/MWh. Thus, the total LC GHG emissions are 33.2 kg CO_2e/MWh, of which land use GHG emissions are a 2 percent share.

When backup power is considered, the percent contribution of GHG emissions from land use is further diminished because the relatively high GHG emissions from fuel combustion at the GTSC power plant overshadow the land use GHG emissions. As shown in **Figure 4-15**, the land use GHG emissions from onshore wind power with GTSC backup power are 5.56 kg CO_2e/MWh. For the same scenario, the GHG emissions from other LC processes are 502 kg CO_2e/MWh. Thus, the total LC GHG emissions for onshore conventional wind power with GTSC backup are 508 kg CO_2e/MWh, of which land use GHG emissions are a 1.1 percent share. Similarly, for offshore wind power with GTSC backup, the GHG emissions from land use are a 0.83 percent share of total LC GHG emissions.

4.10.6 Other Air Emissions

This analysis also accounts for criteria air pollutants and other air emissions from the LC of wind power. An operating wind turbine may not be a direct source of air emissions, but air emissions are released by the maintenance of a wind farm as well as the upstream activities of turbine manufacture. Another source of air emissions is the production and delivery of materials used for the construction of a wind farm. Further, the recycling of wind turbine components during end-of-life waste management results in the displacement of other materials, so the recycling phase of the wind power LC has negative emissions.

Table 4-12 shows the criteria air pollutants and other air emissions associated with the LC of one MWh of wind power delivered to the consumer. It includes three technology categories (onshore conventional, onshore advanced, and offshore wind power) and organizes the results according to key processes within LC Stage #3. Wind power does not require the acquisition and delivery of fuel, so there are no environmental burdens in LC Stages #1 and #2. The only environmental emissions from LC Stages #4 and #5 are SF_6 emissions from electricity T&D.

Table 4-12: Criteria Air Pollutants and Other Emissions from Wind Power

Technology	Emission	Switchyard/ Trunkline Construction	Domestic Turbine Manufacture	Foreign Turbine Manufacture	Wind Farm Construction	Wind Farm Operation	Landfill Waste	Recycling	T&D	Total
Onshore Conventional	Pb	1.06E-06	3.02E-06	3.72E-06	1.46E-06	8.89E-10	2.90E-10	-1.88E-05	0.00E+00	-9.51E-06
	Hg	6.13E-09	6.56E-08	8.29E-08	1.14E-09	1.45E-10	2.93E-11	-1.06E-08	0.00E+00	1.45E-07
	NH_3	3.25E-06	8.44E-06	3.24E-04	4.47E-04	3.91E-05	1.66E-08	-5.55E-06	0.00E+00	8.16E-04
	CO	7.61E-03	1.12E-02	3.73E-02	1.01E-02	3.48E-03	5.42E-05	-2.01E-02	0.00E+00	4.97E-02
	NOx	1.60E-03	7.39E-03	3.01E-02	4.80E-04	8.31E-03	6.29E-05	-3.48E-03	0.00E+00	4.45E-02
	SO_2	2.49E-03	1.27E-02	1.93E-02	5.58E-04	1.31E-04	2.77E-05	-6.73E-03	0.00E+00	2.85E-02
	VOC	1.57E-04	2.07E-03	6.57E-03	5.65E-04	3.03E-04	1.48E-05	-9.16E-04	0.00E+00	8.76E-03
	PM	1.18E-03	2.61E-03	3.22E-03	3.53E-03	1.77E-02	1.74E-04	-1.21E-03	0.00E+00	2.72E-02
Onshore Advanced	Pb	1.06E-06	4.57E-06	5.60E-06	3.71E-07	6.24E-10	3.85E-10	-1.08E-05	0.00E+00	7.91E-07
	Hg	6.13E-09	7.76E-08	9.62E-08	3.35E-10	1.23E-10	3.88E-11	-1.17E-08	0.00E+00	1.69E-07
	NH_3	3.25E-06	1.26E-05	1.74E-04	4.46E-04	1.01E-05	2.20E-08	-4.19E-06	0.00E+00	6.42E-04
	CO	7.61E-03	2.02E-02	3.65E-02	9.53E-03	1.36E-03	7.18E-05	-3.13E-02	0.00E+00	4.39E-02
	NOx	1.60E-03	9.51E-03	2.22E-02	3.15E-04	2.15E-03	8.35E-05	-3.90E-03	0.00E+00	3.20E-02
	SO_2	2.49E-03	1.51E-02	2.04E-02	2.01E-04	9.35E-05	3.68E-05	-7.45E-03	0.00E+00	3.09E-02
	VOC	1.57E-04	2.97E-03	5.66E-03	5.43E-04	1.23E-04	1.96E-05	-1.24E-03	0.00E+00	8.24E-03
	PM	1.18E-03	3.82E-03	4.68E-03	3.37E-03	4.51E-03	2.31E-04	-9.47E-04	0.00E+00	1.68E-02
Offshore	Pb	1.06E-06	3.14E-06	3.85E-06	9.19E-06	5.48E-07	2.91E-10	-8.42E-06	0.00E+00	9.38E-06
	Hg	6.13E-09	5.37E-08	6.65E-08	5.06E-07	3.54E-08	2.94E-11	-1.34E-08	0.00E+00	6.54E-07
	NH_3	3.25E-06	8.55E-06	1.11E-04	4.61E-07	1.70E-04	1.66E-08	-4.02E-06	0.00E+00	2.90E-04
	CO	7.61E-03	1.44E-02	2.79E-02	2.68E-02	4.93E-02	5.67E-05	-2.11E-02	0.00E+00	1.05E-01
	NOx	1.60E-03	6.63E-03	1.49E-02	6.96E-03	1.51E-01	6.31E-05	-4.49E-03	0.00E+00	1.76E-01
	SO_2	2.49E-03	1.06E-02	1.42E-02	9.51E-03	1.48E-02	2.78E-05	-8.42E-03	0.00E+00	4.33E-02
	VOC	1.57E-04	2.00E-03	3.74E-03	1.73E-05	6.20E-03	1.48E-05	-1.51E-03	0.00E+00	1.06E-02
	PM	1.18E-03	2.57E-03	3.16E-03	1.06E-03	2.44E-03	1.75E-04	-9.29E-04	0.00E+00	9.66E-03

The results shown in **Table 4-12** should be interpreted with care. Unlike the results for GHG emissions, this analysis does not apply an impact assessment method to criteria air pollutants or other air emissions. Thus, the results in **Table 4-12** cannot be compared across emission categories (for example, the results for carbon monoxide and nitrogen oxides are not directly comparable).

For onshore wind power, the manufacture of wind turbines account for the majority of criteria air pollutants and other air emissions. For offshore wind power, the operation of the wind farm accounts for the majority of criteria air pollutants and other air emissions.

The following figures are based on the data in **Table 4-12** and provide side-by-side comparisons of selected air emissions for the three wind power technologies. **Figure 4-16** shows carbon monoxide results, **Figure 4-17** shows nitrogen oxide results, and **Figure 4-18** shows sulfur oxide results. For each emission (CO, NO_X, and SO_2), the results for all three technologies fall within the same order of magnitude; however, the emission for offshore wind power are higher than the onshore technologies due to the operation of marine vessels. These figures also demonstrate that the recycling of materials results in a displacement of emissions that offsets a significant portion of manufacturing and construction emissions.

Figure 4-16: Carbon Monoxide Emissions from Wind Power

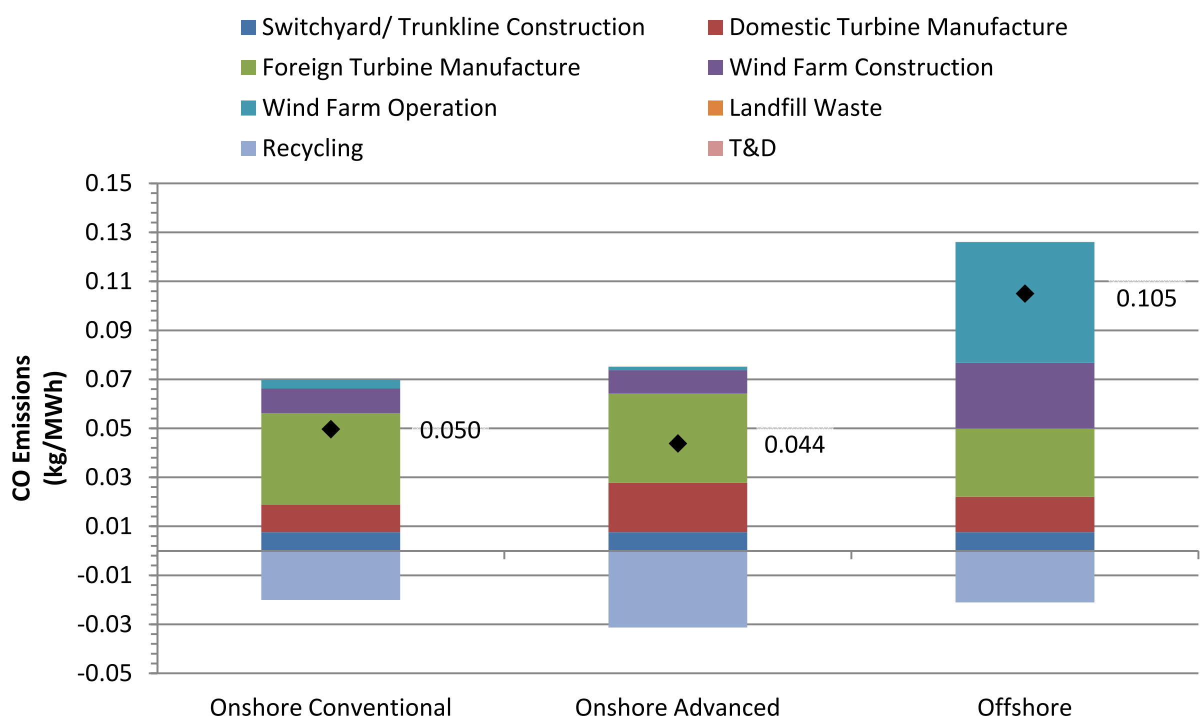


Figure 4-17: Nitrogen Oxide Emissions from Wind Power

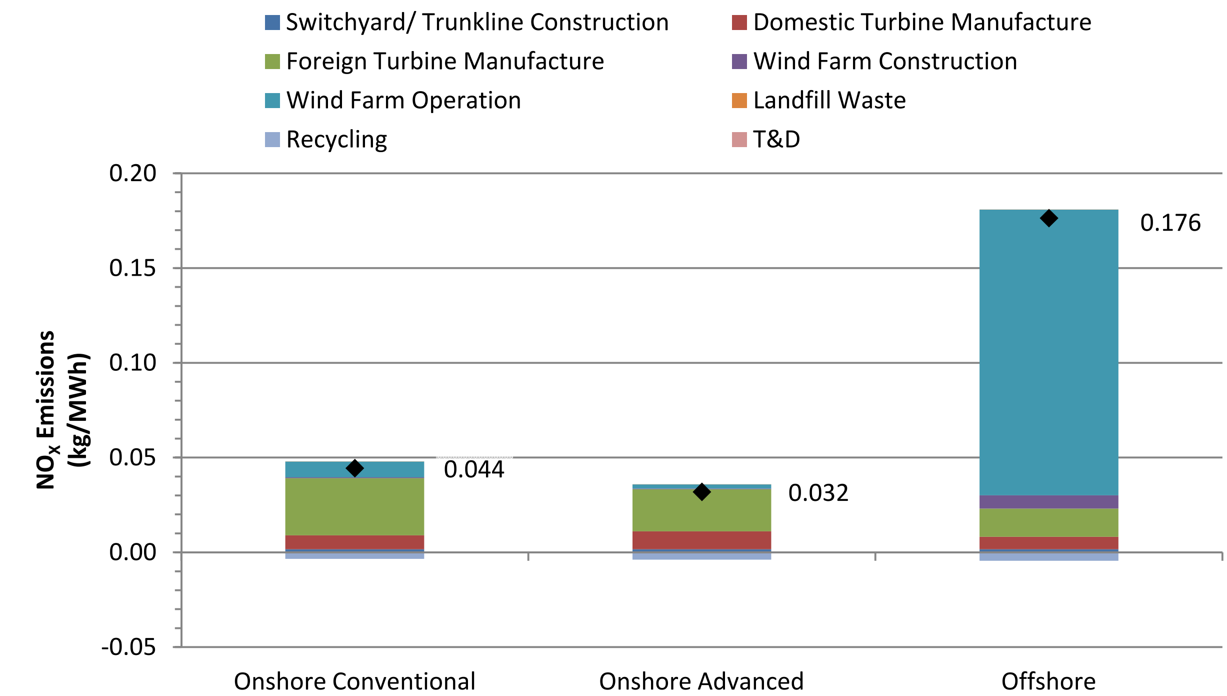
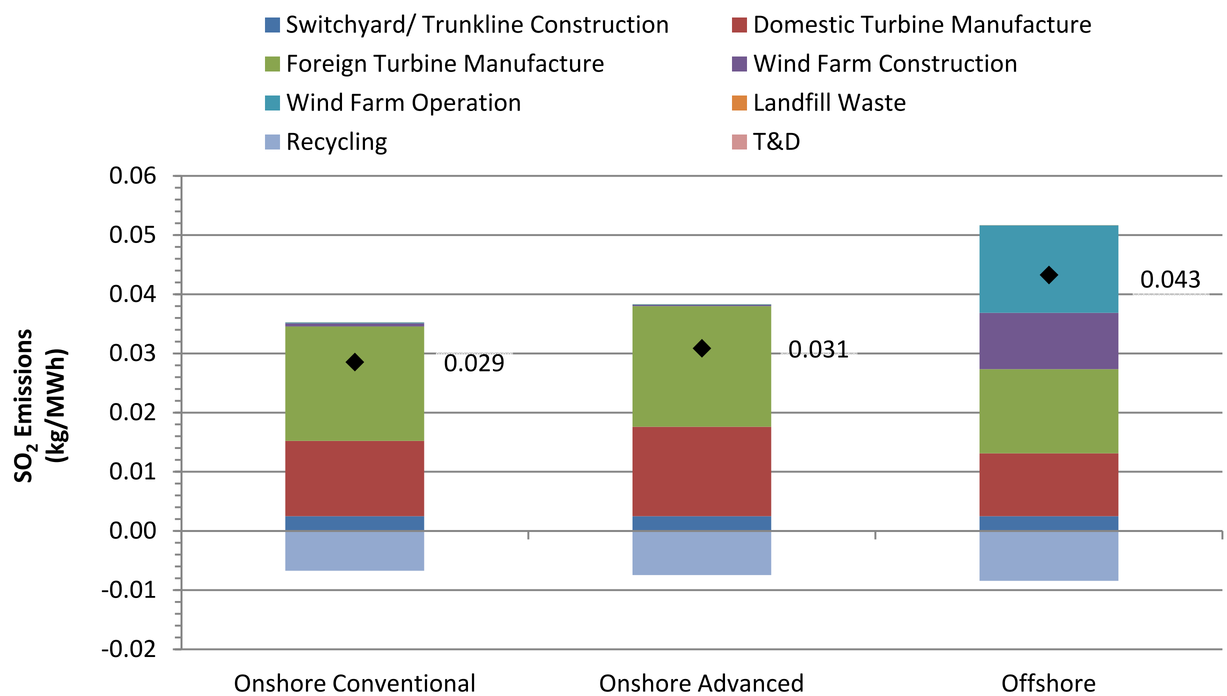


Figure 4-18: Sulfur Dioxide Emissions from Wind Power



5 Cost Analysis of Wind Power

The life cycle costs (LCC) of wind power were calculated by performing a discounted cash flow analysis over the lifetimes of the wind power projects.

5.1 Wind LCC Approach and Financial Assumptions

The LCC analysis accounts for the significant capital and O&M expenses incurred by the wind power systems. The LCC calculates the cost of electricity (COE), which is the revenue received by the generator per net MWh during the first year of operation (NETL, 2010a). The LCC calculations were performed using NETL's Power Systems Financial Model (PSFM), which calculates the capital charge factors necessary for apportioning capital costs per unit of production.

Cash flow is affected by several factors, including cost (capital, O&M, replacement, and decommissioning or salvage), book life of equipment, federal and state income taxes, equipment depreciation, interest rates, and discount rates. For NETL LCC assessments, modified accelerated cost recovery system (MACRS) depreciation rates are used. O&M costs are assumed to be consistent over the study period except for the cost of energy and feedstock materials determined by EIA. However, wind power does not have feedstock requirements so it is not necessary to account for the escalation of fuel costs.

Capital investment costs are defined as equipment, materials, labor (direct and indirect), engineering and construction management, and contingencies (process and project). Capital costs are assumed to be "overnight costs" (not incurring interest charges) and are expressed in 2007 constant dollars. Accordingly, all cost data are normalized to 2007 dollars.

The boundaries of the LCC are consistent with the boundaries of the environmental portion of the LCA, ending with the delivery of 1MWh of electricity to a consumer. The capital costs for the wind power facilities account for all upstream economic activities related to the extraction, processing, and delivery of construction materials. The O&M costs of wind power do not require the purchase of a primary fuel, but do account for labor and maintenance costs. All costs at the wind power facility are scaled according to the delivery of 1MWh of electricity to the consumer, which includes a 7 percent transmission and distribution loss between the power facility and the consumer.

The calculation of LCC also requires the specification of financial assumptions. The expected value case of this cost analysis is a low risk investor owned utility with a 50/50 debt-to-equity ratio, a 4.5 percent interest rate, and an internal rate of return on equity of 12 percent. The low cost and high cost cases were modeled by varying the internal rate of return on equity from 6 percent to 18 percent. The financial assumptions for the low, expected value, and high cost cases are shown in **Table 5-1**.

Table 5-1: Financial Parameters for Onshore and Offshore Wind Power

Scenario	Low Cost	Expected Cost	High Cost
Financial Structure Type	Low Risk Investor-owned Utility With Low Return on Equity	Low Risk Investor-owned Utility	Low Risk Investor-owned Utility with High Return on Equity
Debt Fraction (1 - Equity)	50.0%	50.0%	50.0%
Interest Rate	4.50%	4.50%	4.50%
Debt Term	15	15	15
Plant Lifetime	30	20	20
Depreciation Period (MACRS)	7 yrs.	7 yrs.	7 yrs.
Tax Rate	38.0%	38.0%	38.0%
O&M Escalation Rate	3.0%	3.0%	3.0%
Capital Cost Escalation During the Capital Expenditure Period	3.6%	3.6%	3.6%
Base Year	2007	2007	2007
Required Internal Rate of Return on Equity (IRROE)	6.00%	12.0%	18.0%

5.2 Wind Power Cost Data

The costs of wind power are based on recent reports published by the U.S. Department of Energy (Wiser & Bolinger, 2011), and, for offshore wind power, an economic study completed by an independent research organization (Haughton, 2004).

5.2.1 Capital Costs

The capital cost data for wind power are based on the *2010 Wind Technologies Market Report* published by the Department of Energy (Wiser & Bolinger, 2011), which include costs and other performance factors for U.S. wind power over the last 20 years. The costs for offshore wind power are based on *Updated Capital Cost Estimates for Electricity Generation Plants* published by the Department of Energy (EIA, 2010). The following discussion reports cost data using the same dollar year as stated by the original data sources, but the cost model of this analysis converts all costs to the basis of 2007 dollars.

The onshore conventional wind farm is representative of 98 projects installed in 2009 and 2010, using turbines in the range of 1.00 to 1.75 MW. An expected capacity of 1.5 MW per turbine is used in this analysis because General Electric 1.5 MW turbines currently dominate U.S. onshore wind projects. In 2010 dollars, the expected capital costs for a conventional onshore wind farm turbine are $2,150 per kW, with a low of $1,300per kW and a high of $3,500 per kW (Wiser & Bolinger, 2011).

The onshore advanced wind farm is representative of 12 projects installed in 2009 and 2010, using turbines with capacities greater than 2.5 MW. This cost analysis uses 2.5 MW to define the low end of the capacity range for advanced wind turbines and 3.0 MW as the high end of the capacity range for advanced wind turbines. The midpoint of this range, 2.75 MW, is the expected capacity for advanced wind turbines. In 2010 dollars, the expected capital costs for a conventional onshore wind farm turbine are $2,100 per kW, with a low of $1,500 per kW and a high of $2,600 per kW (Wiser & Bolinger, 2011).

The capital costs of offshore wind power are $5,975 per kW(EIA, 2010). These costs are based on projections for an offshore wind project with 5.0 MW turbines. No offshore wind projects have been completed in the U.S., so this capital cost includes an estimate of unexpected costs that could occur during the installation of a first-of-a-kind technology. This analysis assigns an uncertainty range of +/- 20 percent to the capital costs for offshore wind power; no data are available to assign low and high ranges to these capital costs.

5.2.2 Decommissioning

Decommissioning for onshore wind farms is estimated as 10 percent of the initial capital costs. When offshore wind projects are decommissioned, it is necessary to completely remove foundations and other structures because they are a marine navigation hazard. To account for the extra activities of offshore decommissioning, the decommissioning for offshore wind farms is estimated as 20 percent of the initial capital costs.

5.2.3 O&M Costs

The cost of grid integration is the only variable O&M cost identified by the data source on wind power. To compensate for the unreliability of wind power, other power producers must improve their reliability to provide load following power to balance the intermittency of wind power (Haughton, 2004). The integration cost of the Cape Wind 468 MW project is $2.40 per MWh (in 2004 dollars). The original data source for this cost factor (Parsons, et al., 2003) is not specific to onshore or offshore wind power, and thus the same cost for wind integration was also applied to the onshore wind farm scenario.

Fixed O&M costs for onshore and offshore wind power include wages, maintenance materials, and, for onshore wind power, land lease payments. In 2007 dollars, fixed O&M costs for onshore wind are $9.15/MWh (Wiser & Bolinger, 2011); on an annual basis this is $24,050/MW. Fixed O&M costs for offshore wind power are $16 million per year, which is based on data for the Cape Wind project (Haughton, 2004). On an annual basis, the fixed O&M costs for offshore wind power are $34,188/MW.

This analysis converts all O&M costs to a 2007 dollar basis using an annual inflation rate of three percent. The capital, decommissioning, and O&M costs for onshore and offshore wind power are shown in **Table 5-2**.

Table 5-2: Cost Summary for Onshore and Offshore Wind Power

Parameter	Low Cost	Expected Cost	High Cost
Onshore Conventional Wind Power (All Costs in 2007$)			
Capital, $/kW	1,190	1,970	3,200
Decommissioning, $/kW	119	197	320
Variable O&M (Grid Integration), $/MWh	2.62	2.62	2.62
Fixed O&M (Annual), $/MW-yr.	24,050	24,050	24,050
Life, Years	30	20	20
Total Project Capacity, MW	200	200	200
Single Turbine Capacity, MW	1.0	1.5	1.75
Capacity Factor, %	33.0%	30.0%	25.0%
Construction Period, Years	2	2	2
Onshore Advanced Wind Power (All Costs in 2007$)			
Capital, $/kW	1,370	1,920	2,380
Decommissioning, $/kW	137	192	238
Variable O&M (Grid Integration), $/MWh	2.62	2.62	2.62
Fixed O&M (Annual), $/MW-yr.	24,050	24,050	24,050
Life, Years	30	20	20
Total Project Capacity, MW	200	200	200
Single Turbine Capacity, MW	2.5	2.75	3.0
Capacity Factor, %	33.0%	30.0%	25.0%
Construction Period, Years	2	2	2
Offshore Wind Power (All Costs in 2007$)			
Capital, $/kW	4,370	5,470	6,560
Decommissioning, $/kW	238	875	1,090
Variable O&M (Grid Integration), $/MWh	2.62	2.62	2.62
Fixed O&M (Annual), $/MW-yr.	34,188	34,188	34,188
Life, Years	30	20	20
Total Project Capacity, MW	468	468	468
Single Turbine Capacity, MW	5.0	5.0	5.0
Capacity Factor, %	41.0%	39.0%	37.1%
Construction Period, Years	2	2	2

5.3 Wind LCC Results

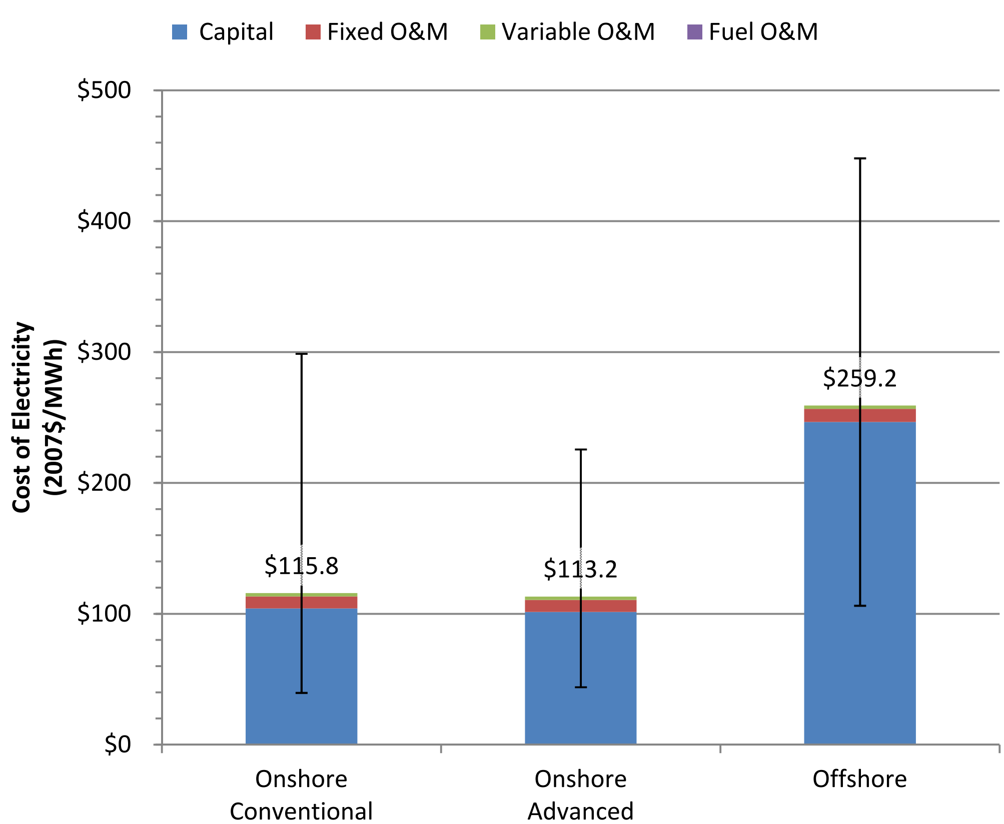
Compared to offshore wind power, onshore wind power (conventional and advanced) has lower capital and O&M costs per kilowatt of power. However, offshore wind power has a higher average capacity factor than onshore wind power, which helps reduce its costs in comparison to onshore wind power. The expected COE of onshore conventional, onshore advanced, and offshore wind power are $115.8, $113.2, and $259.2 per MWh, respectively. These costs are expressed in 2007 dollars, the base year of this analysis.

Wind power does not require the purchase of fuel, so the O&M costs for wind power are low in comparison to power technologies that use fossil fuel or other non-renewable energy sources. Capital costs dominate the COE for wind power, comprising between 89.6 and 95.1 percent of the COE of wind power.

The expected COE of onshore advanced wind power is only 2.3 percent lower than the expected COE of onshore conventional wind power. As indicated by the capital cost data compiled by the EIA (Wiser & Bolinger, 2011), the weighted capital costs of high-capacity wind turbines (greater than 2.5 MW per turbine) are not significantly lower than the weighted capital costs of wind turbines in the 1 to 1.75 MW range. As wind power technology improves, it is possible that advanced wind turbines will achieve a greater economy of scale than conventional wind turbines, but current data does not reflect such a trend.

The uncertainty in these cost results include ranges in capital costs, turbine life, O&M costs, capacity factors, and expected returns on equity used for financing the wind projects (as shown in **Table 5-1** above). The expected cost results show that onshore wind power (conventional and advanced) has a lower COE than offshore wind power, but the overlapping uncertainties of these results indicate that if offshore wind power exceeds performance expectations or has a financing structure with low expected returns, it can be cost competitive with onshore wind power.

Figure 5-1: Life Cycle Cost Results for Wind Power



6 Barriers to Implementation

Key barriers to the implementation of wind power include installation issues (construction, cost, and permitting), grid connection, and grid integration.

6.1 Wind Project Installation Issues: Construction, Cost, and Permitting

Onshore wind farms have experienced much shorter planning and construction horizons, as compared to fossil fueled power plants, with a typical planning cycle of approximately 3-4 years (EIA, 2011b). To this end, onshore wind farms have experienced, for the most part, comparatively lower levels of public scrutiny during the environmental permitting process, and have benefitted from federal and state level measures enacted to support wind production and, in some areas, streamline the permitting processes. Additionally, because many onshore wind farms have been installed and implemented, there is a relatively high level of experience with the permitting process within the onshore wind industry, environmental consultants, and civil servants who support the environmental review and permitting process.

The offshore wind industry, in contrast, lags behind the onshore wind industry in these aspects. For instance, the first major offshore wind project in the U.S. was approved after about a decade of planning and compliance procedures, in April, 2010 (Cape Wind, 2010). This extremely long lead time occurred as a result of a variety of factors. Perhaps first and foremost is the comparatively high cost of the project, which will produce power at a starting price of $0.18/kWh beginning in 2013, plus an annual escalation of 3.5 percent per year through 2028 (Platts, 2010). Preliminary cost models indicate that this will result in a ratepayer increase of only 1-2 percent, however, project cost was a highly contentious issue during the environmental review and permitting process. High costs were driven by a variety of factors including challenging engineering conditions, infrastructure costs, and environmental compliance and permitting.

Domestic offshore wind costs are, however, expected to decrease in the mid-term. For instance, Energy Efficiency and Renewable Energy's (EERE) National Offshore Wind Strategy (EERE, 2011) indicated a goal electricity cost point of $0.07/kWh by 2030, with an interim goal of $0.10/kWh by 2020, in order to remain more closely competitive with other power production technologies. Cost reductions of this order would substantially lessen cost burdens on individual project, and support faster implementation.

For offshore wind facilities, lack of prior projects and lack of available data in support of the permitting process are also key barriers (EERE, 2011). Unlike onshore wind, where topography and wind profiles are or can be easily and quickly evaluated and documented, offshore bathymetries and wind velocities are typically more difficult to acquire. Offshore facilities also face vastly different engineering challenges including very high winds during storms, ocean currents, ocean waves, and mooring related issues. As more offshore wind farms are permitted and constructed, the relative importance of these barriers is anticipated to reduce, at least in part.

Finally, the installation of onshore and offshore wind power can result in various environmental impacts, including increases in bird and bat strikes from wind turbines and aboveground power lines, construction related impacts including erosion and water quality pollution, interference with navigation, loss of benthic biota (offshore only), loss of vegetation/habitat, and interference with cultural and visual resources (USACE, 2006). In some instances, environmental concerns have resulted in significant delays in wind project implementation. For instance, high levels of public concern regarding environmental impact were one of the key issues that resulted on a prolonged environmental compliance and permitting period for the Cape Wind project, which took nearly a decade to acquire approval (USACE, 2006).

6.2 Grid Connection

Availability of power transmission capacity, combined with the difficulty of constructing long distance power transmission lines, is another key barrier to the implementation of both onshore and offshore wind power. The best wind resources are, in many cases, located a far distance from existing population centers, and a far distance from existing power transmission lines needed to carry energy onto the power grid. As a result, many of the best wind resources in the U.S. remain untapped for the simple reason that new transmission facilities are (1) expensive to construct and (2) difficult to permit (Smith & Bruysen, 2010). For remote wind resources, sharing transmission line construction and permitting efforts among many wind developers is the only workable scenario. However, implementing such agreements requires long-term planning due to long lead times for major transmission facility permitting and installation requirements; therefore, such agreements are difficult to reach and administer.

6.3 Grid Integration

Wind generated power is intermittent in nature and as such is not treated in the same way as power generated by steady, predictable energy sources. Wind power can be offered and designated as a capacity resource in a day-ahead market. The capacity that a wind generator can provide depends on historical data rather than its nameplate capacity. The capacity value calculation for a wind power resource depends on the market where the intermittent resource is located. For example, California Independent System Operator calculates a net qualifying capacity based on the adjusted output that the intermittent resources exceed in 70 percent of peak hours during each month over the last three years (CA-ISO, 2011). The Pennsylvania New Jersey Maryland Independent System Operator (PJM ISO) calculates a capacity value as a three-year rolling average of capacity factors during summer peak hours (PJM-ISO, 2010). If the three-year history does not exist, 13 percent is used for the wind power capacity value.

The wind intermittency impact on the system operations depends on the relative wind power penetration level. At low penetration levels, wind based generation can be handled as load variations having negligible impact on the grid. High wind penetration levels would have larger impact on the grid and would require adjustment of reserve resources; a grid operator would have to schedule additional operating reserves to account for the scheduled intermittent resources. The amount of the additional reserve would be directly proportional to wind power penetration level. In 2010, General Electric published a New England wind integration study (GE, 2010b). According to this study, 5 percent of wind penetration would not require total operating reserves increase. Wind penetration of 10 and 20 percent would require 10 percent and 15 to 20 percent reserves increase respectively.

7 Risks of Implementation

Key risks associated with wind power implementation include cost uncertainty and environmental risks, as discussed below.

7.1 Cost

The U.S. onshore wind industry has grown rapidly and consistently over the last decade. While still showing signs characteristic of an emergent market sector (i.e., near exponential growth coupled with high levels of permit applications and project planning announcements), relative risks of onshore wind power implementation have decreased substantially, as compared to a decade ago. Chief among risk, cost per kWh for onshore wind has decreased, in particular since 2008. For instance, industry experts indicate that as of 2011, onshore wind power purchase agreements have been signed within the range of $0.05 to $0.06 per kWh (AWEA, 2011b). This level of cost, while not necessarily applicable to all wind projects due to siting and transmission related cost constraints, remains significant due to its near parity with natural gas power generation costs. Further, they are lower than the expected onshore wind COE calculated in this analysis because they include production tax credits and do not account for a 7 percent electricity transmission loss.

In addition to increasingly lower cost, onshore wind power enjoys an increasing level of institutional experience with wind power permitting. Many relevant examples of certified environmental compliance documentation, for instance in support of the National Environmental Policy Act (NEPA), agency permitting, and state level environmental documentation, are available. Furthermore, industry has increasing experience in the compliance and permitting process and continues to identify procedures that support streamlining of environmental permitting and project cost.

In contrast, the U.S. offshore wind industry holds considerably higher risk. Costs for offshore wind power remain high, above $0.15 per kWh (Platts, 2010). As with onshore wind power, these costs are lower than the expected offshore wind COE calculated in this analysis because they include production tax credits and do not account for a 7 percent electricity transmission loss. Many project engineering and design features are still in early stages of mass implementation, and considerable forethought is required in support of engineering design for individual wind power projects. As a result, offshore wind project design requires more time and more effort, and environmental compliance and permitting issues are, to date, considerably more complex than most onshore wind power installations.

The U.S. government is taking measures to support offshore wind power production. For instance, in February, 2011, the Obama administration announced $50.5 million in new funding opportunities to support offshore wind energy deployment; delineated several high priority Wind Energy Areas in the mid-Atlantic (U.S. Department of the Interior, 2011); and set a goal of reducing offshore wind power cost to $0.07 per kWh by 2030, and $0.10 per kWh by 2020 (EERE, 2011).

7.2 Environmental Risks

As noted above, key environmental risks include increases in bird and bat strikes, construction-related impacts to water quality and air quality, potential for interference with marine navigation (offshore facilities only), loss of habitat or vegetation, and interference with cultural and visual resources (USACE, 2006). Bird strikes and aesthetic concerns have, in particular, received significant public and agency attention. Especially in mountainous western regions, wind farms have been installed along mountain passes and other areas having high wind potential. Many such locations also serve as key migratory routes for various species of birds. Additionally, wind farms commonly serve as foraging habitat for raptors and other birds of prey. Offshore wind farms may interfere with migratory routes, or with foraging. In some cases, collision-related mortality can result in population level effects on certain high-incidence bird species (Drewitt & Langston, 2008). Various site specific mitigation and avoidance measures are available on a site-by-site basis, including modifications to turbine heights, spacing, and positioning.

Levels of concern regarding aesthetics depend heavily on the proximity of a given wind farm project to population centers or to scenic areas. Wind farms located in rural or remote areas without significant scenic resources do not typically attract a great deal of attention from concerned citizens. However, for projects that are close to population centers and/or scenic areas, aesthetic considerations can be substantial. For instance, aesthetic considerations may drive high levels of public comment from concerned citizens and in some cases may result in heightened public opposition to a given project.

8 Expert Opinions

Fearful of entering into a serial boom-bust scenario, many wind developers are currently calling for additional federal policies to support continued wind development. Onshore wind development has, in some cases, reached cost competitiveness with natural gas based power production, on a per kWh basis. However, according to Denise Bode, CEO of the AWEA, wind power lacks predictable federal policies needed to drive consistent wind power growth (AWEA, 2011b). Policies supporting renewables, including wind, are set to expire in the near term. For instance the American Recovery and Reinvestment Act’s Treasury grant program required all new construction to commence by the end of 2011, and the Production Tax Credit is set to expire in 2012. AWEA has positioned itself firmly on the side of increased policy support at the federal level. However, state level support is also important, and AWEA has moved towards promoting other sources of demand, including distributed and community wind projects, as well as corporate purchasing programs (AWEA, 2011b).

Some analysts are predicting that wind growth may shift towards offshore installations in the near to midterm. Based largely on the recent release of the Obama Administration’s *A National Offshore Wind Strategy* (EERE, 2011), economists are anticipating a surge in offshore wind installations (Reuters, 2010). The potential timing on such a surge, however, remains somewhat unclear. Cape Wind received approval in 2010, but only after a long and belabored environmental review and permitting process. Most experts agree that the certification of the Cape Wind project will add momentum to the offshore industry, but there is general disagreement as to when and to what extent.

In terms of offshore wind farm locations, a review of U.S. permit applications, as well as analysis completed by NREL, indicate that most offshore wind projects in the near term will likely be in the Northeast and Mid-Atlantic regions, with additional projects considered in the Gulf Coast, Great Lakes, and West Coast. Water depth is, however, a key factor, and is expected to preclude near term deployment on the west coast, where deep water turbines are not yet readily or commercially available (NREL, 2010a).

9 Summary

This analysis provides insight into the role of wind as a future energy source in the U.S. The criteria used for evaluating the role of wind power are as follows:

- Environmental Profile
- Cost Profile
- Resource Base
- Growth
- Barriers to Implementation
- Risks of Implementation
- Expert Opinions

Key conclusions for these criteria are summarized below.

The **environmental profile** of this analysis focuses on the LC GHG emissions of wind power. The LC GHG emissions for wind power from conventional and advanced onshore wind power are 22.0 and 19.1 kg CO_2e per MWh, respectively. The LC GHG emissions from offshore wind power are 32.5 kg CO_2e per MWh for offshore wind power. The advanced onshore system has lower GHG emissions than the conventional system due to the higher economy of scale between turbine materials and turbine rating (MW) for the advanced systems. There is a nonlinear relationship between turbine materials and turbine rating (MW); for the rotor diameters modeled in this analysis, the ratio of turbine materials to turbine output decreases with increasing turbine capacity. Offshore wind power has higher LC GHG emissions than both onshore scenarios due to added complexity of installing, maintaining, and connecting wind turbines 20 km from the shoreline.

When considering land use GHG emissions in addition to the other GHG emissions, the land use GHG emissions increase total LC GHG by 12 percent (22.0 to 24.7 kg CO_2e/MWh) for onshore conventional wind power, by 14 percent of onshore advanced wind power (19.1 to 21.8 kg CO_2e/MWh), and by 2.0 percent for offshore wind power (32.5 to 33.2 kg CO_2e/MWh). Systems with backup power also have GHG emissions from land use change, but they are dominated by combustion emissions, making land use change a smaller share of total GHG emissions.

When the reliability of power generation is considered, the need for backup power increases the LC GHG emissions of wind power. When a gas turbine simple cycle (GTSC) power plant provides backup power to an *onshore* wind farm, the LC GHG emissions are 502 kg CO_2e per MWh. Similarly, when a GTSC power plant provides backup power to an *offshore* wind farm, the LC GHG emissions are 429 kg CO_2e per MWh. For comparison, an advanced fossil combustion technology such as an integrated gasification combined cycle (IGCC) plant with a carbon capture and sequestration (CCS) system has LC GHG emissions of 218 kg of CO_2e/MWh (NETL, 2010b).

The **cost profile** of wind power was based on a discounted cash flow analysis. Compared to offshore wind power, onshore wind power has lower capital and operating and maintenance (O&M) costs per kilowatt of power. However, offshore wind power has a higher average capacity factor than onshore wind power, which helps reduce its costs in comparison to onshore wind power. The cost results are dominated by capital costs. When the same financial assumptions are applied to onshore and offshore wind power, the cost of electricity (COE) is $115/MWh for onshore conventional, $113/MWh for onshore advanced, and $259/MWh for offshore. The expected cost results show that onshore wind power has a lower COE than offshore wind power, but the overlapping uncertainties of these results indicate that if offshore wind power has better-than-expected performance, or a financing structure with low expected returns, it can be cost competitive with onshore wind power. However, as tax credits and other financial incentives for wind power expire, it is likely that investments in new wind power projects will slow down significantly, and with no long-term federal policies for renewable energy investments, it is difficult for producers to secure power purchase agreements.

The **resource base** of onshore wind power is estimated to be sufficient to supply approximately 10,400,000 MW of wind power capacity, although much of this capacity is located in remote areas (AWEA, 2011a). U.S. offshore wind resources are estimated to be sufficient to support approximately 4,150,000 MW of power production (AWEA, 2011a).These estimates of wind resources, like similar estimates for tidal, solar, and geothermal potential energy, are misleading because not all of the resource is economically accessible. There is a large amount of uncertainty about what percent of the capacity will be installed and, further, what amount of electricity will be generated from that installed capacity (e.g. capacity factor). The fraction of total U.S. power generation from wind power has grown from approximately 0.1 percent in 2000, to approximately 2.3 percent in 2010.

The **barriers to implementation** include uncertainties in construction schedules, especially for offshore wind projects. Onshore wind farms have experienced much shorter planning and construction horizons, as compared to fossil fueled power plants, with a typical planning cycle of approximately 3-4 years (EIA, 2011b). The offshore wind industry, in contrast, lags behind the onshore wind industry in these aspects. For instance, the first major offshore wind project in the U.S. was approved after about a decade of planning and compliance procedures, in April, 2010 (Cape Wind, 2010). Availability of power transmission capacity, combined with the difficulty of constructing long distance power transmission lines, is another barrier to the implementation of wind power.

Even if transmission lines are near a wind farm, the intermittent production of the wind farm may prevent it from meeting the capacity requirements of its market. For example, the California Independent System Operator (CA ISO) calculates a net qualifying capacity based on the adjusted output that the intermittent resources exceed in 70 percent of peak hours during each month over the last three years (CA-ISO, 2011). Further, if wind power becomes a greater share of total grid power, grid operators will have to spend more time scheduling additional operating reserves. In other words, at low wind power penetration, the intermittency of wind power has a negligible impact on the stability of the grid, but at high wind power penetration, grid operators must plan for wind power intermittency.

The **risks of implementation** include various environmental impacts that are unique to wind power, including increases in bird and bat strikes from wind turbines. And in the case of offshore wind power, interference with marine navigation, loss of benthic biota, and interference with cultural and visual resources (USACE, 2006) are further risks are implementation.

The opinions of **wind power experts** include the outlooks of wind developers and industry associations. Fearful of entering into a serial boom-bust scenario, many wind developers are currently calling for additional federal policies to support continued wind development. Onshore wind development has, in some cases, reached cost competitiveness with natural gas based power production, on a per kWh basis. However, according to AWEA, wind power lacks predictable federal policies needed to drive consistent wind power growth. Some analysts are predicting that wind growth may shift towards offshore installations in the near to midterm. Based largely on the recent release of the Obama Administration's *A National Offshore Wind Strategy* (EERE, 2011), economists are anticipating a surge in offshore wind installations (Reuters, 2010).

Wind can be an important energy resource for the U.S., but as its contribution to total U.S. electricity generation increases, it will require a significant amount of fossil resources for backup power to maintain grid reliability. And while wind power has exhibited significant growth over the last decade, most of this growth was made possible through financial incentives such as temporary renewable energy tax credits. Technology advances that result in lower project costs and energy storage devices that enable better power reliability remain crucial research and development areas for the long-term integration of wind power.

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Appendix A:
Constants and Unit Conversion Factors

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Table A-1: Common Unit Conversions

Category	Input			Output	
	Value	Units		Value	Units
Mass	1	lb.	=	0.454	kg
	1	Short Ton	=	0.907	Tonne
Distance	1	Mile	=	1.609	km
	1	Foot	=	0.305	m
Area	1	$ft.^2$	=	0.093	m^2
	1	Acre	=	43,560	$ft.^2$
Volume	1	Gallon	=	3.785	L
	1	$ft.^3$	=	28.320	L
	1	$ft.^3$	=	7.482	Gallons
	1	m^3	=	35.3	$ft.^3$
Energy	1	Btu	=	1,055.056	J
	1	MJ	=	947.817	Btu
	1	kWh	=	3,412.142	Btu
	1	MWh	=	3,600	MJ

Table A-2: IPCC Global Warming Potential Factors (Forester, et. al., 2007)

IPCC GWP Factor	Vintage	20 Year	100 Year	500 Year
CO_2	2007	1	1	1
CH_4	2007	72	25	7.6
N_2O	2007	289	298	153
SF_6	2007	16,300	22,800	32,600
CO_2	2001	1	1	1
CH_4	2001	62	23	7
N_2O	2001	275	296	156
SF_6	2001	15,100	22,200	32,400

Appendix B: Data for Wind Power

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B.1 Manufacture of Turbine Components

The wind turbines modeled in this analysis are based on the National Renewable Energy Laboratory's (NREL) scaling model for wind power (NREL, 2006). The three subsystems of a wind turbine are the rotor, nacelle, and tower. The rotor is comprised of three blades arranged around a hub. The nacelle is a housing for the shaft, bearings, and generator; it is also a manifold between the rotor and tower. The tower elevates the nacelle and rotor. The key components of these three subsystems are as follows:

- Rotor
  - Blades
  - Hub
  - Spinner, nose cone
- Nacelle
  - Main Shaft and Bearings
  - Generator
  - Main frame
  - Nacelle cover
- Tower

Mass of Turbine Components

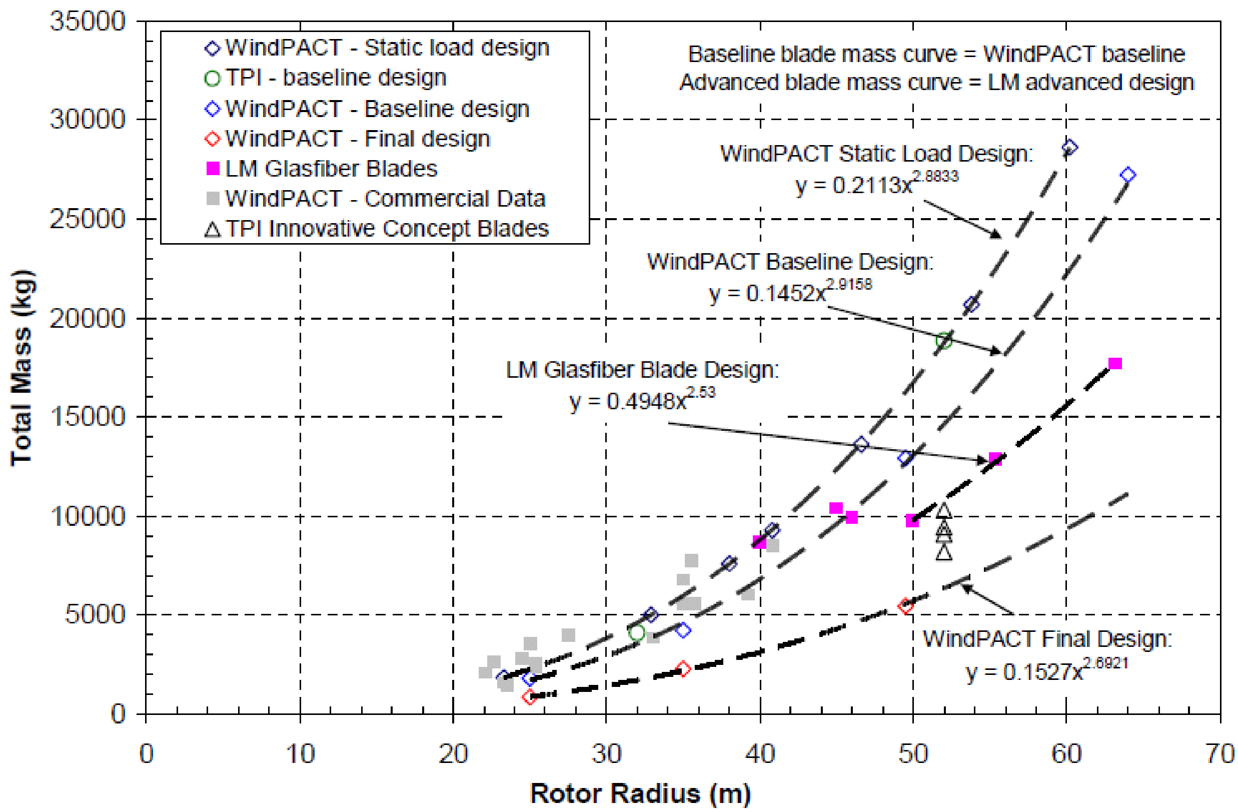
The mass relationships between turbine capacity and turbine components are based on equations developed using a wind turbine scaling model (NREL, 2006). The conventional components are representative of 2002 technologies, while the advanced components represent pending designs. These equations are shown in the **Table B-1.**

Table B-1: Wind Turbine Mass Scaling Equations

Subsystem	Component	Conventional Turbine	Advanced Turbine	Notes
Rotor	Blade (1 Blade)	$0.1452 \times r^{2.92158}$	$0.495 \times r^{2.53}$	r = Rotor Radius in *m*
Rotor	Hub	(0.954 x B) + 5680.30	(0.954 x B) + 5680.30	B = Single Rotor Blade Mass in *kg*
Rotor	Spinner (Nose Cone)	18.5 x d – 520.50	18.5 x d – 520.50	d = Rotor Diameter in *m*
Nacelle	Main Shaft and Small Bearings	$1.6 \times (0.0009 \times d^{3.314})$	$1.6 \times (0.0009 \times d^{3.314})$	d = Rotor Diameter in *m*
Nacelle	Generator	$10.51 \times \text{Turbine Rating}^{0.9223}$	$6.47 \times \text{Turbine Rating}^{0.9223}$	Turbine Rating is in *kW*
Nacelle	Main Frame (1 section)	$1.295 \times d^{1.953}$	$2.233 \times d^{1.953}$	d = Rotor Diameter in *m*
Nacelle	Nacelle Cover	(11.57 x Turbine Rating + 3849.70) / 10	(11.57 x Turbine Rating + 3849.70) / 10	Turbine Rating is in *kw*
Tower	Tower (1 Piece)	0.3973 × Swept Area × Hub Height – 1414	0.2694 × Swept Area × Hub Height + 1779	Swept Area is in m^2 Hub Height is in *m*

As demonstrated by the following figure, developed by NREL's wind power scaling model (NREL, 2006), the material scaling equations for blades demonstrate a non-linear relationship to rotor diameter.

Figure B-1: Non-Linear Relationship Between Rotor Radius and Blade Mass (NREL, 2006)



The mass scaling equations developed by NREL (NREL, 2006) account for the economy of scale realized by advanced turbines. Conventional turbines have power ratings of 1.5 MW or less, while advanced turbines have power ratings from 1.5 to 6 MW. The mass scaling equations shown for conventional turbines in **Table B-1** are based on current commercial wind farm installations, while the equations shown for advanced turbines are based on design projections.

The above equations (shown in **Table B-1**) allow the development of a dynamic model for wind turbine manufacture, with turbine rating (MW) and rotor diameter (meters) as key variables. This analysis uses these equations in to develop a set of eight unit processes that allow the dynamic modeling of the non-linear relationship between rotor size (which is directly related to the power rating of a wind turbine) and the mass of key turbine components.

Material Profile of Turbine Components

In addition to the mass of individual turbine components, the material profile of each turbine component is necessary to model the life cycle (LC) environmental burdens of a wind turbine. **Table B-2** shows the material compositions of conventional and advanced turbine components. The material profiles shown are factored with the mass scaling equations shown in **Table B-1** to arrive at a scalable model for the mass and materials necessary for the manufacture of each turbine component.

Table B-2: Wind Turbine Material Profiles

Subsystem	Component	Conventional Turbine	Advanced Turbine	Reference
Rotor	Blade (1 Blade)	Glass Reinforced Plastic = 78% Carbon Fiber = 0% Resin Glue = 10% Cold Rolled Steel = 12%	Glass Reinforced Plastic = 68% Carbon Fiber = 10% Resin Glue = 10% Cold Rolled Steel = 12%	DOE, 2008
Rotor	Hub	Steel = 100%	Steel = 100%	NREL, 2006
Rotor	Spinner (Nose Cone)	Glass Fibers = 40% Resin Glue = 60%	Glass Fibers = 60% Resin Glue = 40%	DOE, 2008
Nacelle	Main Shaft and Small Bearings	Cold Rolled Steel = 100%	Cold Rolled Steel = 100%	NREL, 2006
Nacelle	Generator	Copper = 65% Silica = 32% Stainless Steel = 3%	Copper = 65% Silica = 32% Stainless Steel = 3%	NREL, 2006
Nacelle	Main Frame (1 section)	Cast Iron = 60% Cold Rolled Steel = 40%	Cast Iron = 40% Cold Rolled Steel = 60%	NREL, 2006
Nacelle	Nacelle Cover	Glass Fibers = 80% Resin Glue = 20%	Glass Fibers = 80% Resin Glue = 20%	NREL, 2006
Tower	Tower (1 Piece)	Cold Rolled Steel = 100%	Cold Rolled Steel = 100%	NREL, 2006

The manufacture of the eight subsystems shown in **Table B-1** and **Table B-2** are discussed in more detail below.

Rotor Blade Manufacture

The mass relationships between turbine capacity and turbine components are based on equations developed using a wind turbine scaling model (NREL, 2006). The conventional components are representative of 2002 technologies, while the advanced components represent pending designs.

The types of materials used for blade manufacture are based on estimated material profiles for wind turbine components (DOE, 2008). Glass reinforced plastic (GRP) material is 78 and 68 percent of the blade mass for conventional and advanced turbines, respectively (DOE, 2008). Carbon fiber is not used for conventional blades, but does comprise 10 percent of total blade mass for advanced turbine blades (DOE, 2008). Resin adhesive comprises 10 percent of the blade mass. The balance of the blade mass is steel.

Scrap material is generated by the manufacturing process at a rate of one percent of the weight of the finished blade. Of this manufacturing scrap, 95 percent is landfilled and 5 percent is recovered for recycling (Nalukowe et. al, 2006).

The flows for the manufacture of one rotor blade are shown in **Table B-3.**

Table B-3: Unit Process Flows for Rotor Blade Manufacture

Flow Name	Onshore Conventional	Onshore Advanced	Offshore	Units
Inputs				
Glass Fibers	2,713	11,763	6,355	kg
Carbon Fibers	399	1,730	934.6	kg
Resin Glue	598	2,595	1,402	kg
Steel	279	1,211	654	kg
Electricity	15,958	69,194	37,384	MJ
Outputs				
Horizontal Turbine Blade	1.00	1.00	1.00	Piece
Solid Waste	3,778	16,382	8,851	kg
Steel Scrap	251	1,090	588	kg

Hub Manufacture

The mass relationships between turbine capacity and turbine components are based on equations developed using a wind turbine scaling model (NREL, 2006). The conventional components are representative of 2002 technologies, while the advanced components represent pending designs.

The types of materials used for hub manufacture are based on estimated material profiles for wind turbine components (NREL, 2006). Cast iron makes up about63 percent of the hub mass for both conventional and advanced turbines (NREL, 2006), while cold rolled steel makes up about 23 percent and stainless steel makes up the remainder.

Scrap material is generated by the manufacturing process at a rate of one percent of the weight of the finished hub piece. Of this manufacturing scrap, 90 percent is recovered for recycling and 10 percent is landfilled (Nalukowe et. al, 2006).

The flows for the manufacture of one hub are shown in **Table B-4**.

Table B-4: Unit Process Flows for Hub Manufacture

Flow Name	Onshore Conventional	Onshore Advanced	Offshore	Units
Inputs				
Cast Iron	10,082	29,555	17,423	kg
Electricity	44,675	150,887	84,715	MJ
Outputs				
Horizontal Turbine Hub	1.00	1.00	1.00	Piece
Solid Waste	1,611	5,443	3,056	kg
Steel Scrap	14,503	48,984	27,502	kg

Spinner Manufacture

The mass relationships between turbine capacity and turbine components are based on equations developed using a wind turbine scaling model (NREL, 2006). The conventional components are representative of 2002 technologies, while the advanced components represent pending designs.

The types of materials used for spinner manufacture are based on estimated material profiles for wind turbine components (NREL, 2006). Glass reinforced plastic (GRP) is 40 percent of the spinner mass for both conventional and advanced turbines (DOE, 2008), with resin glue making up the remainder.

Scrap material is generated by the manufacturing process at a rate of one percent of the weight of the finished spinner piece. Of this manufacturing scrap, 100 percent is landfilled (Nalukowe et. al, 2006).

The flows for the manufacture of one spinner are shown in **Table B-5**.

Table B-5: Unit Process Flows for Spinner Manufacture

Flow Name	Onshore Conventional	Onshore Advanced	Offshore	Units
Inputs				
Glass Fibers	309.8	717	517.0	kg
Resin Glue	464.7	1,075	775.5	kg
Power	8,542	19,766	14,256	MJ
Outputs				
Horizontal Turbine Spinner	1.00	1.00	1.00	Piece
Scrap Waste	782.3	1,810	1,305	kg

Main Shaft and Bearings Manufacture

The mass relationships between turbine capacity and turbine components are based on equations developed using a wind turbine scaling model (NREL, 2006). The conventional components are representative of 2002 technologies, while the advanced components represent pending designs.

The types of materials used for main shaft and bearings manufacture are based on estimated material profiles for wind turbine components (NREL, 2006). Cold rolled steel is 100 percent of the mass of the main shaft and bearings for both conventional and advanced turbines (NREL, 2006), with negligible amounts of other materials.

Scrap material is generated by the manufacturing process at a rate of one percent of the weight of the finished main shaft and bearings piece. Of this manufacturing scrap, 90 percent is recovered for recycling and 10 percent is landfilled (Nalukowe et. al, 2006).

The flows for the manufacture of one set of shaft and bearings are shown in **Table B-6**.

Table B-6: Unit Process Flows for Main Shaft and Bearings Manufacture

Flow Name	Onshore Conventional	Onshore Advanced	Offshore	Units
Inputs				
Cold Rolled Steel	5,241	31,585	14,830	kg
Electricity	445,491	2,684,682	1,260,551	MJ
Outputs				
Horizontal Turbine Shafts & Bearings	1.00	1.00	1.00	Piece
Solid Waste	529.4	3,190	1,498	kg
Steel Scrap	4,764	28,710	13,480	kg

Generator Manufacture

The mass relationships between turbine capacity and turbine components are based on equations developed using a wind turbine scaling model (NREL, 2006). The conventional components are representative of 2002 technologies, while the advanced components represent pending designs.

The types of materials used for generator manufacture are based on estimated material profiles for wind turbine components (NREL, 2006). The generator manufactured from 3 percent stainless steel, 65 percent copper, and 32 percent silica (Martinez et. al, 2009). The direct drive component is modeled with a 100 percent stainless steel composition (Martinez et. al, 2009).

Scrap material is generated by the manufacturing process at a rate of one percent of the weight of the finished generator. Of this manufacturing scrap, 90 percent of the steel and copper materials are recovered for recycling and 10 percent is landfilled (Nalukowe et. al, 2006).

The flows for the manufacture of one generator are shown in **Table B-7**.

Table B-7: Unit Process Flows for Generator Manufacture

Flow Name	Onshore Conventional	Onshore Advanced	Offshore	Units
Inputs				
Cold Rolled Steel	665	1,092	870	kg
Copper Parts	3,574	12,835	8,013	kg
Silicate	1,759	6,319	3,945	kg
Electricity	1,361,570	4,595,987	2,911,888	MJ
Outputs				
Generator	1.00	1.00	1.00	Piece
Solid Waste	2,025	7,141	4,477	kg
Steel Scrap	604	993	791	kg
Copper Scrap	3,429	12,315	7,688	kg

Main Frame Manufacture

The mass relationships between turbine capacity and turbine components are based on equations developed using a wind turbine scaling model (NREL, 2006). The conventional components are representative of 2002 technologies, while the advanced components represent pending designs.

The types of materials used for main frame manufacture are based on estimated material profiles for wind turbine components (NREL, 2006). The main frame is manufactured from 60 percent cast iron, while the rest of the main frame consists of cold rolled steel (NREL, 2006).

Scrap material is generated by the manufacturing process at a rate of one percent of the weight of the finished generator. Of this manufacturing scrap, 90 percent of the cast iron and steel materials are recovered for recycling and 10 percent is landfilled (Nalukowe et. al, 2006).

The flows for the manufacture of one main frame are shown in **Table B-8**.

Table B-8: Unit Process Flows for Main Frame Manufacture

Flow Name	Onshore Conventional	Onshore Advanced	Offshore	Units
Inputs				
Cast Iron	5,376	16,684	10,373	kg
Cold Rolled Steel	3,584	11,123	6,915	kg
Electricity	27,690	85,924	53,421	MJ
Outputs				
Horizontal Turbine Main Frame	1.00	1.00	1.00	Piece
Solid Waste	905.1	2,809	1,746	kg
Steel Scrap	8,145	25,277	15,715	kg

Nacelle Cover Manufacture

The mass relationships between turbine capacity and turbine components are based on equations developed using a wind turbine scaling model (NREL, 2006). The conventional components are representative of 2002 technologies, while the advanced components represent pending designs.

The types of materials used for nacelle cover manufacture are based on estimated material profiles for wind turbine components (NREL, 2006). Glass reinforced plastic (GRP) is 80 percent of the mass of the nacelle cover for both conventional and advanced turbines (NREL, 2006), with resin glue making up the remaining mass.

Scrap material is generated by the manufacturing process at a rate of one percent of the weight of the finished main shaft and bearings piece. Of this manufacturing scrap, 100 percent is landfilled (Nalukowe et. al, 2006).

The flows for the manufacture of one nacelle cover are shown in **Table B-9**.

Table B-9: Unit Process Inputs and Outputs for Nacelle Cover Manufacture

Flow Name	Onshore Conventional	Onshore Advanced	Offshore	Units
Inputs				
Glass Fibers	2,153	5,846	3,631	kg
Resin Glue	538.5	1,461	908	kg
Electricity	30,046	81,548	50,647	MJ
Outputs				
Nacelle Cover	1.00	1.00	1.00	Piece
Solid Waste	2,719	7,380	4,583	kg

Tower Manufacture

The mass relationships between turbine capacity and turbine components are based on equations developed using a wind turbine scaling model (NREL, 2006). The conventional components are representative of 2002 technologies, while the advanced components represent pending designs.

The types of materials used for tower manufacture are based on estimated material profiles for wind turbine components (NREL, 2006). Cold rolled steel is 100 percent of the mass of the tower for both conventional and advanced turbines (NREL, 2006), with negligible amounts of other materials.

Scrap material is generated by the manufacturing process at a rate of one percent of the weight of the finished tower piece. Of this manufacturing scrap, 90 percent is recovered for recycling and 10 percent is landfilled (Nalukowe et. al, 2006).

The flows for the manufacture of one tower are shown in **Table B-10**.

Table B-10: Unit Process Flows for Tower Manufacture

Flow Name	Onshore Conventional	Onshore Advanced	Offshore	Units
Inputs				
Cold Rolled Steel	117,787	378,690	232,219	kg
Power	103,652	333,248	204,353	MJ
Outputs				
Tower	1.00	1.00	1.00	Piece
Steel Scrap	107,068	344,230	211,087	kg
Solid Waste	11,896	38,248	23,454	kg

B.2 Onshore Wind Farm Construction

Each turbine on a wind farm has a transformer the steps up the turbine generator voltage to a medium voltage suitable for the distribution of electricity to a central switchyard. These transformers are located at the base of each turbine. The cables that connect the individual wind turbines to the switchyard are 35-kV copper cables and are buried underground. A 100-mile trunkline is necessary to connect the wind farm to the electricity transmission grid. The mass and types of materials required for the construction of transformers, cables, switchyard equipment, and the trunkline are based on vendor specifications and discussions with industry experts.

Gravel Road Construction

The scope of this process covers the materials required for the construction of a gravel road used at an onshore wind farm by trucks and other heavy duty vehicles. The road is constructed entirely of gravel. Installation of the road requires conventional diesel fuel for the use of grading and other construction equipment.

The total weight for a one meter length of gravel road, having a thickness of 1.0 feet and a default width of 5.0m, was estimated to be approximately 2,320 kg (5,115 lbs.). This value is based on a gravel mass of 1,522 kg per cubic meter (95 lbs./ft.^{3}) (Simetric, 2009). Carbon dioxide emissions were estimated based on three data sources for the construction of forest access roads, and two life cycle analyses (LCA) of sustainable or green roads (Loeffler et. al, 2008;Chappat and Bial, 2003; University of Washington, 2010). Resulting average carbon dioxide emissions were 0.467 kg CO_2/m^2. The amount of diesel required for road construction was estimated by back-calculating the mass of diesel that would need to be combusted in order to account for this CO_2 emission rate. Nitrous oxide, methane, ammonia, and non-methane volatile organic carbon (NMVOC) emissions were then calculated based on USEPA emissions standards for stationary and non-road diesel emissions. Emissions estimates for nitrogen oxides (NO_X), carbon monoxide, sulfur dioxide, and particulate matter (PM10) were generated using URBEMIS air emissions software (Rimpo and Associates, 2009), a standardized air emissions model used widely in California for the calculation of air emissions in support of various construction activities.

Table B-11 summarizes the relevant properties used to calculate the amount of diesel and gravel contained in a 1 meter of gravel road, and the airborne emissions that would result. **Table B-12** provides a summary of modeled input and output flows.

Table B-11: Properties for Gravel and Road Materials

Item	Value	Reference
Width of Gravel Road, m (ft.)	5.0 (16.4)	Estimated
Depth of Gravel Road, m (ft.)	0.30 (1.0)	Wisconsin Transportation Information Center, 2002
Mass of gravel per meter of road, based on a 5m road width, kg (lbs.)	1,522 (3,355)	Simetric, 2009
Diesel use per meter of road, based on a 5m road width, kg (lbs.)	0.741 (1.63)	Rimpo and Associates, 2009

Table B-12: Unit Process Flows for Gravel Road Construction

Flow Name	Value	Units
Inputs		
Diesel	0.741	kg
Gravel	2319.5	kg
Outputs		
Gravel Road, 12 Inch Deep Roadbed	1.00	m
CO_2	2.33E+00	kg
CH_4	3.33E-04	kg
N_2O	5.93E-05	kg
NO_X	2.95E-01	kg
SO_2	3.36E-04	kg
CO	1.01E-01	kg
VOC	4.92E-04	kg
Dust	5.17E-01	kg
NH_3	9.67E-05	kg

Wind Farm Switchyard Construction

This unit process provides a summary of relevant input and output flows associated with the construction of a switchyard for a wind farm. Materials include metals, mineral oil (for transformers), and concrete (for the foundation). Input metals (steel, aluminum, and copper) are recovered during decommissioning of the switchyard based on a parameterized recycling rate. The reference flow of this unit process is the construction of 1 switchyard.

Wind farms require a switchyard provides an interface between the generated electricity and the trunk line (which leads to the main electricity transmission grid). This unit process accounts for the materials required for the construction of a switchyard.

The total mass of switchyard equipment is estimated to be five times higher than the specifications for a 10 MW substation transformer as shown in a Department of Energy scaling study for wind farms (Shafer, 2001). Transformers are not the only type of equipment used by a switchyard, but they are a heavy type of equipment and represent the majority of total switchyard equipment mass. The total mass of transformers used by a single, 10 MW turbine is 46,500 lbs. (Shafer, 2001); increase this weight by a factor of five and converting to SI units results in an estimated switchyard mass of 105,000 kg. (This decision to scale a 10 MW substation is an approximation based on professional judgment. A 10 MW substation is not adequate to support a 200 MW wind farm, but it is likely that an economy of scale is realized when designing switchyards for larger systems.)

The mineral oil used by switchyards is also estimated from information in a Department of energy scaling study for wind farms (Shafer, 2001). The volume of mineral oil for a transformer used by a 10 MW turbine is 1,600 gallons. When scaled upward by five times (the same scaling factor used for the switchyard transformers) and converted to SI units of mass (using a specific gravity of 0.95 for mineral oil), the total mass of mineral oil for switchyard construction is 28,800 kg. If switchyard equipment is well-maintained, there are negligible mineral oil losses during the life of the switchyard. Due to data limitations, this analysis uses the cradle-to-gate production of kerosene as a proxy for the cradle-to-gate production of mineral oil.

This analysis also estimates the mass of metal used by circuit breakers in a wind farm switchyard. The mass of a circuit breaker is 4,785 kg (Mitsubishi Electric Power Products, Date Unknown). The switchyard has three circuit breakers (Shafer, 2001). The circuit breakers used by wind farms use mineral oil, not SF_6 (sulfur hexafluoride).

Steel, aluminum, and copper each account for one third of total mass of metal materials used for switchyard construction. This split is parameterized in the model to allow sensitivity analysis if necessary.

Scrap material is generated by the end-of-life disposition of the switchyard. The outputs of this unit process include the mass of metals that are recovered for recycling and the mass of metals that are landfilled. 95 percent of the metal in the switchyard is recovered for recycling and 5 percent is landfilled. The concrete used by the switchyard is not recovered for recycling and is landfilled during the end-of-life disposition of the switchyard.

The concrete foundation of the switchyard has an estimated area of 1,000 square meters. At a 0.3 meter thickness and a concrete density of 2,300 kg/m^3, this translates to 690,000 kg of concrete per switchyard.

This unit process is representative of a 200 MW wind farm and is not scalable according to the turbine technologies used by the wind farm.

The properties of the wind farm switchyard are summarized in **Table B-13.** The input and outputs of this unit process are shown in **Table B-14**.

Table B-13: Switchyard Characteristics

Property	Value	Source
Transformer Mass	105,000 kg/switchyard	Shafer, 2001
Mineral Oil Mass	28,800 kg/switchyard	Shafer, 2001
Circuit Breaker Mass	14,400 kg/switchyard	Mitsubishi Electric Power Products
Concrete Mass	690,000 kg/switchyard	Calculated

Table B-14: Unit Process Input and Output Flows for Wind Farm Switchyard Construction

Flow Name	Value	Units
Inputs		
Kerosene	2.88E+04	kg
Cold Rolled Steel	3.99E+04	kg
Aluminum	3.99E+04	kg
Copper Sheet	3.99E+04	kg
Concrete	6.90E+05	kg
Outputs		
Transformer	1.00	Piece
Steel Scrap	3.79E+04	kg
Aluminum Scrap	3.79E+04	kg
Copper Scrap	3.79E+04	kg
Solid Waste	5.99E+03	kg

Transformer Construction

The scope of this unit process provides a summary of relevant materials used for the construction of a transformer with a rating of 1,000 to 7,500 kVA. The data are representative of a padmount transformer used for a wind turbine. A linear relationship between transformer construction materials and transformer rating is applied in order to scale material requirements to wind turbine rating (0.75 to 5 MW).

Wind farms require a transformer at the base of each wind turbine, known as a padmount transformer. Padmount transformers step up the voltage of the electricity generated by wind turbines and allow the distribution of the electricity to the central switchyard of the wind farm.

Steel accounts for 50 percent, aluminum accounts for 25 percent, and copper accounts for 25 percent of the total mass of transformer metals. The total mass of metals used for the construction of a transformer used by a 0.75 MW wind turbine is 4,580 kg; the mass of a transformer used by a 2.5 MW turbine is 8,550 kg; the mass of a transformer used by a 5 MW wind turbine is 19,000 kg (Shafer, 2001). The relationship between wind turbine rating (MW) and transformer mass (kg) is described by the following linear equation:

$$\textit{Transformer mass (kg)} = 3{,}450 \times \textit{Turbine rating (MW)} + 1230$$

In addition to metals used for the construction of padmount transformers, mineral oil is also necessary. The total mass of mineral oil used by a 0.75 MW wind turbine is 1,730 kg; the total mass of mineral oil used by a 2.5 MW wind turbine is 2,730 kg; the mass of mineral oil used by a 5 MW wind turbine is 5,680 kg (Shafer, 2001). This analysis uses kerosene as a surrogate for mineral oil. The relationship between wind turbine rating (MW) and the mass (kg) of mineral oil used by a transformer is described by the following linear equation:

$$\textit{Mineral oil mass (kg)} = 948 \times \textit{Turbine rating (MW)} + 774$$

Scrap material is generated by the end-of-life disposition of the transformer. The outputs of this unit process include the mass of metals that are recovered for recycling and the mass of metals that are landfilled. Ninety percent of the metal in the transformer is recovered for recycling and 10 percent is landfilled (Nalukowe et. al, 2006).

The properties of the wind farm transformers are summarized in **Table B-15**.The input and outputs of this unit process are shown in **Table B-16**.

Table B-15: Transformer Characteristics

Component	Value	Source
Transformer Mass Scaling Equation: Metals	Transformer mass (kg) = 3,450 x Turbine Rating (MW) + 1230	Shafer, 2001
Transformer Mass Scaling Equation: Mineral Oil	Mineral Oil Mass (kg) = 948 x Turbine Rating (MW) + 774	Shafer, 2001
Steel Percent Mass	50%	Estimate
Aluminum Percent Mass	25%	Estimate
Copper Percent Mass	25%	Estimate

Table B-16: Unit Process Flows for Transformer Construction

Flow Name	Onshore Conventional	Onshore Advanced	Offshore	Units
Inputs				
Kerosene	2,196	6,462	4,187	kg
Steel Plate From Blast Furnace With An 85% Recovery Rate	3,203	10,965	6,825	kg
Aluminum	1,601	5,483	3,413	kg
Copper Sheet	1,601	5,483	3,413	kg
Outputs				
Transformer	1.00	1.00	1.00	Piece
Steel Scrap	3,042	10,417	6484	kg
Aluminum Scrap	1,521	5,208	6242	kg
Copper Scrap	1,521	5,208	3242	kg
Solid Waste	320	1,097	683	kg

Cable Construction (35 kV)

The mass of materials needed for the construction of 1 meter of 35 kV cable, in support of 1.5-6 MW wind turbines, was estimated based on available manufacturing data for the fabrication of 20.04 mm wires, including two layers of insulation, for a total diameter of 42.20 mm (Energex, 2010). These weights are representative of 2010 technologies, and are applicable to both conventional and advanced wind turbine designs. These values are summarized in **Table B-16**.

The material profile for cable manufacture is approximately 62 percent copper-by-mass, while the remaining 38 percent is aluminum (Energex, 2010). Although the cables considered for use in this unit process include insulation, the mass of insulation on a per meter basis is a small share of the total cable mass. Accurate data representing the mass of insulation included in the cable were not available, and therefore are considered a data limitation within this unit process.

No waste metal is generated during the cable fabrication process. NETL recommends the use of zero percent waste for this parameter. However, this value is included as an adjustable parameter, and can be altered by the analyst as warranted. During the decommissioning process, 95 percent of the total copper and aluminum mass is landfilled, with the remaining 5 percent recovered for recycling, consistent with manufacture and decommissioning for other horizontal wind turbine components.

The properties of the wind farm cables are summarized in **Table B-17**.The input and outputs of this unit process are shown in **Table B-18**.

Table B-17: Characteristics of 35 kV Cables

Component	Value	Source
Conductor Diameter	20.04 mm	Energex, 2010
Total Diameter (Conductor + Insulation)	42.20 mm	Energex, 2010
Copper: mass per km	4,025 kg	Energex, 2010
Aluminum: mass per km	2,425 kg	Energex, 2010

Table B-18: Unit Process Flows for Cable Construction

Flow Name	Value	Units
Inputs		
Copper Wire	4.03	kg
Aluminum	2.43	kg
Outputs		
Horizontal Turbine, 35 kV Cables	1.0	m
Copper Scrap	3.82	kg
Aluminum Scrap	2.30	kg
Solid Waste	0.32	kg

Trunkline Construction

Wind farms require a trunkline that connects the switchyard of the wind farm to the main electricity transmission grid. This unit process accounts for the materials required for the construction of a trunkline.

Most wind farms are located in remote areas that are farther from the main electricity transmission grid than other types of power plants. The length of the trunkline is 100 miles. This distance has been parameterized in the model and can thus be evaluated through sensitivity analysis if necessary.

The construction materials required for the construction of a trunkline tower are estimated from a case study on the restoration of a damaged power line system in Nebraska (Brune, 2008). A single tower requires 7,940 kg of steel, 14,100 kg of concrete. Aluminum-clad, steel-reinforced cables are required for the transmission lines. The mass is aluminum in a transmission cable is 5,360 kg/km; the mass of steel in a transmission cable is 885 kg/km (Phelps Dodge, 2005). These material requirements are scaled to the basis of the entire trunkline system by using a distance of 274 meters (900 feet) between towers.

Scrap material is generated by the end-of-life disposition of the trunkline. The outputs of this unit process include the mass of metals that are recovered for recycling and the mass of metals that are landfilled. 95 percent of the metal in the trunkline is recovered for recycling and 5 percent is landfilled. The concrete used by the trunkline is not recovered for recycling and is landfilled during the end-of-life disposition of the trunkline.

This analysis apportions the construction requirements for the trunkline to 1 MWh of electricity generation. The fraction of construction requirements per 1 MWh of electricity generation is the reciprocal of the lifetime electricity produced by the wind farm. Lifetime electricity is a function of wind farm capacity factor (which has a default value of 30 percent), and wind farm life span (which has a default value of 30 years).

The properties of the wind farm cables are summarized in **Table B-19**.The input and outputs of this unit process are shown in **Table B-20**.

Table B-19: Trunkline Characteristics

Property	Value	Source
Tower Construction: Steel Requirements	7,940 kg/tower	Brune, 2008
Tower Construction: Concrete Requirements	14,100 kg/tower	Brune, 2008
Cable Construction: Steel Requirements	885 kg/km	Phelps Dodge, 2005
Cable Construction: Aluminum Requirements	5,360 kg/km	Phelps Dodge, 2005

Table B-20: Unit Process Flows for Trunkline Construction

Flow Name	Value	Units
Inputs		
Cold Rolled Steel	3.04E-01	kg
Aluminum	5.47E-02	kg
Concrete	5.25E-01	kg
Outputs		
Trunkline Construction	1.00	Piece/MWh
Steel Scrap	2.89E-01	kg
Aluminum Scrap	5.20E-02	kg
Solid Waste	5.43E-01	kg

B.3 Wind Farm Operation

This unit process calculates the number of turbines, parasitic electricity, and maintenance operations for a wind farm. The reference flow of this unit process is 1 MWh of electricity production. The inputs to this unit process include the electricity demands of parasitic power (which is the electricity necessary to keep turbines on standby and to support wind farm control operations), diesel used as fuel for maintenance equipment, lubrication oil used by turbines, and the share of the wind farm construction requirements apportioned to 1 MWh of production (the reference flow). The outputs of this unit process are air emissions due to the combustion of diesel and waste lubricating oil.

This unit process accounts for the maintenance requirements and parasitic power of a wind farm. Adjustable parameters are used to allow scaling of the wind farm according to a chosen turbine size. Specifically, the total wind farm capacity (which has a default value of 200 MW) is divided by the power rating of the turbines (which can range from 1.5 to 6 MW) to determine the number of turbines required for the wind farm.

Based on personal communication with an engineer for a wind farm in the Altamont Pass (California), the parasitic load of a wind farm is 1.6 kW for a 2 MW turbine. A linear relationship between turbine size and parasitic load is modeled, which translates to 0.0008 kW per MW of installed capacity.

A 1.6 MW turbine has 250 liters of gearbox oil (Schaeffer Manufacturing Company, 2010); the volume of gearbox oil is assumed to vary linearly with turbine rating. At a specific gravity of 0.88, the mass of gearbox oil is 144 kg/MW. This analysis assumes that the gearbox oil for a wind turbine is changed two times per year.

All maintenance vehicles are fueled by diesel and have a fuel economy of 8 miles per gallon. The total distance of onsite maintenance vehicles is modeled as 1,000 miles per year; no information is available for this activity, which is a data limitation. The combustion of diesel produces air emissions, which are calculated in this analysis by applying emission factors to total diesel consumption (DOE, 2006). The dust from the use of maintenance vehicles on unpaved roads is categorized as particulate matter and is estimated from EPA AP42 emission factors (EPA, 2006).

The portion of wind farm construction that is apportion to 1 MWh of electricity generation is the reciprocal of the total MWh produced by the wind farm in its lifetime, which is a function of total installed turbine capacity (MW), capacity factor (30 percent), and a 30 year life.

The characteristics of the wind farm operations are summarized in **Table B-21**.The input and outputs of this unit process are shown in **Table B-22**.

Table B-21: Requirements for Wind Farm Operations

Variable	Value	Source
Parasitic Electricity	0.0008 kWh/MW	Altamont Pass 2010
Gearbox Oil	144 kg/MW	Schaeffer Manufacturing Company, 2010
Maintenance Vehicle	Fuel economy = 8 miles/gal Annual travel = 1,000 miles	NETL Estimate

Table B-22: Unit Process Flows for Wind Farm Operation

Flow Name	Onshore Conventional	Onshore Advanced	Offshore	Units
Inputs				
Power	1.87E-03	1.87E-03	1.25E-03	MWh
Diesel	7.59E-04	3.24E-04	2.5E-04	kg
Lubrication Oil	7.30E-02	1.82E-02	2.34E-02	kg
Outputs				
Electricity (Electric Power)	1.00	1.00	1.00	MWh
CO_2	2.39E-03	2.39E-03	7.85E-04	kg
CH_4	3.42E-07	3.42E-07	1.13E-07	kg
N_2O	6.18E-08	6.18E-08	2.03E-08	kg
NO_X	1.08E-06	1.08E-06	3.55E-07	kg
SO_2	2.27E-08	2.27E-08	7.48E-09	kg
CO	1.33E-05	1.33E-05	4.38E-06	kg
VOC	5.04E-07	5.04E-07	1.66E-07	kg
Dust	2.53E-03	2.53E-03	8.33E-04	kg
Waste Oil	7.30E-02	1.82E-02	2.34E-02	kg

B.4 Offshore Wind Farm Processes

Offshore wind farms require special foundations, the use of marine vessels for installation and maintenance, and submarine cables that connect the offshore wind farm to an onshore grid connection.

Offshore Wind Project Construction

This unit process accounts for the relevant input and output flows associated with the construction of an offshore wind project. It is representative of the Cape Wind project located in Nantucket Sound. Cape Wind will have 130 3.6-MW turbines, for a total capacity 468 MW. Key inputs to this unit process include the construction materials and the use of marine vessels. This unit process does not account for the manufacture of wind turbine equipment; it accounts only for the construction and installation of the turbine foundation (monopile), sour protection, corrosion-resistant surface coatings, and the offshore trunkline.

Carbon steel is used for the construction of offshore monopiles. A single monopile is 5.3 meters in diameter, is constructed of steel sheet with a 0.15 meter thickness, and has a total length of 41.2 meters. This length includes 26 meters under the ocean floor, a 12.2 meter water depth, and 3.0 meters above the water (Kurian, 2010). The cross-sectional area of the monopile is 1.23 m^2 (based on the above diameter and thickness). Factoring the cross sectional area by the height and density of steel (8,000 kg/m^3) results in a total mass of 406,000 kg per monopile.

Gravel is used for scour protection, which is necessary to prevent the erosion of the monopile base by ocean currents. No data are available for the exact composition of scour mats. The mass of gravel used for scour protection is 10 percent of the mass of the monopile. This translates to 40,600 kg of gravel used for scour protection per monopile.

The monopile is constructed of carbon steel that should be protected from corrosion by ocean conditions. 50 percent of the surface of a monopile is coated with paint.

Upon decommissioning, 95 percent of the steel in the monopile is recovered for recycling; the remaining 5 percent is modeled as solid waste.

Data for the production and delivery of steel, gravel, and surface coatings used for the construction of the monopiles are accounted for by upstream processes. Marine vessels are used for transporting crew and equipment; they also provide a stable platform and power source at the offshore construction sites. The environmental burdens for the production, delivery, and combustion of diesel consumed by marine vessels are accounted for by upstream processes that are outside the scope of this unit process. The tracked output of this unit process is 1 MWh of electricity produced by the wind project.

The input and outputs of this unit process are shown in **Table B-23**.

Table B-23: Unit Process Flows for Offshore Wind Projection Construction

Flow Name	Value	Units
Inputs		
Steel	1.65E+00	kg
Gravel	1.65E-01	kg
Coating	8.25E-03	kg
Trunkline	6.29E-07	km
Marine Vessel, Travel	3.43E-02	km
Marine Vessel, Idling	6.85E-03	hr.
Outputs		
Electricity from Offshore Wind Power	1	MWh
Steel Scrap	1.57	kg
Solid Waste	8.25E-02	kg

Submarine Cable Construction

This unit process accounts for the relevant inputs and outputs associated with the construction of a submarine cable that connects an offshore wind project to an onshore trunkline. It is representative of the Cape Wind project located in Nantucket Sound (MMS, 2009). The calculations of this unit process are based on the reference flow of 1 km of 115 kV copper cable.

The mass per unit length of copper cable for this application is 25 kg/m (CWA, 2004), which is equivalent to 25,000 kg/km.

The production and delivery of copper used for the construction of submarine cable is accounted for by upstream processes. The tracked output of this unit process is the 1 km of cable. (The scaling of this unit process to the actual distance from the offshore wind farm to the onshore trunkline connection should be accounted for within the LCA model.)

The input and outputs of this unit process are shown in **Table B-24**.

Table B-24: Unit Process Flows for Submarine Cable Construction

Flow Name	Value	Units
Inputs		
Copper	25,000	kg
Outputs		
Cable	1	km

Marine Vessel Travel

This unit process accounts for the diesel consumption and carbon dioxide emissions associated with the travel of a marine vessel (tugboat or cargo ship) during the installation, maintenance, and decommissioning of an offshore wind project. The key input to this unit process is diesel fuel that is combusted in the engine of the marine vessel. The calculations for this unit process are based on the reference flow of 1 km of vessel travel.

The engine rating for a marine vessel used for short range transport of personnel and construction materials ranges from 3,000 to 6,000 horsepower, with a midpoint of 4,500 horsepower (EPA, 2000). Using a conversion factor of 1,341 horsepower per megawatt, these engine ratings translate to a range of 2.24 to 4.47 MW with a midpoint of 2.24 MW. This unit process uses the midpoint of these engine ratings as the expected engine rating, and the low and high engine ratings are used to set boundaries for uncertainty analysis.

The Environmental Protection Agency (EPA) developed correlations between the engine load of marine vessels, diesel fuel consumption, and CO_2 emissions (EPA, 2000). The diesel consumption rate and CO_2 emission rate, in grams/kW-hr., is described by the following equations:

Fuel consumption (g/kW-hr.) = 14.12/(fractional load) + 205.717 **(Equation B-1)**

CO_2 emissions (g/kW-hr.) = 44.1/(fractional load)+ 648.6 **(Equation B-2)**

For this unit process, the default value for fraction load is 0.30. In other words, the travel of the marine vessel for offshore construction and maintenance requires the engine to run at 30 percent of its maximum capacity (EPA, 2000).

The speed of a marine vessel used for the short range transport of personnel, equipment, and construction materials is modeled at 10 knots (EPA, 2000). One knot is equal to 1.85 km/hr., thus the above speed of 10 knots is equal to 18.5 km/hr. This speed is necessary to translate the above fuel and CO_2 emissions to the basis of one km of travel.

The production and delivery of diesel is accounted for by processes that are upstream of this unit process. The tracked output of this unit process is one kilometer of travel by the marine vessel used during the construction, maintenance, and decommissioning of the offshore wind project.

The input and outputs of this unit process are shown in **Table B-25**.

Table B-25: Unit Process Flows for Marine Vessel Travel

Flow Name	Value	Units
Inputs		
Diesel	44.6	kg
Outputs		
Vessel Travel	1	km
CO_2	140	kg

Marine Vessel Idling

This unit process accounts for the diesel consumption and CO_2 emissions associated with the idling of a marine vessel (tugboat or cargo ship) during the installation, maintenance, and decommissioning of an offshore wind project. The key input to this unit process is diesel fuel that is combusted in the engine of the marine vessel. The calculations presented for this unit process are based on the reference flow of one hour of vessel idling.

The engine rating for a marine vessel used for short range transport of personnel and construction materials ranges from 3,000 to 6,000 horsepower with a midpoint of 4,500 horsepower (EPA 2000). Using a conversion factor of 1,341 horsepower per megawatt, these engine ratings translate to a range of 2.24 to 4.47 MW with a midpoint of 2.24 MW. This unit process uses the midpoint of these engine ratings as the expected engine rating, and the low and high engine ratings are used to set boundaries for uncertainty analysis.

The EPA (2000) developed correlations between the engine load of marine vessels, diesel fuel consumption, and CO_2 emissions. The diesel consumption rate and CO_2 emission rate, in grams/kW-hr., is described by the following equations:

$$\textit{Fuel consumption (g/kW-hr.)} = 14.12/(\textit{fractional load}) + 205.717 \qquad \textbf{(Equation B-3)}$$

$$CO_2 \textit{ emissions (g/kW-hr.)} = 44.1/(\textit{fractional load}) + 648.6 \qquad \textbf{(Equation B-4)}$$

For this unit process, the default value for fraction load is 0.20. In other words, the idling and maneuvering of the marine vessel for offshore construction and maintenance requires the engine to run at 20 percent of its maximum capacity (EPA, 2000).

The production and delivery of diesel is accounted for by processes that are upstream of this unit process. The tracked output of this unit process is one hour of idling by the marine vessel used during the construction, maintenance, and decommissioning of the offshore wind project.

The input and outputs of this unit process are shown in **Table B-26**.

Table B-26: Unit Process Flows for Marine Vessel Idling

Flow Name	Value	Units
Inputs		
Diesel	927	kg
Outputs		
Vessel Idling	1	hr.
CO_2	2.92E+03	kg

B.5 Maintenance and Replacement

The maintenance of a wind farm includes the on-site transportation of personnel, requiring the operation of a light-duty, diesel truck driven about 1,000 miles per year. Construction and operation of the maintenance truck, routine oil replacement (twice a year), and lubrication of ancillary materials are included in this analysis. Each turbine station has a working and turning area that provides easy access for maintenance vehicles.

The replacement of broken turbine components is modeled in conjunction with original equipment production, as shown in **Table B-27**.

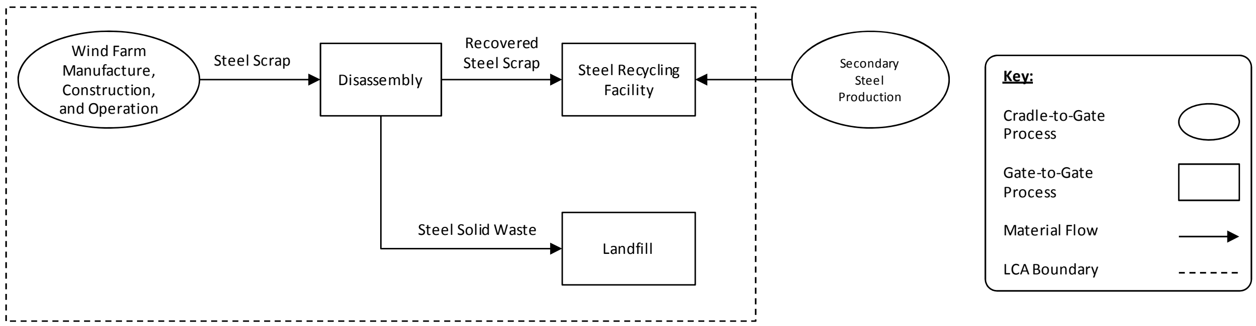
Table B-27: Wind Farm Component Replacement Rates

Component	Part Life (Years)			Pieces per Wind Farm Life (pieces/30 Years)		
	Low	Expected Value	High	Low	Expected Value	High
Rotor	18	20	22	1.4	1.5	1.7
Nacelle (Bearing, Shafts, Motors, Frames, etc.)	12	16	20	1.5	1.9	2.5
Generator	15	17.5	20	1.5	1.7	2.0
Gearbox	10	15	20	1.5	2.0	3.0

B.6 Waste Management

This analysis models the production of wind turbines from virgin materials. The manufacture of wind turbines produces scrap materials that are recovered for recycling. The end-of-life management of turbines also generates recyclable materials, which are recovered at a 90 percent rate. All recyclable materials that are recovered during turbine manufacture and end-of-life management are assumed to displace similar material streams that are outside the boundaries of this analysis. System expansion is used to model the interaction between the recycled materials of wind power and the material streams of other supply chains. The boundaries of the system expansion used for modeling the end-of-life management of wind turbines are shown in **Table B-10**.

Figure B-2: Example of System Expansion for Material Recycling



All non-recyclable materials, such as concrete or metal/fiber composites, are landfilled.

Scrap is produced during the manufacture of all wind turbine components. One percent of all materials that enter the turbine manufacturing process end up as scrap. Further, 90 percent of metallic scrap is recovered for recycling. Non-metallic, composite scrap is not recyclable and is thus landfilled. The LCA model includes parameters that allow the adjustment of these manufacturing scrap rates.

This analysis assumes that scrap is also produced during the end-of-life disposition of wind turbine components. It is assumed that 90 percent of metallic scrap is recovered for recycling. Non-metallic, composite scrap is not recyclable and is thus landfilled.

Due to the high value of some wind turbine components, remanufacture or refurbishment is more likely than recycling of materials. However, lack of data prevented the modeling of refurbishment scenarios. The lower environmental benefits of recycling relative to reuse mean manufacturing impacts are likely overestimated.

Appendix B: References

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Appendix C: Detailed Results

List of Tables

Table C-1: Full Life Cycle Metrics for Onshore Conventional Wind Power

Category (Units)	Material or Energy Flow	ECF																	
		Switchyard	Trunkline				Recycling			Domestic Turbine MFG					Foreign Turbine MFG				
			Electricity	Aluminum Sheet	Cold Rolled Steel	Concrete	Aluminum	Copper	Steel	Rotor	Tower	Transport	Nacelle	Transformer	Rotor	Tower	Transport	Nacelle	Transformer
GHG (kg/MWh)	CO_2	6.00E-02	6.13E-02	3.89E-01	3.80E-01	4.90E-02	-1.59E-01	-6.37E-01	-1.62E+00	7.02E-01	7.24E-01	2.80E-07	2.91E+00	1.41E-01	8.58E-01	8.85E-01	8.64E+00	3.55E+00	1.72E-01
	N_2O	1.27E-06	9.69E-07	8.43E-06	2.47E-06	0.00E+00	-2.46E-07	-2.79E-05	-1.67E-06	1.52E-04	5.27E-06	7.40E-12	8.89E-05	2.34E-06	1.86E-04	6.44E-06	2.13E-04	1.09E-04	2.86E-06
	CH_4	9.82E-05	1.85E-04	6.17E-04	4.46E-04	0.00E+00	-6.72E-04	-8.74E-04	-6.84E-04	2.19E-03	9.60E-04	8.17E-10	7.51E-03	2.78E-04	2.68E-03	1.17E-03	9.79E-03	9.18E-03	3.40E-04
	SF_6	1.72E-09	1.29E-08	4.93E-11	2.76E-12	0.00E+00	0.00E+00	-3.17E-11	0.00E+00	3.71E-08	1.26E-08	8.98E-19	4.30E-07	2.33E-12	4.54E-08	1.54E-08	2.71E-12	5.26E-07	2.85E-12
	CO_2e (IPCC 2007 100-yr GWP)	6.29E-02	6.65E-02	4.07E-01	3.92E-01	4.90E-02	-1.76E-01	-6.67E-01	-1.64E+00	8.03E-01	7.50E-01	3.03E-07	3.13E+00	1.49E-01	9.81E-01	9.17E-01	8.95E+00	3.83E+00	1.82E-01
Other Air (kg/MWh)	Pb	3.25E-07	4.06E-10	5.16E-08	6.86E-07	0.00E+00	-3.49E-08	-1.87E-05	-9.70E-09	1.62E-07	1.20E-06	7.01E-14	4.59E-07	1.20E-06	1.97E-07	1.47E-06	3.25E-08	5.61E-07	1.46E-06
	Hg	5.02E-10	1.13E-09	3.62E-09	8.77E-10	0.00E+00	-1.10E-09	-4.25E-09	-5.21E-09	9.17E-09	2.64E-09	3.92E-15	5.23E-08	1.50E-09	1.12E-08	3.23E-09	2.70E-09	6.40E-08	1.83E-09
	NH_3	2.39E-07	5.79E-08	1.72E-06	1.24E-06	0.00E+00	-9.15E-08	-4.52E-06	-9.46E-07	1.36E-06	2.22E-06	2.22E-12	4.15E-06	7.14E-07	1.66E-06	2.71E-06	3.14E-04	5.08E-06	8.73E-07
	CO	3.34E-04	1.19E-05	3.59E-03	3.61E-03	6.32E-05	-1.22E-04	-6.03E-04	-1.93E-02	1.11E-03	6.32E-03	6.71E-10	3.04E-03	7.80E-04	1.36E-03	7.73E-03	2.35E-02	3.71E-03	9.54E-04
	NO_X	1.07E-04	9.39E-05	5.32E-04	7.20E-04	1.50E-04	-2.48E-04	-1.45E-03	-1.79E-03	1.23E-03	1.35E-03	2.30E-10	4.47E-03	3.38E-04	1.50E-03	1.65E-03	2.11E-02	5.47E-03	4.13E-04
	SO_2	1.97E-04	1.96E-04	1.46E-03	5.26E-04	1.14E-04	-1.31E-03	-2.30E-03	-3.12E-03	2.45E-03	1.11E-03	4.21E-10	8.54E-03	6.18E-04	3.00E-03	1.36E-03	3.79E-03	1.04E-02	7.55E-04
	VOC	1.46E-05	1.66E-05	7.12E-05	5.42E-05	0.00E+00	-5.14E-05	-1.86E-04	-6.79E-04	9.19E-04	1.11E-04	3.10E-10	9.75E-04	6.45E-05	1.12E-03	1.36E-04	4.04E-03	1.19E-03	7.88E-05
	PM	9.07E-05	2.51E-06	7.07E-04	2.32E-04	1.46E-04	-3.17E-05	-9.40E-04	-2.37E-04	9.79E-04	4.08E-04	2.04E-11	1.02E-03	1.97E-04	1.20E-03	4.99E-04	3.31E-05	1.25E-03	2.41E-04
Solid Waste (kg/MWh)	Heavy metals to industrial soil	5.39E-05	4.04E-04	1.74E-06	6.52E-07	0.00E+00	0.00E+00	-3.26E-06	0.00E+00	1.16E-03	3.96E-04	2.30E-12	1.35E-02	4.55E-07	1.42E-03	4.84E-04	2.31E-05	1.65E-02	5.57E-07
	Heavy metals to agricultural soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (L/MWh)	Withdrawal	6.53E-01	2.13E+00	2.23E+00	8.74E-01	2.10E-02	0.00E+00	-1.12E+01	0.00E+00	9.23E+00	3.61E+00	8.78E-07	7.55E+01	8.21E-01	1.13E+01	4.41E+00	5.33E+00	9.22E+01	1.00E+00
	Discharge	5.50E-01	1.97E+00	1.59E+00	8.03E-01	0.00E+00	0.00E+00	-9.61E+00	0.00E+00	7.77E+00	3.33E+00	1.41E-10	6.81E+01	6.84E-01	9.50E+00	4.06E+00	1.30E+00	8.33E+01	8.37E-01
	Consumption	1.02E-01	1.64E-01	6.35E-01	7.13E-02	2.10E-02	0.00E+00	-1.59E+00	0.00E+00	1.46E+00	2.85E-01	8.78E-07	7.36E+00	1.37E-01	1.78E+00	3.49E-01	4.03E+00	9.00E+00	1.67E-01
Water Quality (kg/MWh)	Aluminum	1.16E-09	8.70E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.53E-08	8.51E-09	0.00E+00	2.91E-07	0.00E+00	3.09E-08	1.04E-08	0.00E+00	3.55E-07	0.00E+00
	Arsenic (+V)	4.14E-08	9.44E-08	1.34E-08	3.06E-09	0.00E+00	-4.31E-08	-1.70E-08	0.00E+00	3.01E-07	9.76E-08	2.17E-12	3.16E-06	1.97E-07	3.68E-07	1.19E-07	3.00E-05	3.87E-06	2.41E-07
	Copper (+II)	1.37E-07	1.12E-07	2.44E-08	1.17E-08	0.00E+00	-3.36E-08	-4.81E-06	0.00E+00	4.31E-07	1.30E-07	3.18E-12	3.84E-06	5.74E-07	5.26E-07	1.59E-07	4.39E-05	4.69E-06	7.02E-07
	Iron	1.02E-05	1.88E-06	8.70E-05	1.70E-05	0.00E+00	-1.26E-05	-7.70E-05	-1.91E-04	1.08E-04	3.16E-05	1.66E-10	2.00E-04	2.47E-05	1.32E-04	3.87E-05	2.24E-03	2.44E-04	3.01E-05
	Lead (+II)	1.65E-07	4.60E-09	4.40E-08	6.32E-09	0.00E+00	-6.39E-08	-4.10E-06	-1.08E-04	8.78E-08	1.56E-08	7.30E-12	2.12E-07	8.98E-07	1.07E-07	1.90E-08	1.01E-04	2.59E-07	1.10E-06
	Manganese (+II)	3.89E-08	1.45E-07	1.95E-07	1.58E-07	0.00E+00	0.00E+00	-1.90E-07	0.00E+00	5.85E-07	4.18E-07	1.71E-14	5.15E-06	3.15E-08	7.15E-07	5.11E-07	1.34E-07	6.30E-06	3.85E-08
	Nickel (+II)	1.32E-06	4.31E-06	1.50E-08	1.78E-08	0.00E+00	-3.44E-08	-5.80E-07	-1.18E-06	1.24E-05	4.24E-06	5.77E-11	1.44E-04	5.10E-06	1.52E-05	5.19E-06	7.99E-04	1.76E-04	6.23E-06
	Strontium	4.23E-08	3.13E-09	2.81E-07	7.54E-07	0.00E+00	-1.05E-05	-6.31E-07	0.00E+00	5.83E-06	1.32E-06	1.02E-13	2.73E-06	1.51E-06	7.13E-06	1.62E-06	7.36E-07	3.34E-06	1.84E-06
	Zinc (+II)	1.62E-06	1.20E-06	1.88E-08	1.72E-08	0.00E+00	-1.16E-07	-1.15E-05	5.16E-05	3.56E-06	1.20E-06	1.00E-10	4.00E-05	9.50E-06	4.35E-06	1.47E-06	1.39E-03	4.89E-05	1.16E-05
	Ammonium/ammonia	1.56E-06	1.01E-05	1.32E-06	7.79E-07	0.00E+00	-5.78E-09	-6.80E-06	9.78E-03	3.10E-05	1.12E-05	1.62E-12	3.49E-04	5.29E-07	3.79E-05	1.37E-05	2.68E-06	4.26E-04	6.47E-07
	Hydrogen chloride	2.72E-12	7.35E-13	2.57E-11	3.24E-12	0.00E+00	0.00E+00	-2.76E-11	0.00E+00	1.55E-10	6.38E-12	2.15E-17	4.25E-10	3.75E-12	1.89E-10	7.80E-12	2.82E-10	5.19E-10	4.58E-12
	Nitrogen (as total N)	4.05E-09	3.04E-08	0.00E+00	0.00E+00	0.00E+00	-1.44E-08	0.00E+00	-5.53E-04	9.38E-08	2.98E-08	0.00E+00	1.03E-06	7.21E-09	1.15E-07	3.64E-08	0.00E+00	1.26E-06	8.81E-09
	Phosphate	2.33E-08	3.59E-10	8.06E-08	4.07E-07	0.00E+00	0.00E+00	-7.16E-07	5.94E-06	1.04E-06	7.12E-07	3.14E-14	9.47E-07	8.31E-08	1.27E-06	8.71E-07	3.33E-08	1.16E-06	1.02E-07
	Phosphorus	9.32E-07	6.78E-08	1.35E-08	5.14E-09	0.00E+00	0.00E+00	-2.68E-08	-1.11E-05	2.04E-07	7.53E-08	7.32E-11	2.28E-06	6.36E-06	2.49E-07	9.20E-08	1.00E-03	2.78E-06	7.77E-06
Resource Energy (MJ/MWh)	Crude oil	2.70E-01	2.20E-02	1.40E+00	4.29E-01	0.00E+00	-9.21E-02	-4.70E+00	-2.11E+00	6.60E-01	7.71E-01	7.05E-06	1.90E+00	1.01E+00	8.07E-01	9.42E-01	9.16E+01	2.32E+00	1.23E+00
	Hard coal	1.73E-01	1.94E-01	1.06E+00	3.90E+00	0.00E+00	-5.99E-01	-1.02E+00	-1.49E+01	2.79E+00	7.00E+00	4.13E-07	1.12E+01	9.32E-01	3.41E+00	8.56E+00	1.34E+00	1.37E+01	1.14E+00
	Lignite	4.81E-02	1.02E-04	5.18E-01	9.76E-02	0.00E+00	0.00E+00	-5.11E-01	0.00E+00	1.21E-01	1.71E-01	2.23E-08	2.44E-01	4.78E-02	1.48E-01	2.09E-01	4.92E-02	2.99E-01	5.84E-02
	Natural gas	1.79E-01	2.75E-01	1.26E+00	5.69E-01	0.00E+00	-2.01E+00	-2.05E+00	-1.73E+00	4.69E+00	1.26E+00	1.12E-06	1.22E+01	4.41E-01	5.73E+00	1.55E+00	1.03E+01	1.49E+01	5.38E-01
	Uranium	1.07E-01	3.74E-04	1.17E+00	1.14E-01	0.00E+00	0.00E+00	-1.15E+00	0.00E+00	5.93E-01	2.00E-01	1.02E-07	9.79E-01	1.13E-01	7.25E-01	2.44E-01	6.55E-01	1.20E+00	1.38E-01
	Total resource energy	7.77E-01	4.91E-01	5.40E+00	5.11E+00	0.00E+00	-2.70E+00	-9.43E+00	-1.88E+01	8.86E+00	9.41E+00	8.70E-06	2.66E+01	2.54E+00	1.08E+01	1.15E+01	1.04E+02	3.25E+01	3.11E+00
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table C-1: Full Life Cycle Metrics for Onshore Conventional Wind Power (continued)

Category (Units)	Material or Energy Flow	ECF											PT	Total
		Wind Farm Operation					Wind Farm Construction					Landfill Waste	T&D	
		Electricity	Diesel Upstream	Lubricating Oil	Wind Farm	Cable	Concrete	Gravel Road	Steel	Diesel Upstream	Wind Farm			
GHG (kg/MWh)	CO_2	3.81E-04	5.25E-04	1.10E-02	2.57E-03	1.29E-01	6.33E-03	8.10E-02	3.17E-03	2.13E-02	1.04E-01	1.06E-02	0.00E+00	1.75E+01
	N_2O	6.02E-09	1.03E-08	5.79E-05	6.65E-08	3.89E-06	5.61E-08	2.44E-05	3.42E-09	4.18E-07	2.69E-06	8.74E-08	0.00E+00	8.38E-04
	CH_4	1.15E-06	3.35E-06	3.03E-03	3.68E-07	1.95E-04	1.07E-05	2.34E-04	1.36E-06	1.36E-04	1.49E-05	3.11E-04	0.00E+00	3.72E-02
	SF_6	8.02E-11	9.86E-16	1.08E-13	0.00E+00	1.26E-11	7.36E-10	2.96E-14	1.48E-16	3.99E-14	0.00E+00	2.63E-15	1.43E-04	1.44E-04
	CO_2e (IPCC 2007 100-yr GWP)	4.13E-04	6.12E-04	1.04E-01	2.60E-03	1.35E-01	6.63E-03	9.41E-02	3.21E-03	2.48E-02	1.05E-01	1.84E-02	3.27E+00	2.20E+01
Other Air (kg/MWh)	Pb	2.52E-12	1.18E-11	3.69E-10	0.00E+00	1.46E-06	3.37E-11	3.56E-10	2.08E-11	4.79E-10	0.00E+00	2.90E-10	0.00E+00	-9.51E-06
	Hg	7.05E-12	9.81E-13	5.36E-11	0.00E+00	1.07E-09	6.53E-11	2.95E-11	1.03E-11	3.98E-11	0.00E+00	2.93E-11	0.00E+00	1.45E-07
	NH_3	3.60E-10	6.70E-09	4.46E-04	0.00E+00	7.02E-07	3.52E-09	3.88E-05	1.89E-09	2.71E-07	0.00E+00	1.66E-08	0.00E+00	8.16E-04
	CO	7.38E-08	5.00E-07	9.31E-03	1.43E-05	7.86E-04	4.42E-06	2.84E-03	3.78E-05	2.03E-05	5.81E-04	5.42E-05	0.00E+00	4.97E-02
	NO_X	5.83E-07	6.86E-07	2.57E-04	1.16E-06	2.21E-04	1.39E-05	8.27E-03	3.50E-06	2.78E-05	0.00E+00	6.29E-05	0.00E+00	4.45E-02
	SO_2	1.22E-06	1.38E-06	7.71E-05	2.45E-08	4.78E-04	1.78E-05	5.08E-05	6.11E-06	5.57E-05	9.91E-07	2.77E-05	0.00E+00	2.85E-02
	VOC	1.03E-07	1.47E-06	5.34E-04	5.42E-07	2.90E-05	9.66E-07	2.41E-04	1.33E-06	5.95E-05	0.00E+00	1.48E-05	0.00E+00	8.76E-03
	PM	1.56E-08	1.20E-08	5.86E-04	2.73E-03	2.18E-04	8.49E-06	1.77E-02	4.66E-07	4.88E-07	0.00E+00	1.74E-04	0.00E+00	2.72E-02
Solid Waste (kg/MWh)	Heavy metals to industrial soil	2.51E-06	8.41E-09	1.04E-07	0.00E+00	6.10E-07	2.30E-05	2.53E-07	6.30E-11	3.41E-07	0.00E+00	2.28E-07	0.00E+00	3.39E-02
	Heavy metals to agricultural soil	0.00E+00	0.00E+00	4.32E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.32E-08
Water Use (L/MWh)	Withdrawal	1.32E-02	1.94E-03	3.22E-02	0.00E+00	1.32E+00	1.23E-01	5.82E-02	2.22E-05	7.84E-02	0.00E+00	2.33E-01	0.00E+00	2.00E+02
	Discharge	1.22E-02	4.71E-04	3.35E-02	0.00E+00	1.07E+00	1.12E-01	1.42E-02	2.72E-06	1.91E-02	0.00E+00	5.17E-01	0.00E+00	1.76E+02
	Consumption	1.02E-03	1.47E-03	-1.29E-03	0.00E+00	2.54E-01	1.07E-02	4.41E-02	1.94E-05	5.93E-02	0.00E+00	-2.85E-01	0.00E+00	2.41E+01
Water Quality (kg/MWh)	Aluminum	5.40E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.96E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.32E-07
	Arsenic (+V)	5.86E-10	1.09E-08	4.79E-10	0.00E+00	4.08E-09	5.38E-09	3.28E-07	3.40E-13	4.41E-07	0.00E+00	1.79E-10	0.00E+00	3.92E-05
	Copper (+II)	6.98E-10	1.60E-08	1.11E-08	0.00E+00	3.76E-07	6.42E-09	4.80E-07	2.92E-12	6.46E-07	0.00E+00	5.03E-09	0.00E+00	5.19E-05
	Iron	1.17E-08	8.14E-07	1.73E-06	0.00E+00	2.39E-05	1.10E-07	2.45E-05	3.74E-07	3.30E-05	0.00E+00	3.40E-06	0.00E+00	2.97E-03
	Lead (+II)	2.86E-11	3.67E-08	9.39E-08	0.00E+00	3.25E-07	2.69E-10	1.10E-06	2.12E-07	1.49E-06	0.00E+00	2.84E-10	0.00E+00	-5.32E-06
	Manganese (+II)	8.99E-10	4.89E-11	2.36E-09	0.00E+00	5.48E-08	8.25E-09	1.47E-09	1.23E-12	1.98E-09	0.00E+00	3.00E-09	0.00E+00	1.43E-05
	Nickel (+II)	2.68E-08	2.90E-07	9.38E-08	0.00E+00	4.79E-08	2.46E-07	8.73E-06	2.30E-09	1.18E-05	0.00E+00	2.85E-10	0.00E+00	1.19E-03
	Strontium	1.95E-11	2.68E-10	1.04E-08	0.00E+00	1.07E-07	3.08E-10	8.04E-09	2.28E-11	1.08E-08	0.00E+00	4.58E-09	0.00E+00	1.62E-05
	Zinc (+II)	7.45E-09	5.04E-07	4.70E-08	0.00E+00	8.88E-07	6.84E-08	1.52E-05	-1.01E-07	2.04E-05	0.00E+00	1.91E-10	0.00E+00	1.59E-03
	Ammonium/ammonia	6.25E-08	9.73E-10	2.65E-06	0.00E+00	7.96E-07	5.74E-07	2.93E-08	-1.91E-05	3.94E-08	0.00E+00	7.73E-08	0.00E+00	1.06E-02
	Hydrogen chloride	4.57E-15	1.03E-13	3.36E-13	0.00E+00	7.42E-12	4.50E-14	3.08E-12	5.44E-16	4.15E-12	0.00E+00	3.14E-14	0.00E+00	1.61E-09
	Nitrogen (as total N)	1.89E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.74E-09	0.00E+00	1.08E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-5.50E-04
	Phosphate	2.23E-12	1.21E-11	8.58E-06	0.00E+00	7.19E-08	3.56E-11	3.64E-10	-1.16E-08	4.90E-10	0.00E+00	7.25E-09	0.00E+00	2.06E-05
	Phosphorus	4.21E-10	3.65E-07	8.09E-10	0.00E+00	4.87E-09	4.00E-09	1.10E-05	2.18E-08	1.48E-05	0.00E+00	4.85E-08	0.00E+00	1.04E-03
Resource Energy (MJ/MWh)	Crude oil	1.37E-04	3.33E-02	8.42E-02	0.00E+00	6.50E-01	2.21E-03	1.00E+00	4.30E-03	1.35E+00	0.00E+00	8.71E-02	0.00E+00	9.97E+01
	Hard coal	1.20E-03	4.89E-04	1.51E-02	0.00E+00	2.97E-01	1.11E-02	1.47E-02	2.92E-02	1.98E-02	0.00E+00	1.09E-02	0.00E+00	3.93E+01
	Lignite	6.34E-07	1.79E-05	7.47E-03	0.00E+00	1.46E-01	1.76E-05	5.38E-04	2.07E-06	7.25E-04	0.00E+00	3.82E-03	0.00E+00	1.66E+00
	Natural gas	1.71E-03	3.75E-03	6.89E-02	0.00E+00	4.17E-01	1.58E-02	1.13E-01	3.41E-03	1.52E-01	0.00E+00	3.31E-02	0.00E+00	4.90E+01
	Uranium	2.32E-06	2.38E-04	1.38E-02	0.00E+00	3.29E-01	6.09E-05	7.16E-03	6.99E-06	9.64E-03	0.00E+00	5.69E-03	0.00E+00	5.44E+00
	Total resource energy	3.05E-03	3.78E-02	1.90E-01	0.00E+00	1.84E+00	2.92E-02	1.14E+00	3.69E-02	1.53E+00	0.00E+00	1.41E-01	0.00E+00	1.95E+02
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	18.5:1

Table C-2: Full Life Cycle Metrics for Onshore Advanced Wind Power

Category (Units)	Material or Energy Flow	ECF																	
		Switchyard	Trunkline				Recycling			Domestic Turbine MFG					Foreign Turbine MFG				
			Electricity	Aluminum Sheet	Steel Cold Rolled	Concrete	Aluminum	Copper	Steel	Rotor	Tower	Transport	Nacelle	Transformer	Rotor	Tower	Transport	Nacelle	Transformer
GHG (kg/MWh)	CO_2	6.00E-02	6.13E-02	3.89E-01	3.80E-01	4.90E-02	-1.39E-01	-3.66E-01	-2.59E+00	1.21E+00	1.75E+00	2.80E-07	2.43E+00	1.20E-01	1.48E+00	2.13E+00	4.36E+00	2.97E+00	1.46E-01
	N_2O	1.27E-06	9.69E-07	8.43E-06	2.47E-06	0.00E+00	-2.15E-07	-1.60E-05	-2.66E-06	3.06E-04	1.27E-05	7.40E-12	7.45E-05	1.99E-06	3.74E-04	1.55E-05	1.07E-04	9.11E-05	2.43E-06
	CH_4	9.82E-05	1.85E-04	6.17E-04	4.46E-04	0.00E+00	-5.86E-04	-5.03E-04	-1.09E-03	3.99E-03	2.31E-03	8.17E-10	5.83E-03	2.32E-04	4.88E-03	2.83E-03	4.93E-03	7.12E-03	2.83E-04
	SF_6	1.72E-09	1.29E-08	4.93E-11	2.76E-12	0.00E+00	0.00E+00	-1.82E-11	0.00E+00	5.08E-08	3.04E-08	8.98E-19	3.05E-07	1.99E-12	6.21E-08	3.72E-08	1.37E-12	3.73E-07	2.44E-12
	CO_2e (IPCC 2007 100-yr GWP)	6.29E-02	6.65E-02	4.07E-01	3.92E-01	4.90E-02	-1.54E-01	-3.83E-01	-2.61E+00	1.40E+00	1.81E+00	3.03E-07	2.60E+00	1.26E-01	1.71E+00	2.21E+00	4.51E+00	3.18E+00	1.54E-01
Other Air (kg/MWh)	Pb	3.25E-07	4.06E-10	5.16E-08	6.86E-07	0.00E+00	-3.05E-08	-1.08E-05	-1.55E-08	1.98E-07	2.89E-06	7.01E-14	4.54E-07	1.03E-06	2.42E-07	3.53E-06	1.64E-08	5.55E-07	1.25E-06
	Hg	5.02E-10	1.13E-09	3.62E-09	8.77E-10	0.00E+00	-9.59E-10	-2.45E-09	-8.32E-09	1.45E-08	6.37E-09	3.92E-15	5.55E-08	1.28E-09	1.77E-08	7.79E-09	1.36E-09	6.79E-08	1.57E-09
	NH_3	2.39E-07	5.79E-08	1.72E-06	1.24E-06	0.00E+00	-7.98E-08	-2.60E-06	-1.51E-06	2.61E-06	5.34E-06	2.22E-12	4.05E-06	6.00E-07	3.19E-06	6.53E-06	1.58E-04	4.95E-06	7.33E-07
	CO	3.34E-04	1.19E-05	3.59E-03	3.61E-03	6.32E-05	-1.07E-04	-3.47E-04	-3.09E-02	1.52E-03	1.52E-02	6.71E-10	2.73E-03	6.67E-04	1.86E-03	1.86E-02	1.19E-02	3.34E-03	8.15E-04
	NO_X	1.07E-04	9.39E-05	5.32E-04	7.20E-04	1.50E-04	-2.16E-04	-8.32E-04	-2.86E-03	2.25E-03	3.25E-03	2.30E-10	3.71E-03	2.88E-04	2.75E-03	3.98E-03	1.06E-02	4.53E-03	3.52E-04
	SO_2	1.97E-04	1.96E-04	1.46E-03	5.26E-04	1.14E-04	-1.14E-03	-1.32E-03	-4.98E-03	4.49E-03	2.68E-03	4.21E-10	7.41E-03	5.26E-04	5.49E-03	3.28E-03	1.91E-03	9.06E-03	6.43E-04
	VOC	1.46E-05	1.66E-05	7.12E-05	5.42E-05	0.00E+00	-4.48E-05	-1.07E-04	-1.08E-03	1.86E-03	2.68E-04	3.10E-10	7.91E-04	5.24E-05	2.27E-03	3.27E-04	2.04E-03	9.67E-04	6.41E-05
	PM	9.07E-05	2.51E-06	7.07E-04	2.32E-04	1.46E-04	-2.76E-05	-5.40E-04	-3.79E-04	1.75E-03	9.84E-04	2.04E-11	9.16E-04	1.69E-04	2.14E-03	1.20E-03	1.67E-05	1.12E-03	2.06E-04
Solid Waste (kg/MWh)	Heavy metals to industrial soil	5.39E-05	4.04E-04	1.74E-06	6.52E-07	0.00E+00	0.00E+00	-1.88E-06	0.00E+00	1.59E-03	9.54E-04	2.30E-12	9.55E-03	3.73E-07	1.95E-03	1.17E-03	1.17E-05	1.17E-02	4.55E-07
	Heavy metals to agricultural soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (L/MWh)	Withdrawal	6.53E-01	2.13E+00	2.23E+00	8.74E-01	2.10E-02	0.00E+00	-6.44E+00	0.00E+00	1.45E+01	8.70E+00	8.78E-07	5.71E+01	6.99E-01	1.78E+01	1.06E+01	2.68E+00	6.97E+01	8.54E-01
	Discharge	5.50E-01	1.97E+00	1.59E+00	8.03E-01	0.00E+00	0.00E+00	-5.53E+00	0.00E+00	1.21E+01	8.02E+00	1.41E-10	5.00E+01	5.85E-01	1.48E+01	9.80E+00	6.53E-01	6.11E+01	7.15E-01
	Consumption	1.02E-01	1.64E-01	6.35E-01	7.13E-02	2.10E-02	0.00E+00	-9.14E-01	0.00E+00	2.41E+00	6.87E-01	8.78E-07	7.06E+00	1.14E-01	2.94E+00	8.40E-01	2.03E+00	8.63E+00	1.39E-01
Water Quality (kg/MWh)	Aluminum	1.16E-09	8.70E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.45E-08	2.05E-08	0.00E+00	2.06E-07	0.00E+00	4.21E-08	2.51E-08	0.00E+00	2.52E-07	0.00E+00
	Arsenic (+V)	4.14E-08	9.44E-08	1.34E-08	3.06E-09	0.00E+00	-3.76E-08	-9.76E-09	0.00E+00	4.28E-07	2.35E-07	2.17E-12	2.25E-06	1.46E-07	5.23E-07	2.88E-07	1.51E-05	2.75E-06	1.78E-07
	Copper (+II)	1.37E-07	1.12E-07	2.44E-08	1.17E-08	0.00E+00	-2.93E-08	-2.77E-06	0.00E+00	6.99E-07	3.14E-07	3.18E-12	2.75E-06	4.58E-07	8.54E-07	3.84E-07	2.21E-05	3.37E-06	5.60E-07
	Iron	1.02E-05	1.88E-06	8.70E-05	1.70E-05	0.00E+00	-1.10E-05	-4.43E-05	-3.05E-04	2.27E-04	7.63E-05	1.66E-10	2.66E-04	1.94E-05	2.77E-04	9.32E-05	1.13E-03	3.25E-04	2.37E-05
	Lead (+II)	1.65E-07	4.60E-09	4.40E-08	6.32E-09	0.00E+00	-5.57E-08	-2.35E-06	-1.73E-04	1.69E-07	3.75E-08	7.30E-12	1.86E-07	6.92E-07	2.07E-07	4.58E-08	5.09E-05	2.27E-07	8.45E-07
	Manganese (+II)	3.89E-08	1.45E-07	1.95E-07	1.58E-07	0.00E+00	0.00E+00	-1.09E-07	0.00E+00	8.60E-07	1.01E-06	1.71E-14	3.84E-06	2.69E-08	1.05E-06	1.23E-06	6.78E-08	4.69E-06	3.28E-08
	Nickel (+II)	1.32E-06	4.31E-06	1.50E-08	1.78E-08	0.00E+00	-3.00E-08	-3.34E-07	-1.88E-06	1.71E-05	1.02E-05	5.77E-11	1.02E-04	3.75E-06	2.09E-05	1.25E-05	4.03E-04	1.25E-04	4.59E-06
	Strontium	4.23E-08	3.13E-09	2.81E-07	7.54E-07	0.00E+00	-9.14E-06	-3.63E-07	0.00E+00	1.04E-05	3.19E-06	1.02E-13	2.60E-06	1.29E-06	1.28E-05	3.89E-06	3.71E-07	3.18E-06	1.57E-06
	Zinc (+II)	1.62E-06	1.20E-06	1.88E-08	1.72E-08	0.00E+00	-1.01E-07	-6.59E-06	8.25E-05	4.93E-06	2.90E-06	1.00E-10	2.84E-05	7.07E-06	6.02E-06	3.54E-06	6.99E-04	3.47E-05	8.64E-06
	Ammonium/ammonia	1.56E-06	1.01E-05	1.32E-06	7.79E-07	0.00E+00	-5.04E-09	-3.91E-06	1.56E-02	4.56E-05	2.70E-05	1.62E-12	2.51E-04	4.51E-07	5.57E-05	3.30E-05	1.35E-06	3.06E-04	5.51E-07
	Hydrogen chloride	2.72E-12	7.35E-13	2.57E-11	3.24E-12	0.00E+00	0.00E+00	-1.59E-11	0.00E+00	2.55E-10	1.54E-11	2.15E-17	8.46E-10	3.02E-12	3.12E-10	1.88E-11	1.42E-10	1.03E-09	3.69E-12
	Nitrogen (as total N)	4.05E-09	3.04E-08	0.00E+00	0.00E+00	0.00E+00	-1.25E-08	0.00E+00	-8.84E-04	1.26E-07	7.17E-08	0.00E+00	7.30E-07	6.17E-09	1.54E-07	8.77E-08	0.00E+00	8.92E-07	7.54E-09
	Phosphate	2.33E-08	3.59E-10	8.06E-08	4.07E-07	0.00E+00	0.00E+00	-4.12E-07	9.49E-06	1.97E-06	1.72E-06	3.14E-14	1.36E-06	7.11E-08	2.41E-06	2.10E-06	1.68E-08	1.66E-06	8.69E-08
	Phosphorus	9.32E-07	6.78E-08	1.35E-08	5.14E-09	0.00E+00	0.00E+00	-1.54E-08	-1.78E-05	2.85E-07	1.82E-07	7.32E-11	1.63E-06	4.68E-06	3.49E-07	2.22E-07	5.06E-04	1.99E-06	5.71E-06
Resource Energy (MJ/MWh)	Crude oil	2.70E-01	2.20E-02	1.40E+00	4.29E-01	0.00E+00	-8.03E-02	-2.70E+00	-3.37E+00	2.13E+00	1.86E+00	7.05E-06	2.04E+00	7.98E-01	2.60E+00	2.27E+00	4.62E+01	2.49E+00	9.75E-01
	Hard coal	1.73E-01	1.94E-01	1.06E+00	3.90E+00	0.00E+00	-5.23E-01	-5.86E-01	-2.38E+01	4.23E+00	1.69E+01	4.13E-07	9.75E+00	7.97E-01	5.17E+00	2.06E+01	6.78E-01	1.19E+01	9.74E-01
	Lignite	4.81E-02	1.02E-04	5.18E-01	9.76E-02	0.00E+00	0.00E+00	-2.94E-01	0.00E+00	2.08E-01	4.11E-01	2.23E-08	3.18E-01	4.09E-02	2.55E-01	5.03E-01	2.48E-02	3.89E-01	5.00E-02
	Natural gas	1.79E-01	2.75E-01	1.26E+00	5.69E-01	0.00E+00	-1.75E+00	-1.18E+00	-2.77E+00	9.16E+00	3.05E+00	1.12E-06	9.71E+00	3.70E-01	1.12E+01	3.72E+00	5.20E+00	1.19E+01	4.53E-01
	Uranium	1.07E-01	3.74E-04	1.17E+00	1.14E-01	0.00E+00	0.00E+00	-6.62E-01	0.00E+00	1.22E+00	4.81E-01	1.02E-07	1.60E+00	9.59E-02	1.49E+00	5.88E-01	3.30E-01	1.96E+00	1.17E-01
	Total resource energy	7.77E-01	4.91E-01	5.40E+00	5.11E+00	0.00E+00	-2.36E+00	-5.42E+00	-2.99E+01	1.69E+01	2.27E+01	8.70E-06	2.34E+01	2.10E+00	2.07E+01	2.77E+01	5.24E+01	2.86E+01	2.57E+00
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table C-2: Full Life Cycle Metrics for Onshore Advanced Wind Power (continued)

Category (Units)	Material or Energy Flow	ECF											PT	Total
		Wind Farm Operation					Wind Farm Construction					Landfill Waste	T&D	
		Electricity	Diesel Upstream	Lubricating Oil	Wind Farm	Cable	Concrete	Steel	Diesel Upstream	Wind Farm	Gravel Road			
GHG (kg/MWh)	CO_2	3.81E-04	5.25E-04	1.10E-02	2.57E-03	3.30E-02	6.33E-03	2.06E-02	3.17E-03	2.13E-02	1.04E-01	1.40E-02	0.00E+00	1.47E+01
	N_2O	6.02E-09	1.03E-08	5.79E-05	6.65E-08	9.90E-07	5.61E-08	6.21E-06	3.42E-09	4.18E-07	2.69E-06	1.16E-07	0.00E+00	1.05E-03
	CH_4	1.15E-06	3.35E-06	3.03E-03	3.68E-07	4.96E-05	1.07E-05	5.95E-05	1.36E-06	1.36E-04	1.49E-05	4.13E-04	0.00E+00	3.53E-02
	SF_6	8.02E-11	9.86E-16	1.08E-13	0.00E+00	3.21E-12	7.36E-10	7.53E-15	1.48E-16	3.99E-14	0.00E+00	3.49E-15	1.43E-04	1.44E-04
	CO_2e (IPCC 2007 100-yr GWP)	4.13E-04	6.12E-04	1.04E-01	2.60E-03	3.45E-02	6.63E-03	2.39E-02	3.21E-03	2.48E-02	1.05E-01	2.44E-02	3.27E+00	1.91E+01
Other Air (kg/MWh)	Pb	2.52E-12	1.18E-11	3.69E-10	0.00E+00	3.71E-07	3.37E-11	9.03E-11	2.08E-11	4.79E-10	0.00E+00	3.85E-10	0.00E+00	7.91E-07
	Hg	7.05E-12	9.81E-13	5.36E-11	0.00E+00	2.73E-10	6.53E-11	7.50E-12	1.03E-11	3.98E-11	0.00E+00	3.88E-11	0.00E+00	1.69E-07
	NH_3	3.60E-10	6.70E-09	4.46E-04	0.00E+00	1.79E-07	3.52E-09	9.87E-06	1.89E-09	2.71E-07	0.00E+00	2.20E-08	0.00E+00	6.42E-04
	CO	7.38E-08	5.00E-07	9.31E-03	1.43E-05	2.00E-04	4.42E-06	7.22E-04	3.78E-05	2.03E-05	5.81E-04	7.18E-05	0.00E+00	4.39E-02
	NO_X	5.83E-07	6.86E-07	2.57E-04	1.16E-06	5.63E-05	1.39E-05	2.10E-03	3.50E-06	2.78E-05	0.00E+00	8.35E-05	0.00E+00	3.20E-02
	SO_2	1.22E-06	1.38E-06	7.71E-05	2.45E-08	1.22E-04	1.78E-05	1.29E-05	6.11E-06	5.57E-05	9.91E-07	3.68E-05	0.00E+00	3.09E-02
	VOC	1.03E-07	1.47E-06	5.34E-04	5.42E-07	7.38E-06	9.66E-07	6.12E-05	1.33E-06	5.95E-05	0.00E+00	1.96E-05	0.00E+00	8.24E-03
	PM	1.56E-08	1.20E-08	5.86E-04	2.73E-03	5.56E-05	8.49E-06	4.50E-03	4.66E-07	4.88E-07	0.00E+00	2.31E-04	0.00E+00	1.68E-02
Solid Waste (kg/MWh)	Heavy metals to industrial soil	2.51E-06	8.41E-09	1.04E-07	0.00E+00	1.55E-07	2.30E-05	6.42E-08	6.30E-11	3.41E-07	0.00E+00	3.02E-07	0.00E+00	2.74E-02
	Heavy metals to agricultural soil	0.00E+00	0.00E+00	4.32E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.32E-08
Water Use (L/MWh)	Withdrawal	1.32E-02	1.94E-03	3.22E-02	0.00E+00	3.37E-01	1.23E-01	1.48E-02	2.22E-05	7.84E-02	0.00E+00	3.09E-01	0.00E+00	1.83E+02
	Discharge	1.22E-02	4.71E-04	3.35E-02	0.00E+00	2.72E-01	1.12E-01	3.60E-03	2.72E-06	1.91E-02	0.00E+00	6.86E-01	0.00E+00	1.58E+02
	Consumption	1.02E-03	1.47E-03	-1.29E-03	0.00E+00	6.46E-02	1.07E-02	1.12E-02	1.94E-05	5.93E-02	0.00E+00	-3.77E-01	0.00E+00	2.47E+01
Water Quality (kg/MWh)	Aluminum	5.40E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.96E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.91E-07
	Arsenic (+V)	5.86E-10	1.09E-08	4.79E-10	0.00E+00	1.04E-09	5.38E-09	8.32E-08	3.40E-13	4.41E-07	0.00E+00	2.37E-10	0.00E+00	2.26E-05
	Copper (+II)	6.98E-10	1.60E-08	1.11E-08	0.00E+00	9.59E-08	6.42E-09	1.22E-07	2.92E-12	6.46E-07	0.00E+00	6.68E-09	0.00E+00	2.99E-05
	Iron	1.17E-08	8.14E-07	1.73E-06	0.00E+00	6.08E-06	1.10E-07	6.22E-06	3.74E-07	3.30E-05	0.00E+00	4.51E-06	0.00E+00	2.24E-03
	Lead (+II)	2.86E-11	3.67E-08	9.39E-08	0.00E+00	8.28E-08	2.69E-10	2.80E-07	2.12E-07	1.49E-06	0.00E+00	3.77E-10	0.00E+00	-1.20E-04
	Manganese (+II)	8.99E-10	4.89E-11	2.36E-09	0.00E+00	1.39E-08	8.25E-09	3.73E-10	1.23E-12	1.98E-09	0.00E+00	3.99E-09	0.00E+00	1.33E-05
	Nickel (+II)	2.68E-08	2.90E-07	9.38E-08	0.00E+00	1.22E-08	2.46E-07	2.22E-06	2.30E-09	1.18E-05	0.00E+00	3.78E-10	0.00E+00	7.16E-04
	Strontium	1.95E-11	2.68E-10	1.04E-08	0.00E+00	2.72E-08	3.08E-10	2.04E-09	2.28E-11	1.08E-08	0.00E+00	6.08E-09	0.00E+00	3.09E-05
	Zinc (+II)	7.45E-09	5.04E-07	4.70E-08	0.00E+00	2.26E-07	6.84E-08	3.85E-06	-1.01E-07	2.04E-05	0.00E+00	2.54E-10	0.00E+00	8.99E-04
	Ammonium/ammonia	6.25E-08	9.73E-10	2.65E-06	0.00E+00	2.03E-07	5.74E-07	7.43E-09	-1.91E-05	3.94E-08	0.00E+00	1.02E-07	0.00E+00	1.63E-02
	Hydrogen chloride	4.57E-15	1.03E-13	3.36E-13	0.00E+00	1.89E-12	4.50E-14	7.83E-13	5.44E-16	4.15E-12	0.00E+00	4.16E-14	0.00E+00	2.65E-09
	Nitrogen (as total N)	1.89E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.74E-09	0.00E+00	1.08E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-8.80E-04
	Phosphate	2.23E-12	1.21E-11	8.58E-06	0.00E+00	1.83E-08	3.56E-11	9.25E-11	-1.16E-08	4.90E-10	0.00E+00	9.62E-09	0.00E+00	2.96E-05
	Phosphorus	4.21E-10	3.65E-07	8.09E-10	0.00E+00	1.24E-09	4.00E-09	2.79E-06	2.18E-08	1.48E-05	0.00E+00	6.44E-08	0.00E+00	5.22E-04
Resource Energy (MJ/MWh)	Crude oil	1.37E-04	3.33E-02	8.42E-02	0.00E+00	1.66E-01	2.21E-03	2.54E-01	4.30E-03	1.35E+00	0.00E+00	1.15E-01	0.00E+00	5.93E+01
	Hard coal	1.20E-03	4.89E-04	1.51E-02	0.00E+00	7.55E-02	1.11E-02	3.73E-03	2.92E-02	1.98E-02	0.00E+00	1.45E-02	0.00E+00	5.16E+01
	Lignite	6.34E-07	1.79E-05	7.47E-03	0.00E+00	3.72E-02	1.76E-05	1.37E-04	2.07E-06	7.25E-04	0.00E+00	5.07E-03	0.00E+00	2.62E+00
	Natural gas	1.71E-03	3.75E-03	6.89E-02	0.00E+00	1.06E-01	1.58E-02	2.86E-02	3.41E-03	1.52E-01	0.00E+00	4.39E-02	0.00E+00	5.17E+01
	Uranium	2.32E-06	2.38E-04	1.38E-02	0.00E+00	8.39E-02	6.09E-05	1.82E-03	6.99E-06	9.64E-03	0.00E+00	7.55E-03	0.00E+00	8.73E+00
	Total resource energy	3.05E-03	3.78E-02	1.90E-01	0.00E+00	4.69E-01	2.92E-02	2.89E-01	3.69E-02	1.53E+00	0.00E+00	1.86E-01	0.00E+00	1.74E+02
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	20.7:1

Table C-3: Full Life Cycle Metrics for Offshore Wind Power

Category (Units)	Material or Energy Flow	ECF																	
		Switchyard	Trunkline				Recycling			Domestic Turbine MFG					Foreign Turbine MFG				
			Electricity	Aluminum Sheet	Cold Rolled Steel	Concrete	Aluminum	Copper	Steel	Rotor	Tower	Transport	Nacelle	Transformer	Rotor	Tower	Transport	Nacelle	Transformer
GHG (kg/MWh)	CO_2	6.00E-02	6.13E-02	3.89E-01	3.80E-01	4.90E-02	-1.25E-01	-2.80E-01	-1.73E+00	8.50E-01	1.23E+00	2.16E-07	1.87E+00	9.36E-02	1.04E+00	1.50E+00	3.77E+00	2.29E+00	1.14E-01
	N_2O	1.27E-06	9.69E-07	8.43E-06	2.47E-06	0.00E+00	-1.94E-07	-1.22E-05	-1.79E-06	2.12E-04	8.91E-06	5.69E-12	5.80E-05	1.55E-06	2.59E-04	1.09E-05	9.29E-05	7.08E-05	1.90E-06
	CH_4	9.82E-05	1.85E-04	6.17E-04	4.46E-04	0.00E+00	-5.29E-04	-3.84E-04	-7.32E-04	2.79E-03	1.62E-03	6.29E-10	4.56E-03	1.82E-04	3.41E-03	1.98E-03	4.27E-03	5.57E-03	2.22E-04
	SF_6	1.72E-09	1.29E-08	4.93E-11	2.76E-12	0.00E+00	0.00E+00	-1.39E-11	0.00E+00	3.62E-08	2.14E-08	6.91E-19	2.43E-07	1.56E-12	4.43E-08	2.61E-08	1.18E-12	2.97E-07	1.90E-12
	CO_2e (IPCC 2007 100-yr GWP)	6.29E-02	6.65E-02	4.07E-01	3.92E-01	4.90E-02	-1.38E-01	-2.93E-01	-1.75E+00	9.84E-01	1.27E+00	2.33E-07	2.01E+00	9.86E-02	1.20E+00	1.55E+00	3.91E+00	2.46E+00	1.21E-01
Other Air (kg/MWh)	Pb	3.25E-07	4.06E-10	5.16E-08	6.86E-07	0.00E+00	-2.75E-08	-8.22E-06	-1.04E-08	1.40E-07	2.03E-06	5.39E-14	3.52E-07	8.01E-07	1.71E-07	2.48E-06	1.42E-08	4.30E-07	9.79E-07
	Hg	5.02E-10	1.13E-09	3.62E-09	8.77E-10	0.00E+00	-8.65E-10	-1.87E-09	-5.58E-09	1.02E-08	4.47E-09	3.02E-15	4.08E-08	1.00E-09	1.25E-08	5.46E-09	1.18E-09	4.99E-08	1.22E-09
	NH_3	2.39E-07	5.79E-08	1.72E-06	1.24E-06	0.00E+00	-7.20E-08	-1.98E-06	-1.01E-06	1.83E-06	3.75E-06	1.71E-12	3.05E-06	4.69E-07	2.23E-06	4.58E-06	1.37E-04	3.73E-06	5.74E-07
	CO	3.34E-04	1.19E-05	3.59E-03	3.61E-03	6.32E-05	-9.61E-05	-2.65E-04	-2.07E-02	1.07E-03	1.07E-02	5.17E-10	2.14E-03	5.21E-04	1.31E-03	1.31E-02	1.03E-02	2.62E-03	6.36E-04
	NO_x	1.07E-04	9.39E-05	5.32E-04	7.20E-04	1.50E-04	-1.95E-04	-6.35E-04	-1.91E-03	1.58E-03	2.28E-03	1.77E-10	2.87E-03	2.25E-04	1.93E-03	2.79E-03	9.20E-03	3.50E-03	2.75E-04
	SO_2	1.97E-04	1.96E-04	1.46E-03	5.26E-04	1.14E-04	-1.03E-03	-1.01E-03	-3.34E-03	3.14E-03	1.88E-03	3.23E-10	5.66E-03	4.11E-04	3.84E-03	2.30E-03	1.65E-03	6.92E-03	5.02E-04
	VOC	1.46E-05	1.66E-05	7.12E-05	5.42E-05	0.00E+00	-4.04E-05	-8.14E-05	-7.27E-04	1.29E-03	1.88E-04	2.38E-10	6.17E-04	4.12E-05	1.57E-03	2.29E-04	1.76E-03	7.54E-04	5.03E-05
	PM	9.07E-05	2.51E-06	7.07E-04	2.32E-04	1.46E-04	-2.49E-05	-4.13E-04	-2.54E-04	1.22E-03	6.90E-04	1.57E-11	7.05E-04	1.32E-04	1.49E-03	8.44E-04	1.45E-05	8.62E-04	1.61E-04
Solid Waste (kg/MWh)	Heavy metals to industrial soil	5.39E-05	4.04E-04	1.74E-06	6.52E-07	0.00E+00	0.00E+00	-1.43E-06	0.00E+00	1.13E-03	6.69E-04	1.77E-12	7.59E-03	2.92E-07	1.39E-03	8.18E-04	1.01E-05	9.28E-03	3.57E-07
	Heavy metals to agricultural soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (L/MWh)	Withdrawal	6.53E-01	2.13E+00	2.23E+00	8.74E-01	2.10E-02	0.00E+00	-4.92E+00	0.00E+00	1.03E+01	6.11E+00	6.75E-07	4.48E+01	5.46E-01	1.26E+01	7.46E+00	2.33E+00	5.47E+01	6.67E-01
	Discharge	5.50E-01	1.97E+00	1.59E+00	8.03E-01	0.00E+00	0.00E+00	-4.22E+00	0.00E+00	8.58E+00	5.62E+00	1.09E-10	3.95E+01	4.57E-01	1.05E+01	6.87E+00	5.66E-01	4.82E+01	5.58E-01
	Consumption	1.02E-01	1.64E-01	6.35E-01	7.13E-02	2.10E-02	0.00E+00	-6.98E-01	0.00E+00	1.69E+00	4.82E-01	6.75E-07	5.29E+00	8.92E-02	2.07E+00	5.89E-01	1.76E+00	6.46E+00	1.09E-01
Water Quality (kg/MWh)	Aluminum	1.16E-09	8.70E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.46E-08	1.44E-08	0.00E+00	1.64E-07	0.00E+00	3.01E-08	1.76E-08	0.00E+00	2.00E-07	0.00E+00
	Arsenic (+V)	4.14E-08	9.44E-08	1.34E-08	3.06E-09	0.00E+00	-3.39E-08	-7.45E-09	0.00E+00	3.04E-07	1.65E-07	1.67E-12	1.79E-06	1.16E-07	3.72E-07	2.02E-07	1.31E-05	2.19E-06	1.42E-07
	Copper (+II)	1.37E-07	1.12E-07	2.44E-08	1.17E-08	0.00E+00	-2.65E-08	-2.11E-06	0.00E+00	4.93E-07	2.20E-07	2.45E-12	2.18E-06	3.60E-07	6.03E-07	2.69E-07	1.92E-05	2.67E-06	4.41E-07
	Iron	1.02E-05	1.88E-06	8.70E-05	1.70E-05	0.00E+00	-9.88E-06	-3.38E-05	-2.04E-04	1.58E-04	5.35E-05	1.28E-10	1.89E-04	1.53E-05	1.93E-04	6.54E-05	9.78E-04	2.31E-04	1.87E-05
	Lead (+II)	1.65E-07	4.60E-09	4.40E-08	6.32E-09	0.00E+00	-5.03E-08	-1.80E-06	-1.16E-04	1.19E-07	2.63E-08	5.62E-12	1.41E-07	5.47E-07	1.45E-07	3.22E-08	4.41E-05	1.73E-07	6.68E-07
	Manganese (+II)	3.89E-08	1.45E-07	1.95E-07	1.58E-07	0.00E+00	0.00E+00	-8.35E-08	0.00E+00	6.10E-07	7.07E-07	1.31E-14	3.02E-06	2.10E-08	7.45E-07	8.64E-07	5.87E-08	3.69E-06	2.56E-08
	Nickel (+II)	1.32E-06	4.31E-06	1.50E-08	1.78E-08	0.00E+00	-2.71E-08	-2.55E-07	-1.26E-06	1.22E-05	7.18E-06	4.44E-11	8.11E-05	2.98E-06	1.49E-05	8.77E-06	3.49E-04	9.91E-05	3.65E-06
	Strontium	4.23E-08	3.13E-09	2.81E-07	7.54E-07	0.00E+00	-8.24E-06	-2.77E-07	0.00E+00	7.33E-06	2.23E-06	7.85E-14	1.99E-06	1.01E-06	8.96E-06	2.73E-06	3.21E-07	2.44E-06	1.23E-06
	Zinc (+II)	1.62E-06	1.20E-06	1.88E-08	1.72E-08	0.00E+00	-9.13E-08	-5.03E-06	5.53E-05	3.51E-06	2.03E-06	7.70E-11	2.26E-05	5.61E-06	4.29E-06	2.49E-06	6.05E-04	2.76E-05	6.86E-06
	Ammonium/ammonia	1.56E-06	1.01E-05	1.32E-06	7.79E-07	0.00E+00	-4.55E-09	-2.98E-06	1.05E-02	3.24E-05	1.89E-05	1.24E-12	1.98E-04	3.52E-07	3.96E-05	2.31E-05	1.17E-06	2.43E-04	4.31E-07
	Hydrogen chloride	2.72E-12	7.35E-13	2.57E-11	3.24E-12	0.00E+00	0.00E+00	-1.21E-11	0.00E+00	1.79E-10	1.08E-11	1.66E-17	5.74E-10	2.37E-12	2.19E-10	1.32E-11	1.23E-10	7.01E-10	2.90E-12
	Nitrogen (as total N)	4.05E-09	3.04E-08	0.00E+00	0.00E+00	0.00E+00	-1.13E-08	0.00E+00	-5.92E-04	9.03E-08	5.03E-08	0.00E+00	5.80E-07	4.82E-09	1.10E-07	6.15E-08	0.00E+00	7.09E-07	5.89E-09
	Phosphate	2.33E-08	3.59E-10	8.06E-08	4.07E-07	0.00E+00	0.00E+00	-3.14E-07	6.36E-06	1.37E-06	1.20E-06	2.42E-14	9.68E-07	5.55E-08	1.67E-06	1.47E-06	1.45E-08	1.18E-06	6.78E-08
	Phosphorus	9.32E-07	6.78E-08	1.35E-08	5.14E-09	0.00E+00	0.00E+00	-1.18E-08	-1.19E-05	2.03E-07	1.27E-07	5.63E-11	1.29E-06	3.71E-06	2.48E-07	1.56E-07	4.38E-04	1.58E-06	4.54E-06
Resource Energy (MJ/MWh)	Crude oil	2.70E-01	2.20E-02	1.40E+00	4.29E-01	0.00E+00	-7.24E-02	-2.06E+00	-2.26E+00	1.48E+00	1.30E+00	5.42E-06	1.50E+00	6.28E-01	1.81E+00	1.59E+00	4.00E+01	1.83E+00	7.68E-01
	Hard coal	1.73E-01	1.94E-01	1.06E+00	3.90E+00	0.00E+00	-4.71E-01	-4.47E-01	-1.60E+01	2.99E+00	1.18E+01	3.18E-07	7.53E+00	6.22E-01	3.65E+00	1.45E+01	5.87E-01	9.20E+00	7.61E-01
	Lignite	4.81E-02	1.02E-04	5.18E-01	9.76E-02	0.00E+00	0.00E+00	-2.24E-01	0.00E+00	1.46E-01	2.89E-01	1.72E-08	2.29E-01	3.19E-02	1.79E-01	3.53E-01	2.15E-02	2.80E-01	3.90E-02
	Natural gas	1.79E-01	2.75E-01	1.26E+00	5.69E-01	0.00E+00	-1.58E+00	-8.99E-01	-1.85E+00	6.39E+00	2.14E+00	8.59E-07	7.54E+00	2.90E-01	7.81E+00	2.61E+00	4.50E+00	9.22E+00	3.54E-01
	Uranium	1.07E-01	3.74E-04	1.17E+00	1.14E-01	0.00E+00	0.00E+00	-5.06E-01	0.00E+00	8.49E-01	3.38E-01	7.82E-08	1.11E+00	7.50E-02	1.04E+00	4.13E-01	2.86E-01	1.36E+00	9.16E-02
	Total resource energy	7.77E-01	4.91E-01	5.40E+00	5.11E+00	0.00E+00	-2.12E+00	-4.14E+00	-2.01E+01	1.19E+01	1.59E+01	6.69E-06	1.79E+01	1.65E+00	1.45E+01	1.94E+01	4.54E+01	2.19E+01	2.01E+00
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table C-3: Full Life Cycle Metrics for Offshore Wind Power (continued)

Category (Units)	Material or Energy Flow	ECF										PT	Total
		Wind Farm Operation					Wind Farm Construction				Landfill Waste	T&D	
		Marine Vessel Idling	Marine Vessel Travel	Electricity	Marine Vessel Construction	Lubricating Oil	Submarine Cable	Gravel	Coating	Steel Plate			
GHG (kg/MWh)	CO_2	6.47E+00	6.23E+00	2.55E-04	4.01E-01	3.53E-03	7.17E-02	6.53E-04	1.34E-04	3.17E+00	1.11E-02	0.00E+00	2.79E+01
	N_2O	2.16E-05	2.08E-05	4.03E-09	1.32E-05	1.85E-05	1.77E-06	0.00E+00	4.31E-10	1.65E-04	9.16E-08	0.00E+00	9.55E-04
	CH_4	7.02E-03	6.75E-03	7.72E-07	1.99E-04	9.70E-04	7.12E-05	0.00E+00	2.95E-07	2.40E-03	3.26E-04	0.00E+00	4.21E-02
	SF_6	2.06E-12	1.98E-12	5.37E-11	8.97E-14	3.46E-14	1.95E-12	3.59E-11	0.00E+00	0.00E+00	2.76E-15	1.43E-04	1.44E-04
	CO_2e (IPCC 2007 100-yr GWP)	6.66E+00	6.41E+00	2.77E-04	4.10E-01	3.33E-02	7.40E-02	6.54E-04	1.42E-04	3.28E+00	1.93E-02	3.27E+00	3.25E+01
Other Air (kg/MWh)	Pb	2.48E-08	2.38E-08	1.69E-12	4.99E-07	1.18E-10	1.14E-06	6.34E-10	1.06E-11	6.27E-06	3.04E-10	0.00E+00	8.16E-06
	Hg	2.05E-09	1.98E-09	4.72E-12	3.14E-08	1.72E-11	2.77E-10	5.56E-11	2.09E-12	3.94E-07	3.07E-11	0.00E+00	5.54E-07
	NH_3	1.40E-05	1.35E-05	2.41E-10	1.55E-08	1.43E-04	3.04E-07	1.22E-07	1.72E-10	0.00E+00	1.73E-08	0.00E+00	3.28E-04
	CO	2.70E-02	1.70E-02	4.95E-08	2.38E-03	2.99E-03	8.81E-05	2.53E-06	6.86E-08	2.67E-02	5.67E-05	0.00E+00	1.05E-01
	NO_X	7.47E-02	7.52E-02	3.91E-07	7.29E-04	8.22E-05	1.54E-04	5.10E-06	3.50E-07	5.30E-03	6.59E-05	0.00E+00	1.80E-01
	SO_2	6.94E-03	6.67E-03	8.17E-07	1.16E-03	2.47E-05	2.62E-04	1.12E-06	9.25E-07	7.21E-03	2.90E-05	0.00E+00	4.57E-02
	VOC	3.08E-03	2.96E-03	6.92E-08	7.35E-07	1.71E-04	1.72E-05	0.00E+00	7.40E-08	-1.23E-11	1.55E-05	0.00E+00	1.21E-02
	PM	2.01E-03	2.43E-05	1.05E-08	2.21E-04	1.88E-04	8.86E-05	0.00E+00	8.03E-08	7.59E-04	1.82E-04	0.00E+00	1.01E-02
Solid Waste (kg/MWh)	Heavy metals to industrial soil	1.76E-05	1.69E-05	1.68E-06	3.34E-08	3.32E-08	2.84E-07	0.00E+00	0.00E+00	0.00E+00	2.38E-07	0.00E+00	2.14E-02
	Heavy metals to agricultural soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.39E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.39E-08
Water Use (L/MWh)	Withdrawal	4.05E+00	3.90E+00	8.87E-03	2.49E+00	1.03E-02	9.19E-01	0.00E+00	0.00E+00	1.67E+01	2.44E-01	0.00E+00	1.69E+02
	Discharge	9.86E-01	9.48E-01	8.18E-03	1.39E-02	1.07E-02	5.97E-01	0.00E+00	0.00E+00	0.00E+00	5.42E-01	0.00E+00	1.25E+02
	Consumption	3.07E+00	2.95E+00	6.84E-04	2.48E+00	-4.14E-04	3.21E-01	0.00E+00	0.00E+00	1.67E+01	-2.98E-01	0.00E+00	4.41E+01
Water Quality (kg/MWh)	Aluminum	0.00E+00	0.00E+00	3.62E-11	5.71E-07	0.00E+00	1.10E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.14E-06
	Arsenic (+V)	2.28E-05	2.19E-05	3.93E-10	7.43E-11	1.54E-10	1.46E-09	0.00E+00	1.01E-11	0.00E+00	1.87E-10	0.00E+00	6.32E-05
	Copper (+II)	3.34E-05	3.21E-05	4.68E-10	2.88E-10	3.57E-09	2.97E-07	0.00E+00	2.09E-11	0.00E+00	5.27E-09	0.00E+00	9.04E-05
	Iron	1.70E-03	1.64E-03	7.84E-09	1.28E-05	5.54E-07	6.20E-06	0.00E+00	4.73E-09	1.02E-04	3.56E-06	0.00E+00	5.24E-03
	Lead (+II)	7.68E-05	7.39E-05	1.92E-11	1.33E-07	3.01E-08	2.57E-07	0.00E+00	1.75E-11	1.30E-06	2.98E-10	0.00E+00	8.08E-05
	Manganese (+II)	1.02E-07	9.84E-08	6.02E-10	1.85E-07	7.57E-10	4.80E-08	0.00E+00	0.00E+00	0.00E+00	3.15E-09	0.00E+00	1.06E-05
	Nickel (+II)	6.08E-04	5.85E-04	1.79E-08	2.09E-07	3.01E-08	7.69E-08	0.00E+00	8.16E-12	1.77E-07	2.99E-10	0.00E+00	1.78E-03
	Strontium	5.60E-07	5.39E-07	1.30E-11	2.14E-09	3.34E-09	5.64E-08	0.00E+00	2.26E-09	0.00E+00	4.80E-09	0.00E+00	2.20E-05
	Zinc (+II)	1.06E-03	1.01E-03	4.99E-09	1.55E-07	1.51E-08	7.19E-07	0.00E+00	5.75E-11	7.79E-07	2.00E-10	0.00E+00	2.80E-03
	Ammonium/ammonia	2.04E-06	1.96E-06	4.19E-08	1.51E-08	8.49E-07	5.10E-07	0.00E+00	1.48E-11	0.00E+00	8.09E-08	0.00E+00	1.10E-02
	Hydrogen chloride	2.15E-10	2.06E-10	3.06E-15	1.26E-13	1.08E-13	2.18E-12	0.00E+00	0.00E+00	0.00E+00	3.29E-14	0.00E+00	2.27E-09
	Nitrogen (as total N)	0.00E+00	0.00E+00	1.27E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.68E-11	0.00E+00	0.00E+00	0.00E+00	-5.91E-04
	Phosphate	2.53E-08	2.44E-08	1.49E-12	4.16E-10	2.75E-06	4.56E-08	0.00E+00	0.00E+00	0.00E+00	7.60E-09	0.00E+00	1.74E-05
	Phosphorus	7.64E-04	7.35E-04	2.82E-10	9.75E-07	2.59E-10	2.68E-08	0.00E+00	0.00E+00	1.07E-05	5.09E-08	0.00E+00	1.95E-03
Resource Energy (MJ/MWh)	Crude oil	6.97E+01	6.70E+01	9.18E-05	7.60E-01	2.70E-02	4.47E-01	0.00E+00	1.06E-04	6.95E+00	9.12E-02	0.00E+00	1.94E+02
	Hard coal	1.02E+00	9.84E-01	8.07E-04	2.92E+00	4.85E-03	1.67E-01	0.00E+00	1.53E-03	3.03E+01	1.14E-02	0.00E+00	7.55E+01
	Lignite	3.75E-02	3.60E-02	4.25E-07	2.48E-02	2.39E-03	3.66E-02	0.00E+00	0.00E+00	0.00E+00	4.00E-03	0.00E+00	2.15E+00
	Natural gas	7.85E+00	7.54E+00	1.14E-03	7.96E-01	2.21E-02	2.36E-01	0.00E+00	3.56E-04	6.04E+00	3.47E-02	0.00E+00	6.13E+01
	Uranium	4.98E-01	4.79E-01	1.56E-06	1.81E-02	4.44E-03	7.62E-02	0.00E+00	0.00E+00	0.00E+00	5.96E-03	0.00E+00	7.53E+00
	Total resource energy	7.91E+01	7.61E+01	2.04E-03	4.52E+00	6.08E-02	9.63E-01	0.00E+00	1.99E-03	4.33E+01	1.47E-01	0.00E+00	3.40E+02
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10.6:1

Table C-4: Full Life Cycle Metrics for Onshore Conventional Wind Power in Alternate Units

Category (Units)	Material or Energy Flow	ECF																	
		Switchyard	Trunkline				Recycling			Domestic Turbine MFG					Foreign Turbine MFG				
			Electricity	Aluminum Sheet	Steel Cold Rolled	Concrete	Aluminum	Copper	Steel	Rotor	Tower	Transport	Nacelle	Transformer	Rotor	Tower	Transport	Nacelle	Transformer
GHG (lb/MWh)	CO_2	1.32E-01	1.35E-01	8.59E-01	8.38E-01	1.08E-01	-3.51E-01	-1.40E+00	-3.57E+00	1.55E+00	1.60E+00	6.18E-07	6.41E+00	3.11E-01	1.89E+00	1.95E+00	1.91E+01	7.83E+00	3.80E-01
	N_2O	2.80E-06	2.14E-06	1.86E-05	5.45E-06	0.00E+00	-5.42E-07	-6.14E-05	-3.68E-06	3.36E-04	1.16E-05	1.63E-11	1.96E-04	5.16E-06	4.10E-04	1.42E-05	4.69E-04	2.40E-04	6.31E-06
	CH_4	2.16E-04	4.09E-04	1.36E-03	9.82E-04	0.00E+00	-1.48E-03	-1.93E-03	-1.51E-03	4.83E-03	2.12E-03	1.80E-09	1.66E-02	6.14E-04	5.90E-03	2.59E-03	2.16E-02	2.02E-02	7.50E-04
	SF_6	3.79E-09	2.85E-08	1.09E-10	6.08E-12	0.00E+00	0.00E+00	-6.99E-11	0.00E+00	8.19E-08	2.78E-08	1.98E-18	9.49E-07	5.14E-12	1.00E-07	3.40E-08	5.98E-12	1.16E-06	6.28E-12
	CO_2e (IPCC 2007 100-yr GWP)	1.39E-01	1.47E-01	8.98E-01	8.64E-01	1.08E-01	-3.88E-01	-1.47E+00	-3.61E+00	1.77E+00	1.65E+00	6.68E-07	6.90E+00	3.28E-01	2.16E+00	2.02E+00	1.97E+01	8.44E+00	4.00E-01
Other Air (lb/MWh)	Pb	7.16E-07	8.96E-10	1.14E-07	1.51E-06	0.00E+00	-7.70E-08	-4.13E-05	-2.14E-08	3.56E-07	2.64E-06	1.54E-13	1.01E-06	2.64E-06	4.35E-07	3.23E-06	7.17E-08	1.24E-06	3.23E-06
	Hg	1.11E-09	2.50E-09	7.97E-09	1.93E-09	0.00E+00	-2.42E-09	-9.38E-09	-1.15E-08	2.02E-08	5.83E-09	8.65E-15	1.15E-07	3.31E-09	2.47E-08	7.12E-09	5.95E-09	1.41E-07	4.04E-09
	NH_3	5.28E-07	1.28E-07	3.79E-06	2.72E-06	0.00E+00	-2.02E-07	-9.96E-06	-2.09E-06	3.00E-06	4.89E-06	4.90E-12	9.15E-06	1.57E-06	3.67E-06	5.97E-06	6.92E-04	1.12E-05	1.92E-06
	CO	7.36E-04	2.62E-05	7.91E-03	7.96E-03	1.39E-04	-2.69E-04	-1.33E-03	-4.26E-02	2.45E-03	1.39E-02	1.48E-09	6.69E-03	1.72E-03	2.99E-03	1.70E-02	5.18E-02	8.18E-03	2.10E-03
	NO_X	2.35E-04	2.07E-04	1.17E-03	1.59E-03	3.30E-04	-5.46E-04	-3.19E-03	-3.94E-03	2.71E-03	2.98E-03	5.07E-10	9.86E-03	7.45E-04	3.31E-03	3.64E-03	4.65E-02	1.21E-02	9.10E-04
	SO_2	4.34E-04	4.33E-04	3.22E-03	1.16E-03	2.51E-04	-2.89E-03	-5.07E-03	-6.88E-03	5.40E-03	2.45E-03	9.27E-10	1.88E-02	1.36E-03	6.60E-03	3.00E-03	8.34E-03	2.30E-02	1.66E-03
	VOC	3.21E-05	3.66E-05	1.57E-04	1.20E-04	0.00E+00	-1.13E-04	-4.09E-04	-1.50E-03	2.03E-03	2.45E-04	6.83E-10	2.15E-03	1.42E-04	2.48E-03	2.99E-04	8.91E-03	2.63E-03	1.74E-04
	PM	2.00E-04	5.54E-06	1.56E-03	5.12E-04	3.22E-04	-6.99E-05	-2.07E-03	-5.23E-04	2.16E-03	9.00E-04	4.51E-11	2.25E-03	4.35E-04	2.64E-03	1.10E-03	7.31E-05	2.75E-03	5.31E-04
Solid Waste (lb/MWh)	Heavy metals to industrial soil	1.19E-04	8.90E-04	3.83E-06	1.44E-06	0.00E+00	0.00E+00	-7.20E-06	0.00E+00	2.56E-03	8.73E-04	5.07E-12	2.97E-02	1.00E-06	3.13E-03	1.07E-03	5.10E-05	3.63E-02	1.23E-06
	Heavy metals to agricultural soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (gal/MWh)	Withdrawal	1.72E-01	5.63E-01	5.89E-01	2.31E-01	5.55E-03	0.00E+00	-2.96E+00	0.00E+00	2.44E+00	9.54E-01	2.32E-07	1.99E+01	2.17E-01	2.98E+00	1.17E+00	1.41E+00	2.44E+01	2.65E-01
	Discharge	1.45E-01	5.19E-01	4.21E-01	2.12E-01	0.00E+00	0.00E+00	-2.54E+00	0.00E+00	2.05E+00	8.79E-01	3.73E-11	1.80E+01	1.81E-01	2.51E+00	1.07E+00	3.42E-01	2.20E+01	2.21E-01
	Consumption	2.71E-02	4.34E-02	1.68E-01	1.88E-02	5.55E-03	0.00E+00	-4.20E-01	0.00E+00	3.85E-01	7.53E-02	2.32E-07	1.95E+00	3.61E-02	4.71E-01	9.21E-02	1.06E+00	2.38E+00	4.41E-02
Water Quality (lb/MWh)	Aluminum	2.55E-09	1.92E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.58E-08	1.88E-08	0.00E+00	6.41E-07	0.00E+00	6.81E-08	2.29E-08	0.00E+00	7.83E-07	0.00E+00
	Arsenic (+V)	9.12E-08	2.08E-07	2.96E-08	6.76E-09	0.00E+00	-9.50E-08	-3.74E-08	0.00E+00	6.64E-07	2.15E-07	4.77E-12	6.97E-06	4.35E-07	8.12E-07	2.63E-07	6.61E-05	8.52E-06	5.32E-07
	Copper (+II)	3.03E-07	2.48E-07	5.39E-08	2.59E-08	0.00E+00	-7.41E-08	-1.06E-05	0.00E+00	9.49E-07	2.87E-07	7.01E-12	8.46E-06	1.27E-06	1.16E-06	3.51E-07	9.68E-05	1.03E-05	1.55E-06
	Iron	2.25E-05	4.15E-06	1.92E-04	3.76E-05	0.00E+00	-2.77E-05	-1.70E-04	-4.21E-04	2.38E-04	6.98E-05	3.65E-10	4.40E-04	5.44E-05	2.90E-04	8.53E-05	4.94E-03	5.38E-04	6.64E-05
	Lead (+II)	3.63E-07	1.01E-08	9.70E-08	1.39E-08	0.00E+00	-1.41E-07	-9.03E-06	-2.39E-04	1.93E-07	3.43E-08	1.61E-11	4.68E-07	1.98E-06	2.36E-07	4.19E-08	2.22E-04	5.72E-07	2.42E-06
	Manganese (+II)	8.58E-08	3.19E-07	4.29E-07	3.49E-07	0.00E+00	0.00E+00	-4.19E-07	0.00E+00	1.29E-06	9.22E-07	3.77E-14	1.14E-05	6.94E-08	1.58E-06	1.13E-06	2.96E-07	1.39E-05	8.48E-08
	Nickel (+II)	2.90E-06	9.50E-06	3.30E-08	3.92E-08	0.00E+00	-7.58E-08	-1.28E-06	-2.60E-06	2.74E-05	9.36E-06	1.27E-10	3.17E-04	1.12E-05	3.35E-05	1.14E-05	1.76E-03	3.87E-04	1.37E-05
	Strontium	9.32E-08	6.91E-09	6.21E-07	1.66E-06	0.00E+00	-2.31E-05	-1.39E-06	0.00E+00	1.29E-05	2.91E-06	2.25E-13	6.02E-06	3.32E-06	1.57E-05	3.56E-06	1.62E-06	7.36E-06	4.06E-06
	Zinc (+II)	3.58E-06	2.64E-06	4.14E-08	3.79E-08	0.00E+00	-2.56E-07	-2.53E-05	1.14E-04	7.85E-06	2.65E-06	2.21E-10	8.83E-05	2.09E-05	9.59E-06	3.24E-06	3.06E-03	1.08E-04	2.56E-05
	Ammonium/ammonia	3.44E-06	2.22E-05	2.91E-06	1.72E-06	0.00E+00	-1.27E-08	-1.50E-05	2.16E-02	6.84E-05	2.47E-05	3.56E-12	7.69E-04	1.17E-06	8.36E-05	3.02E-05	5.90E-06	9.40E-04	1.43E-06
	Hydrogen chloride	6.00E-12	1.62E-12	5.66E-11	7.14E-12	0.00E+00	0.00E+00	-6.09E-11	0.00E+00	3.41E-10	1.41E-11	4.75E-17	9.37E-10	8.26E-12	4.17E-10	1.72E-11	6.22E-10	1.14E-09	1.01E-11
	Nitrogen (as total N)	8.92E-09	6.71E-08	0.00E+00	0.00E+00	0.00E+00	-3.17E-08	0.00E+00	-1.22E-03	2.07E-07	6.56E-08	0.00E+00	2.26E-06	1.59E-08	2.53E-07	8.02E-08	0.00E+00	2.77E-06	1.94E-08
	Phosphate	5.15E-08	7.91E-10	1.78E-07	8.98E-07	0.00E+00	0.00E+00	-1.58E-06	1.31E-05	2.28E-06	1.57E-06	6.92E-14	2.09E-06	1.83E-07	2.79E-06	1.92E-06	7.34E-08	2.55E-06	2.24E-07
	Phosphorus	2.06E-06	1.50E-07	2.97E-08	1.13E-08	0.00E+00	0.00E+00	-5.92E-08	-2.46E-05	4.49E-07	1.66E-07	1.61E-10	5.02E-06	1.40E-05	5.49E-07	2.03E-07	2.21E-03	6.14E-06	1.71E-05
Resource Energy (Btu/MWh)	Crude oil	2.55E+02	2.09E+01	1.32E+03	4.06E+02	0.00E+00	-8.73E+01	-4.45E+03	-2.00E+03	6.26E+02	7.31E+02	6.68E-03	1.80E+03	9.57E+02	7.65E+02	8.93E+02	8.68E+04	2.20E+03	1.17E+03
	Hard coal	1.64E+02	1.84E+02	1.00E+03	3.69E+03	0.00E+00	-5.68E+02	-9.66E+02	-1.41E+04	2.65E+03	6.64E+03	3.92E-04	1.06E+04	8.83E+02	3.23E+03	8.11E+03	1.27E+03	1.30E+04	1.08E+03
	Lignite	4.56E+01	9.67E-02	4.91E+02	9.25E+01	0.00E+00	0.00E+00	-4.84E+02	0.00E+00	1.15E+02	1.62E+02	2.11E-05	2.32E+02	4.53E+01	1.40E+02	1.98E+02	4.67E+01	2.83E+02	5.54E+01
	Natural gas	1.69E+02	2.60E+02	1.19E+03	5.40E+02	0.00E+00	-1.90E+03	-1.94E+03	-1.64E+03	4.44E+03	1.20E+03	1.06E-03	1.16E+04	4.18E+02	5.43E+03	1.46E+03	9.77E+03	1.42E+04	5.10E+02
	Uranium	1.02E+02	3.54E-01	1.11E+03	1.08E+02	0.00E+00	0.00E+00	-1.09E+03	0.00E+00	5.62E+02	1.89E+02	9.63E-05	9.28E+02	1.07E+02	6.87E+02	2.31E+02	6.21E+02	1.13E+03	1.30E+02
	Total resource energy	7.36E+02	4.65E+02	5.12E+03	4.84E+03	0.00E+00	-2.56E+03	-8.94E+03	-1.78E+04	8.39E+03	8.92E+03	8.25E-03	2.52E+04	2.41E+03	1.03E+04	1.09E+04	9.85E+04	3.08E+04	2.95E+03
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table C-4: Full Life Cycle Metrics for Onshore Conventional Wind Power in Alternate Units (continued)

Category (Units)	Material or Energy Flow	ECF											PT	Total
		Wind Farm Operation					Wind Farm Construction					Landfill Waste	T&D	
		Electricity	Diesel Upstream	Lubricating Oil	Wind Farm	Cable	Concrete	Gravel Road	Steel	Diesel Upstream	Wind Farm			
GHG (lb/MWh)	CO_2	8.40E-04	1.16E-03	2.43E-02	5.66E-03	2.85E-01	1.39E-02	1.79E-01	6.99E-03	4.69E-02	2.29E-01	2.33E-02	0.00E+00	3.85E+01
	N_2O	1.33E-08	2.27E-08	1.28E-04	1.47E-07	8.57E-06	1.24E-07	5.39E-05	7.54E-09	9.21E-07	5.94E-06	1.93E-07	0.00E+00	1.85E-03
	CH_4	2.54E-06	7.39E-06	6.67E-03	8.12E-07	4.29E-04	2.36E-05	5.17E-04	2.99E-06	2.99E-04	3.29E-05	6.87E-04	0.00E+00	8.19E-02
	SF_6	1.77E-10	2.17E-15	2.38E-13	0.00E+00	2.78E-11	1.62E-09	6.53E-14	3.26E-16	8.80E-14	0.00E+00	5.80E-15	3.16E-04	3.18E-04
	CO_2e (IPCC 2007 100-yr GWP)	9.11E-04	1.35E-03	2.29E-01	5.73E-03	2.99E-01	1.46E-02	2.07E-01	7.07E-03	5.46E-02	2.32E-01	4.05E-02	7.20E+00	4.84E+01
Other Air (lb/MWh)	Pb	5.56E-12	2.61E-11	8.14E-10	0.00E+00	3.21E-06	7.44E-11	7.84E-10	4.59E-11	1.06E-09	0.00E+00	6.40E-10	0.00E+00	-2.10E-05
	Hg	1.55E-11	2.16E-12	1.18E-10	0.00E+00	2.37E-09	1.44E-10	6.51E-11	2.27E-11	8.76E-11	0.00E+00	6.45E-11	0.00E+00	3.21E-07
	NH_3	7.93E-10	1.48E-08	9.83E-04	0.00E+00	1.55E-06	7.77E-09	8.56E-05	4.16E-09	5.98E-07	0.00E+00	3.65E-08	0.00E+00	1.80E-03
	CO	1.63E-07	1.10E-06	2.05E-02	3.16E-05	1.73E-03	9.75E-06	6.26E-03	8.34E-05	4.47E-05	1.28E-03	1.19E-04	0.00E+00	1.10E-01
	NO_X	1.29E-06	1.51E-06	5.66E-04	2.56E-06	4.88E-04	3.07E-05	1.82E-02	7.72E-06	6.13E-05	0.00E+00	1.39E-04	0.00E+00	9.80E-02
	SO_2	2.69E-06	3.03E-06	1.70E-04	5.39E-08	1.05E-03	3.92E-05	1.12E-04	1.35E-05	1.23E-04	2.18E-06	6.11E-05	0.00E+00	6.29E-02
	VOC	2.28E-07	3.24E-06	1.18E-03	1.20E-06	6.39E-05	2.13E-06	5.31E-04	2.93E-06	1.31E-04	0.00E+00	3.25E-05	0.00E+00	1.93E-02
	PM	3.44E-08	2.66E-08	1.29E-03	6.01E-03	4.81E-04	1.87E-05	3.90E-02	1.03E-06	1.08E-06	0.00E+00	3.84E-04	0.00E+00	6.00E-02
Solid Waste (lb/MWh)	Heavy metals to industrial soil	5.53E-06	1.85E-08	2.29E-07	0.00E+00	1.34E-06	5.07E-05	5.58E-07	1.39E-10	7.51E-07	0.00E+00	5.02E-07	0.00E+00	7.47E-02
	Heavy metals to agricultural soil	0.00E+00	0.00E+00	9.53E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.53E-08
Water Use (gal/MWh)	Withdrawal	3.49E-03	5.11E-04	8.52E-03	0.00E+00	3.50E-01	3.24E-02	1.54E-02	5.85E-06	2.07E-02	0.00E+00	6.15E-02	0.00E+00	5.28E+01
	Discharge	3.23E-03	1.24E-04	8.86E-03	0.00E+00	2.83E-01	2.96E-02	3.74E-03	7.18E-07	5.04E-03	0.00E+00	1.37E-01	0.00E+00	4.65E+01
	Consumption	2.69E-04	3.87E-04	-3.41E-04	0.00E+00	6.70E-02	2.82E-03	1.16E-02	5.13E-06	1.57E-02	0.00E+00	-7.52E-02	0.00E+00	6.36E+00
Water Quality (lb/MWh)	Aluminum	1.19E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.09E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.61E-06
	Arsenic (+V)	1.29E-09	2.40E-08	1.06E-09	0.00E+00	8.99E-09	1.19E-08	7.22E-07	7.50E-13	9.73E-07	0.00E+00	3.94E-10	0.00E+00	8.64E-05
	Copper (+II)	1.54E-09	3.52E-08	2.46E-08	0.00E+00	8.30E-07	1.42E-08	1.06E-06	6.45E-12	1.43E-06	0.00E+00	1.11E-08	0.00E+00	1.15E-04
	Iron	2.58E-08	1.79E-06	3.81E-06	0.00E+00	5.26E-05	2.43E-07	5.40E-05	8.24E-07	7.27E-05	0.00E+00	7.50E-06	0.00E+00	6.55E-03
	Lead (+II)	6.30E-11	8.09E-08	2.07E-07	0.00E+00	7.17E-07	5.94E-10	2.43E-06	4.66E-07	3.28E-06	0.00E+00	6.27E-10	0.00E+00	-1.17E-05
	Manganese (+II)	1.98E-09	1.08E-10	5.21E-09	0.00E+00	1.21E-07	1.82E-08	3.24E-09	2.71E-12	4.37E-09	0.00E+00	6.62E-09	0.00E+00	3.15E-05
	Nickel (+II)	5.90E-08	6.40E-07	2.07E-07	0.00E+00	1.06E-07	5.42E-07	1.92E-05	5.08E-09	2.59E-05	0.00E+00	6.28E-10	0.00E+00	2.63E-03
	Strontium	4.29E-11	5.90E-10	2.30E-08	0.00E+00	2.35E-07	6.79E-10	1.77E-08	5.03E-11	2.39E-08	0.00E+00	1.01E-08	0.00E+00	3.57E-05
	Zinc (+II)	1.64E-08	1.11E-06	1.04E-07	0.00E+00	1.96E-06	1.51E-07	3.34E-05	-2.22E-07	4.50E-05	0.00E+00	4.22E-10	0.00E+00	3.50E-03
	Ammonium/ammonia	1.38E-07	2.15E-09	5.84E-06	0.00E+00	1.76E-06	1.26E-06	6.45E-08	-4.22E-05	8.69E-08	0.00E+00	1.70E-07	0.00E+00	2.35E-02
	Hydrogen chloride	1.01E-14	2.26E-13	7.41E-13	0.00E+00	1.64E-11	9.92E-14	6.80E-12	1.20E-15	9.16E-12	0.00E+00	6.92E-14	0.00E+00	3.56E-09
	Nitrogen (as total N)	4.17E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.83E-09	0.00E+00	2.38E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.21E-03
	Phosphate	4.91E-12	2.67E-11	1.89E-05	0.00E+00	1.58E-07	7.85E-11	8.02E-10	-2.56E-08	1.08E-09	0.00E+00	1.60E-08	0.00E+00	4.54E-05
	Phosphorus	9.29E-10	8.05E-07	1.78E-09	0.00E+00	1.07E-08	8.81E-09	2.42E-05	4.81E-08	3.26E-05	0.00E+00	1.07E-07	0.00E+00	2.29E-03
Resource Energy (Btu/MWh)	Crude oil	1.30E-01	3.16E+01	7.98E+01	0.00E+00	6.16E+02	2.10E+00	9.49E+02	4.07E+00	1.28E+03	0.00E+00	8.25E+01	0.00E+00	9.45E+04
	Hard coal	1.14E+00	4.63E-01	1.44E+01	0.00E+00	2.81E+02	1.05E+01	1.39E+01	2.76E+01	1.88E+01	0.00E+00	1.04E+01	0.00E+00	3.73E+04
	Lignite	6.01E-04	1.70E-02	7.08E+00	0.00E+00	1.39E+02	1.67E-02	5.10E-01	1.97E-03	6.87E-01	0.00E+00	3.62E+00	0.00E+00	1.57E+03
	Natural gas	1.62E+00	3.55E+00	6.53E+01	0.00E+00	3.96E+02	1.50E+01	1.07E+02	3.23E+00	1.44E+02	0.00E+00	3.14E+01	0.00E+00	4.64E+04
	Uranium	2.20E-03	2.26E-01	1.31E+01	0.00E+00	3.12E+02	5.77E-02	6.78E+00	6.62E-03	9.14E+00	0.00E+00	5.39E+00	0.00E+00	5.16E+03
	Total resource energy	2.89E+00	3.58E+01	1.80E+02	0.00E+00	1.74E+03	2.77E+01	1.08E+03	3.49E+01	1.45E+03	0.00E+00	1.33E+02	0.00E+00	1.85E+05
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	18.5:1

Table C-5: Full Life Cycle Metrics for Onshore Advanced Wind Power in Alternate Units

Category (Units)	Material or Energy Flow	ECF																	
		Switchyard	Trunkline				Recycling			Domestic Turbine MFG					Foreign Turbine MFG				
			Electricity	Aluminum Sheet	Cold Rolled Steel	Concrete	Aluminum	Copper	Steel	Rotor	Tower	Transport	Nacelle	Transformer	Rotor	Tower	Transport	Nacelle	Transformer
GHG (lb/MWh)	CO_2	1.323E-01	1.352E-01	8.585E-01	8.379E-01	1.081E-01	-3.060E-01	-8.070E-01	-5.703E+00	2.668E+00	3.850E+00	6.180E-07	5.352E+00	2.640E-01	3.261E+00	4.705E+00	9.605E+00	6.542E+00	3.23E-01
	N_2O	2.795E-06	2.135E-06	1.859E-05	5.451E-06	0.000E+00	-4.731E-07	-3.531E-05	-5.872E-06	6.741E-04	2.800E-05	1.631E-11	1.643E-04	4.382E-06	8.239E-04	3.423E-05	2.365E-04	2.008E-04	5.36E-06
	CH_4	2.165E-04	4.088E-04	1.360E-03	9.822E-04	0.000E+00	-1.292E-03	-1.108E-03	-2.408E-03	8.806E-03	5.103E-03	1.802E-09	1.285E-02	5.112E-04	1.076E-02	6.237E-03	1.088E-02	1.571E-02	6.25E-04
	SF_6	3.792E-09	2.846E-08	1.086E-10	6.081E-12	0.000E+00	0.000E+00	-4.018E-11	0.000E+00	1.120E-07	6.709E-08	1.980E-18	6.730E-07	4.393E-12	1.369E-07	8.200E-08	3.013E-12	8.226E-07	5.37E-12
	CO_2e (IPCC 2007 100-yr GWP)	1.386E-01	1.467E-01	8.981E-01	8.641E-01	1.081E-01	-3.385E-01	-8.453E-01	-5.765E+00	3.092E+00	3.987E+00	6.680E-07	5.738E+00	2.781E-01	3.779E+00	4.873E+00	9.947E+00	7.013E+00	3.40E-01
Other Air (lb/MWh)	Pb	7.160E-07	8.955E-10	1.137E-07	1.512E-06	0.000E+00	-6.719E-08	-2.373E-05	-3.416E-08	4.358E-07	6.374E-06	1.545E-13	1.001E-06	2.260E-06	5.327E-07	7.790E-06	3.615E-08	1.223E-06	2.76E-06
	Hg	1.107E-09	2.501E-09	7.974E-09	1.934E-09	0.000E+00	-2.114E-09	-5.393E-09	-1.835E-08	3.189E-08	1.405E-08	8.651E-15	1.224E-07	2.827E-09	3.898E-08	1.717E-08	3.000E-09	1.496E-07	3.46E-09
	NH_3	5.276E-07	1.277E-07	3.787E-06	2.724E-06	0.000E+00	-1.760E-07	-5.725E-06	-3.331E-06	5.749E-06	1.178E-05	4.903E-12	8.931E-06	1.322E-06	7.026E-06	1.440E-05	3.488E-04	1.092E-05	1.62E-06
	CO	7.356E-04	2.621E-05	7.910E-03	7.955E-03	1.393E-04	-2.348E-04	-7.642E-04	-6.809E-02	3.348E-03	3.359E-02	1.480E-09	6.022E-03	1.470E-03	4.092E-03	4.105E-02	2.613E-02	7.360E-03	1.80E-03
	NO_X	2.354E-04	2.071E-04	1.172E-03	1.587E-03	3.299E-04	-4.761E-04	-1.833E-03	-6.296E-03	4.967E-03	7.176E-03	5.068E-10	8.179E-03	6.345E-04	6.071E-03	8.771E-03	2.342E-02	9.997E-03	7.75E-04
	SO_2	4.344E-04	4.327E-04	3.218E-03	1.160E-03	2.514E-04	-2.521E-03	-2.914E-03	-1.098E-02	9.905E-03	5.909E-03	9.271E-10	1.634E-02	1.160E-03	1.211E-02	7.222E-03	4.206E-03	1.998E-02	1.42E-03
	VOC	3.212E-05	3.663E-05	1.570E-04	1.195E-04	0.000E+00	-9.881E-05	-2.351E-04	-2.389E-03	4.093E-03	5.900E-04	6.831E-10	1.745E-03	1.156E-04	5.002E-03	7.211E-04	4.490E-03	2.133E-03	1.41E-04
	PM	1.999E-04	5.539E-06	1.558E-03	5.117E-04	3.221E-04	-6.095E-05	-1.192E-03	-8.356E-04	3.852E-03	2.169E-03	4.507E-11	2.018E-03	3.717E-04	4.708E-03	2.651E-03	3.683E-05	2.467E-03	4.54E-04
Solid Waste (lb/MWh)	Heavy metals to industrial soil	1.188E-04	8.900E-04	3.826E-06	1.437E-06	0.000E+00	0.000E+00	-4.138E-06	0.000E+00	3.508E-03	2.103E-03	5.073E-12	2.105E-02	8.213E-07	4.288E-03	2.571E-03	2.571E-05	2.573E-02	1.00E-06
	Heavy metals to agricultural soil	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.00E+00
Water Use (gal/MWh)	Withdrawal	1.725E-01	5.627E-01	5.885E-01	2.310E-01	5.552E-03	0.000E+00	-1.701E+00	0.000E+00	3.843E+00	2.299E+00	2.319E-07	1.507E+01	1.846E-01	4.696E+00	2.810E+00	7.092E-01	1.842E+01	2.26E-01
	Discharge	1.454E-01	5.193E-01	4.207E-01	2.121E-01	0.000E+00	0.000E+00	-1.460E+00	0.000E+00	3.207E+00	2.118E+00	3.732E-11	1.321E+01	1.545E-01	3.920E+00	2.588E+00	1.725E-01	1.614E+01	1.89E-01
	Consumption	2.707E-02	4.337E-02	1.678E-01	1.883E-02	5.552E-03	0.000E+00	-2.414E-01	0.000E+00	6.355E-01	1.816E-01	2.318E-07	1.865E+00	3.009E-02	7.767E-01	2.219E-01	5.367E-01	2.279E+00	3.68E-02
Water Quality (lb/MWh)	Aluminum	2.550E-09	1.919E-08	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	7.602E-08	4.521E-08	0.000E+00	4.548E-07	0.000E+00	9.291E-08	5.526E-08	0.000E+00	5.559E-07	0.00E+00
	Arsenic (+V)	9.117E-08	2.080E-07	2.960E-08	6.755E-09	0.000E+00	-8.288E-08	-2.151E-08	0.000E+00	9.431E-07	5.187E-07	4.774E-12	4.963E-06	3.219E-07	1.153E-06	6.340E-07	3.330E-05	6.066E-06	3.93E-07
	Copper (+II)	3.025E-07	2.477E-07	5.389E-08	2.587E-08	0.000E+00	-6.467E-08	-6.100E-06	0.000E+00	1.540E-06	6.928E-07	7.011E-12	6.071E-06	1.010E-06	1.882E-06	8.468E-07	4.879E-05	7.420E-06	1.23E-06
	Iron	2.254E-05	4.150E-06	1.918E-04	3.759E-05	0.000E+00	-2.415E-05	-9.765E-05	-6.719E-04	5.000E-04	1.682E-04	3.655E-10	5.860E-04	4.277E-05	6.111E-04	2.056E-04	2.488E-03	7.162E-04	5.23E-05
	Lead (+II)	3.633E-07	1.015E-08	9.705E-08	1.394E-08	0.000E+00	-1.229E-07	-5.192E-06	-3.811E-04	3.735E-07	8.266E-08	1.610E-11	4.094E-07	1.525E-06	4.565E-07	1.010E-07	1.121E-04	5.004E-07	1.86E-06
	Manganese (+II)	8.585E-08	3.189E-07	4.290E-07	3.488E-07	0.000E+00	0.000E+00	-2.410E-07	0.000E+00	1.896E-06	2.221E-06	3.768E-14	8.459E-06	5.920E-08	2.317E-06	2.715E-06	1.494E-07	1.034E-05	7.24E-08
	Nickel (+II)	2.904E-06	9.501E-06	3.305E-08	3.925E-08	0.000E+00	-6.618E-08	-7.356E-07	-4.150E-06	3.767E-05	2.255E-05	1.271E-10	2.248E-04	8.278E-06	4.604E-05	2.757E-05	8.876E-04	2.747E-04	1.01E-05
	Strontium	9.316E-08	6.907E-09	6.205E-07	1.662E-06	0.000E+00	-2.015E-05	-8.003E-07	0.000E+00	2.301E-05	7.022E-06	2.251E-13	5.742E-06	2.840E-06	2.812E-05	8.583E-06	8.177E-07	7.019E-06	3.47E-06
	Zinc (+II)	3.582E-06	2.645E-06	4.142E-08	3.794E-08	0.000E+00	-2.231E-07	-1.453E-05	1.818E-04	1.086E-05	6.392E-06	2.206E-10	6.267E-05	1.559E-05	1.327E-05	7.812E-06	1.540E-03	7.660E-05	1.91E-05
	Ammonium/ammonia	3.438E-06	2.217E-05	2.906E-06	1.718E-06	0.000E+00	-1.112E-08	-8.614E-06	3.444E-02	1.005E-04	5.948E-05	3.564E-12	5.527E-04	9.938E-07	1.228E-04	7.270E-05	2.975E-06	6.755E-04	1.21E-06
	Hydrogen chloride	6.005E-12	1.621E-12	5.663E-11	7.139E-12	0.000E+00	0.000E+00	-3.499E-11	0.000E+00	5.620E-10	3.390E-11	4.750E-17	1.865E-09	6.653E-12	6.869E-10	4.144E-11	3.134E-10	2.280E-09	8.13E-12
	Nitrogen (as total N)	8.920E-09	6.711E-08	0.000E+00	0.000E+00	0.000E+00	-2.763E-08	0.000E+00	-1.948E-03	2.787E-07	1.582E-07	0.000E+00	1.609E-06	1.360E-08	3.406E-07	1.933E-07	0.000E+00	1.967E-06	1.66E-08
	Phosphate	5.146E-08	7.912E-10	1.776E-07	8.978E-07	0.000E+00	0.000E+00	-9.079E-07	2.092E-05	4.346E-06	3.785E-06	6.921E-14	2.998E-06	1.567E-07	5.311E-06	4.626E-06	3.700E-08	3.664E-06	1.91E-07
	Phosphorus	2.055E-06	1.495E-07	2.970E-08	1.134E-08	0.000E+00	0.000E+00	-3.403E-08	-3.924E-05	6.287E-07	4.001E-07	1.614E-10	3.589E-06	1.031E-05	7.684E-07	4.891E-07	1.116E-03	4.386E-06	1.26E-05
Resource Energy (Btu/MWh)	Crude oil	2.555E+02	2.090E+01	1.322E+03	4.063E+02	0.000E+00	-7.613E+01	-2.561E+03	-3.197E+03	2.017E+03	1.762E+03	6.680E-03	1.932E+03	7.559E+02	2.465E+03	2.153E+03	4.375E+04	2.361E+03	9.24E+02
	Hard coal	1.643E+02	1.836E+02	1.003E+03	3.693E+03	0.000E+00	-4.953E+02	-5.554E+02	-2.257E+04	4.011E+03	1.600E+04	3.916E-04	9.238E+03	7.551E+02	4.903E+03	1.955E+04	6.422E+02	1.129E+04	9.23E+02
	Lignite	4.559E+01	9.672E-02	4.912E+02	9.246E+01	0.000E+00	0.000E+00	-2.786E+02	0.000E+00	1.974E+02	3.899E+02	2.114E-05	3.014E+02	3.874E+01	2.413E+02	4.765E+02	2.352E+01	3.684E+02	4.73E+01
	Natural gas	1.694E+02	2.603E+02	1.193E+03	5.398E+02	0.000E+00	-1.661E+03	-1.116E+03	-2.621E+03	8.682E+03	2.888E+03	1.058E-03	9.205E+03	3.512E+02	1.061E+04	3.530E+03	4.924E+03	1.125E+04	4.29E+02
	Uranium	1.017E+02	3.545E-01	1.106E+03	1.081E+02	0.000E+00	0.000E+00	-6.279E+02	0.000E+00	1.155E+03	4.562E+02	9.630E-05	1.521E+03	9.094E+01	1.412E+03	5.576E+02	3.128E+02	1.859E+03	1.11E+02
	Total resource energy	7.365E+02	4.653E+02	5.115E+03	4.840E+03	0.000E+00	-2.233E+03	-5.138E+03	-2.838E+04	1.606E+04	2.149E+04	8.247E-03	2.220E+04	1.992E+03	1.963E+04	2.627E+04	4.966E+04	2.713E+04	2.43E+03
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table C-5: Full Life Cycle Metrics for Onshore Advanced Wind Power in Alternate Units (continued)

Category (Units)	Material or Energy Flow	ECF											PT	Total
		Wind Farm Operation					Wind Farm Construction					Landfill Waste	T&D	
		Electricity	Diesel Upstream	Lubricating Oil	Wind Farm	Cable	Concrete	Steel	Diesel Upstream	Wind Farm	Gravel Road			
GHG (lb/MWh)	CO_2	8.40E-04	1.16E-03	2.43E-02	5.66E-03	7.26E-02	1.39E-02	4.53E-02	6.99E-03	4.69E-02	2.29E-01	3.09E-02	0.00E+00	3.23E+01
	N_2O	1.33E-08	2.27E-08	1.28E-04	1.47E-07	2.18E-06	1.24E-07	1.37E-05	7.54E-09	9.21E-07	5.94E-06	2.56E-07	0.00E+00	2.31E-03
	CH_4	2.54E-06	7.39E-06	6.67E-03	8.12E-07	1.09E-04	2.36E-05	1.31E-04	2.99E-06	2.99E-04	3.29E-05	9.11E-04	0.00E+00	7.78E-02
	SF_6	1.77E-10	2.17E-15	2.38E-13	0.00E+00	7.07E-12	1.62E-09	1.66E-14	3.26E-16	8.80E-14	0.00E+00	7.69E-15	3.16E-04	3.18E-04
	CO_2e (IPCC 2007 100-yr GWP)	9.11E-04	1.35E-03	2.29E-01	5.73E-03	7.60E-02	1.46E-02	5.27E-02	7.07E-03	5.46E-02	2.32E-01	5.37E-02	7.20E+00	4.22E+01
Other Air (lb/MWh)	Pb	5.56E-12	2.61E-11	8.14E-10	0.00E+00	8.17E-07	7.44E-11	1.99E-10	4.59E-11	1.06E-09	0.00E+00	8.49E-10	0.00E+00	1.74E-06
	Hg	1.55E-11	2.16E-12	1.18E-10	0.00E+00	6.03E-10	1.44E-10	1.65E-11	2.27E-11	8.76E-11	0.00E+00	8.56E-11	0.00E+00	3.72E-07
	NH_3	7.93E-10	1.48E-08	9.83E-04	0.00E+00	3.94E-07	7.77E-09	2.17E-05	4.16E-09	5.98E-07	0.00E+00	4.84E-08	0.00E+00	1.41E-03
	CO	1.63E-07	1.10E-06	2.05E-02	3.16E-05	4.41E-04	9.75E-06	1.59E-03	8.34E-05	4.47E-05	1.28E-03	1.58E-04	0.00E+00	9.67E-02
	NO_X	1.29E-06	1.51E-06	5.66E-04	2.56E-06	1.24E-04	3.07E-05	4.63E-03	7.72E-06	6.13E-05	0.00E+00	1.84E-04	0.00E+00	7.05E-02
	SO_2	2.69E-06	3.03E-06	1.70E-04	5.39E-08	2.68E-04	3.92E-05	2.84E-05	1.35E-05	1.23E-04	2.18E-06	8.11E-05	0.00E+00	6.81E-02
	VOC	2.28E-07	3.24E-06	1.18E-03	1.20E-06	1.63E-05	2.13E-06	1.35E-04	2.93E-06	1.31E-04	0.00E+00	4.32E-05	0.00E+00	1.82E-02
	PM	3.44E-08	2.66E-08	1.29E-03	6.01E-03	1.23E-04	1.87E-05	9.91E-03	1.03E-06	1.08E-06	0.00E+00	5.09E-04	0.00E+00	3.71E-02
Solid Waste (lb/MWh)	Heavy metals to industrial soil	5.53E-06	1.85E-08	2.29E-07	0.00E+00	3.42E-07	5.07E-05	1.42E-07	1.39E-10	7.51E-07	0.00E+00	6.65E-07	0.00E+00	6.04E-02
	Heavy metals to agricultural soil	0.00E+00	0.00E+00	9.53E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.53E-08
Water Use (gal/MWh)	Withdrawal	3.49E-03	5.11E-04	8.52E-03	0.00E+00	8.90E-02	3.24E-02	3.91E-03	5.85E-06	2.07E-02	0.00E+00	8.16E-02	0.00E+00	4.84E+01
	Discharge	3.23E-03	1.24E-04	8.86E-03	0.00E+00	7.20E-02	2.96E-02	9.50E-04	7.18E-07	5.04E-03	0.00E+00	1.81E-01	0.00E+00	4.18E+01
	Consumption	2.69E-04	3.87E-04	-3.41E-04	0.00E+00	1.71E-02	2.82E-03	2.96E-03	5.13E-06	1.57E-02	0.00E+00	-9.97E-02	0.00E+00	6.52E+00
Water Quality (lb/MWh)	Aluminum	1.19E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.09E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.30E-06
	Arsenic (+V)	1.29E-09	2.40E-08	1.06E-09	0.00E+00	2.29E-09	1.19E-08	1.83E-07	7.50E-13	9.73E-07	0.00E+00	5.23E-10	0.00E+00	4.97E-05
	Copper (+II)	1.54E-09	3.52E-08	2.46E-08	0.00E+00	2.11E-07	1.42E-08	2.69E-07	6.45E-12	1.43E-06	0.00E+00	1.47E-08	0.00E+00	6.59E-05
	Iron	2.58E-08	1.79E-06	3.81E-06	0.00E+00	1.34E-05	2.43E-07	1.37E-05	8.24E-07	7.27E-05	0.00E+00	9.95E-06	0.00E+00	4.95E-03
	Lead (+II)	6.30E-11	8.09E-08	2.07E-07	0.00E+00	1.83E-07	5.94E-10	6.18E-07	4.66E-07	3.28E-06	0.00E+00	8.32E-10	0.00E+00	-2.64E-04
	Manganese (+II)	1.98E-09	1.08E-10	5.21E-09	0.00E+00	3.07E-08	1.82E-08	8.23E-10	2.71E-12	4.37E-09	0.00E+00	8.79E-09	0.00E+00	2.92E-05
	Nickel (+II)	5.90E-08	6.40E-07	2.07E-07	0.00E+00	2.69E-08	5.42E-07	4.89E-06	5.08E-09	2.59E-05	0.00E+00	8.33E-10	0.00E+00	1.58E-03
	Strontium	4.29E-11	5.90E-10	2.30E-08	0.00E+00	5.99E-08	6.79E-10	4.50E-09	5.03E-11	2.39E-08	0.00E+00	1.34E-08	0.00E+00	6.82E-05
	Zinc (+II)	1.64E-08	1.11E-06	1.04E-07	0.00E+00	4.99E-07	1.51E-07	8.48E-06	-2.22E-07	4.50E-05	0.00E+00	5.59E-10	0.00E+00	1.98E-03
	Ammonium/ammonia	1.38E-07	2.15E-09	5.84E-06	0.00E+00	4.47E-07	1.26E-06	1.64E-08	-4.22E-05	8.69E-08	0.00E+00	2.26E-07	0.00E+00	3.60E-02
	Hydrogen chloride	1.01E-14	2.26E-13	7.41E-13	0.00E+00	4.17E-12	9.92E-14	1.73E-12	1.20E-15	9.16E-12	0.00E+00	9.18E-14	0.00E+00	5.85E-09
	Nitrogen (as total N)	4.17E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.83E-09	0.00E+00	2.38E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.94E-03
	Phosphate	4.91E-12	2.67E-11	1.89E-05	0.00E+00	4.04E-08	7.85E-11	2.04E-10	-2.56E-08	1.08E-09	0.00E+00	2.12E-08	0.00E+00	6.52E-05
	Phosphorus	9.29E-10	8.05E-07	1.78E-09	0.00E+00	2.73E-09	8.81E-09	6.14E-06	4.81E-08	3.26E-05	0.00E+00	1.42E-07	0.00E+00	1.15E-03
Resource Energy (Btu/MWh)	Crude oil	1.30E-01	3.16E+01	7.98E+01	0.00E+00	1.57E+02	2.10E+00	2.41E+02	4.07E+00	1.28E+03	0.00E+00	1.09E+02	0.00E+00	5.62E+04
	Hard coal	1.14E+00	4.63E-01	1.44E+01	0.00E+00	7.16E+01	1.05E+01	3.54E+00	2.76E+01	1.88E+01	0.00E+00	1.37E+01	0.00E+00	4.89E+04
	Lignite	6.01E-04	1.70E-02	7.08E+00	0.00E+00	3.53E+01	1.67E-02	1.30E-01	1.97E-03	6.87E-01	0.00E+00	4.80E+00	0.00E+00	2.48E+03
	Natural gas	1.62E+00	3.55E+00	6.53E+01	0.00E+00	1.01E+02	1.50E+01	2.71E+01	3.23E+00	1.44E+02	0.00E+00	4.16E+01	0.00E+00	4.90E+04
	Uranium	2.20E-03	2.26E-01	1.31E+01	0.00E+00	7.95E+01	5.77E-02	1.72E+00	6.62E-03	9.14E+00	0.00E+00	7.16E+00	0.00E+00	8.27E+03
	Total resource energy	2.89E+00	3.58E+01	1.80E+02	0.00E+00	4.44E+02	2.77E+01	2.74E+02	3.49E+01	1.45E+03	0.00E+00	1.77E+02	0.00E+00	1.65E+05
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	20.7:1

Table C-6: Full Life Cycle Metrics for Offshore Wind Power in Alternate Units

Category (Units)	Material or Energy Flow	ECF																	
		Switchyard	Trunkline				Recycling			Domestic Turbine MFG					Foreign Turbine MFG				
			Electricity	Aluminum Sheet	Cold Rolled Steel	Concrete	Aluminum	Copper	Steel	Rotor	Tower	Transport	Nacelle	Transformer	Rotor	Tower	Transport	Nacelle	Transformer
GHG (lb/MWh)	CO_2	1.32E-01	1.35E-01	8.59E-01	8.38E-01	1.08E-01	-2.76E-01	-6.16E-01	-3.82E+00	1.87E+00	2.70E+00	4.75E-07	4.13E+00	2.06E-01	2.29E+00	3.30E+00	8.32E+00	5.05E+00	2.52E-01
	N_2O	2.80E-06	2.14E-06	1.86E-05	5.45E-06	0.00E+00	-4.27E-07	-2.70E-05	-3.94E-06	4.67E-04	1.96E-05	1.25E-11	1.28E-04	3.43E-06	5.71E-04	2.40E-05	2.05E-04	1.56E-04	4.19E-06
	CH_4	2.16E-04	4.09E-04	1.36E-03	9.82E-04	0.00E+00	-1.17E-03	-8.46E-04	-1.61E-03	6.16E-03	3.58E-03	1.39E-09	1.01E-02	4.00E-04	7.52E-03	4.38E-03	9.42E-03	1.23E-02	4.89E-04
	SF_6	3.79E-09	2.85E-08	1.09E-10	6.08E-12	0.00E+00	0.00E+00	-3.07E-11	0.00E+00	7.99E-08	4.71E-08	1.52E-18	5.35E-07	3.43E-12	9.76E-08	5.75E-08	2.61E-12	6.54E-07	4.19E-12
	CO_2e (IPCC 2007 100-yr GWP)	1.39E-01	1.47E-01	8.98E-01	8.64E-01	1.08E-01	-3.05E-01	-6.45E-01	-3.86E+00	2.17E+00	2.80E+00	5.14E-07	4.43E+00	2.17E-01	2.65E+00	3.42E+00	8.62E+00	5.42E+00	2.66E-01
Other Air (lb/MWh)	Pb	7.16E-07	8.96E-10	1.14E-07	1.51E-06	0.00E+00	-6.06E-08	-1.81E-05	-2.29E-08	3.08E-07	4.47E-06	1.19E-13	7.75E-07	1.77E-06	3.76E-07	5.47E-06	3.13E-08	9.48E-07	2.16E-06
	Hg	1.11E-09	2.50E-09	7.97E-09	1.93E-09	0.00E+00	-1.91E-09	-4.12E-09	-1.23E-08	2.25E-08	9.85E-09	6.65E-15	9.00E-08	2.21E-09	2.75E-08	1.20E-08	2.60E-09	1.10E-07	2.70E-09
	NH_3	5.28E-07	1.28E-07	3.79E-06	2.72E-06	0.00E+00	-1.59E-07	-4.37E-06	-2.23E-06	4.03E-06	8.27E-06	3.77E-12	6.72E-06	1.03E-06	4.92E-06	1.01E-05	3.02E-04	8.21E-06	1.26E-06
	CO	7.36E-04	2.62E-05	7.91E-03	7.96E-03	1.39E-04	-2.12E-04	-5.84E-04	-4.57E-02	2.36E-03	2.36E-02	1.14E-09	4.72E-03	1.15E-03	2.89E-03	2.88E-02	2.26E-02	5.77E-03	1.40E-03
	NO_X	2.35E-04	2.07E-04	1.17E-03	1.59E-03	3.30E-04	-4.29E-04	-1.40E-03	-4.22E-03	3.47E-03	5.03E-03	3.90E-10	6.32E-03	4.96E-04	4.24E-03	6.15E-03	2.03E-02	7.72E-03	6.06E-04
	SO_2	4.34E-04	4.33E-04	3.22E-03	1.16E-03	2.51E-04	-2.27E-03	-2.23E-03	-7.36E-03	6.93E-03	4.15E-03	7.13E-10	1.25E-02	9.06E-04	8.47E-03	5.07E-03	3.64E-03	1.53E-02	1.11E-03
	VOC	3.21E-05	3.66E-05	1.57E-04	1.20E-04	0.00E+00	-8.91E-05	-1.80E-04	-1.60E-03	2.84E-03	4.14E-04	5.25E-10	1.36E-03	9.08E-05	3.47E-03	5.06E-04	3.89E-03	1.66E-03	1.11E-04
	PM	2.00E-04	5.54E-06	1.56E-03	5.12E-04	3.22E-04	-5.50E-05	-9.10E-04	-5.60E-04	2.69E-03	1.52E-03	3.47E-11	1.55E-03	2.90E-04	3.28E-03	1.86E-03	3.19E-05	1.90E-03	3.55E-04
Solid Waste (lb/MWh)	Heavy metals to industrial soil	1.19E-04	8.90E-04	3.83E-06	1.44E-06	0.00E+00	0.00E+00	-3.16E-06	0.00E+00	2.50E-03	1.48E-03	3.90E-12	1.67E-02	6.45E-07	3.06E-03	1.80E-03	2.23E-05	2.05E-02	7.88E-07
	Heavy metals to agricultural soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (gal/MWh)	Withdrawal	1.72E-01	5.63E-01	5.89E-01	2.31E-01	5.55E-03	0.00E+00	-1.30E+00	0.00E+00	2.71E+00	1.61E+00	1.78E-07	1.18E+01	1.44E-01	3.32E+00	1.97E+00	6.14E-01	1.45E+01	1.76E-01
	Discharge	1.45E-01	5.19E-01	4.21E-01	2.12E-01	0.00E+00	0.00E+00	-1.11E+00	0.00E+00	2.27E+00	1.49E+00	2.87E-11	1.04E+01	1.21E-01	2.77E+00	1.82E+00	1.49E-01	1.27E+01	1.48E-01
	Consumption	2.71E-02	4.34E-02	1.68E-01	1.88E-02	5.55E-03	0.00E+00	-1.84E-01	0.00E+00	4.47E-01	1.27E-01	1.78E-07	1.40E+00	2.36E-02	5.47E-01	1.56E-01	4.65E-01	1.71E+00	2.88E-02
Water Quality (lb/MWh)	Aluminum	2.55E-09	1.92E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.42E-08	3.17E-08	0.00E+00	3.62E-07	0.00E+00	6.63E-08	3.88E-08	0.00E+00	4.42E-07	0.00E+00
	Arsenic (+V)	9.12E-08	2.08E-07	2.96E-08	6.76E-09	0.00E+00	-7.47E-08	-1.64E-08	0.00E+00	6.71E-07	3.64E-07	3.67E-12	3.94E-06	2.56E-07	8.20E-07	4.45E-07	2.88E-05	4.82E-06	3.12E-07
	Copper (+II)	3.03E-07	2.48E-07	5.39E-08	2.59E-08	0.00E+00	-5.83E-08	-4.66E-06	0.00E+00	1.09E-06	4.86E-07	5.39E-12	4.81E-06	7.95E-07	1.33E-06	5.94E-07	4.23E-05	5.88E-06	9.71E-07
	Iron	2.25E-05	4.15E-06	1.92E-04	3.76E-05	0.00E+00	-2.18E-05	-7.46E-05	-4.50E-04	3.48E-04	1.18E-04	2.81E-10	4.17E-04	3.37E-05	4.26E-04	1.44E-04	2.16E-03	5.10E-04	4.12E-05
	Lead (+II)	3.63E-07	1.01E-08	9.70E-08	1.39E-08	0.00E+00	-1.11E-07	-3.96E-06	-2.56E-04	2.61E-07	5.80E-08	1.24E-11	3.12E-07	1.20E-06	3.19E-07	7.09E-08	9.71E-05	3.81E-07	1.47E-06
	Manganese (+II)	8.58E-08	3.19E-07	4.29E-07	3.49E-07	0.00E+00	0.00E+00	-1.84E-07	0.00E+00	1.34E-06	1.56E-06	2.90E-14	6.66E-06	4.63E-08	1.64E-06	1.90E-06	1.29E-07	8.14E-06	5.65E-08
	Nickel (+II)	2.90E-06	9.50E-06	3.30E-08	3.92E-08	0.00E+00	-5.97E-08	-5.62E-07	-2.78E-06	2.69E-05	1.58E-05	9.78E-11	1.79E-04	6.58E-06	3.28E-05	1.93E-05	7.69E-04	2.18E-04	8.04E-06
	Strontium	9.32E-08	6.91E-09	6.21E-07	1.66E-06	0.00E+00	-1.82E-05	-6.11E-07	0.00E+00	1.62E-05	4.93E-06	1.73E-13	4.39E-06	2.22E-06	1.98E-05	6.02E-06	7.08E-07	5.37E-06	2.71E-06
	Zinc (+II)	3.58E-06	2.64E-06	4.14E-08	3.79E-08	0.00E+00	-2.01E-07	-1.11E-05	1.22E-04	7.74E-06	4.48E-06	1.70E-10	4.98E-05	1.24E-05	9.46E-06	5.48E-06	1.33E-03	6.09E-05	1.51E-05
	Ammonium/ammonia	3.44E-06	2.22E-05	2.91E-06	1.72E-06	0.00E+00	-1.00E-08	-6.58E-06	2.31E-02	7.14E-05	4.17E-05	2.74E-12	4.38E-04	7.77E-07	8.73E-05	5.10E-05	2.58E-06	5.35E-04	9.49E-07
	Hydrogen chloride	6.00E-12	1.62E-12	5.66E-11	7.14E-12	0.00E+00	0.00E+00	-2.67E-11	0.00E+00	3.94E-10	2.38E-11	3.65E-17	1.26E-09	5.23E-12	4.82E-10	2.91E-11	2.72E-10	1.55E-09	6.39E-12
	Nitrogen (as total N)	8.92E-09	6.71E-08	0.00E+00	0.00E+00	0.00E+00	-2.49E-08	0.00E+00	-1.31E-03	1.99E-07	1.11E-07	0.00E+00	1.28E-06	1.06E-08	2.43E-07	1.36E-07	0.00E+00	1.56E-06	1.30E-08
	Phosphate	5.15E-08	7.91E-10	1.78E-07	8.98E-07	0.00E+00	0.00E+00	-6.93E-07	1.40E-05	3.02E-06	2.66E-06	5.32E-14	2.13E-06	1.22E-07	3.69E-06	3.25E-06	3.21E-08	2.61E-06	1.50E-07
	Phosphorus	2.06E-06	1.50E-07	2.97E-08	1.13E-08	0.00E+00	0.00E+00	-2.60E-08	-2.63E-05	4.48E-07	2.81E-07	1.24E-10	2.85E-06	8.19E-06	5.47E-07	3.43E-07	9.66E-04	3.48E-06	1.00E-05
Resource Energy (Btu/MWh)	Crude oil	2.55E+02	2.09E+01	1.32E+03	4.06E+02	0.00E+00	-6.87E+01	-1.96E+03	-2.14E+03	1.40E+03	1.24E+03	5.14E-03	1.42E+03	5.96E+02	1.72E+03	1.51E+03	3.79E+04	1.74E+03	7.28E+02
	Hard coal	1.64E+02	1.84E+02	1.00E+03	3.69E+03	0.00E+00	-4.47E+02	-4.24E+02	-1.51E+04	2.83E+03	1.12E+04	3.01E-04	7.13E+03	5.90E+02	3.46E+03	1.37E+04	5.56E+02	8.72E+03	7.21E+02
	Lignite	4.56E+01	9.67E-02	4.91E+02	9.25E+01	0.00E+00	0.00E+00	-2.13E+02	0.00E+00	1.39E+02	2.74E+02	1.63E-05	2.17E+02	3.03E+01	1.69E+02	3.34E+02	2.04E+01	2.66E+02	3.70E+01
	Natural gas	1.69E+02	2.60E+02	1.19E+03	5.40E+02	0.00E+00	-1.50E+03	-8.52E+02	-1.76E+03	6.05E+03	2.03E+03	8.14E-04	7.15E+03	2.75E+02	7.40E+03	2.48E+03	4.27E+03	8.73E+03	3.36E+02
	Uranium	1.02E+02	3.54E-01	1.11E+03	1.08E+02	0.00E+00	0.00E+00	-4.79E+02	0.00E+00	8.05E+02	3.20E+02	7.41E-05	1.06E+03	7.11E+01	9.84E+02	3.91E+02	2.71E+02	1.29E+03	8.68E+01
	Total resource energy	7.36E+02	4.65E+02	5.12E+03	4.84E+03	0.00E+00	-2.01E+03	-3.92E+03	-1.90E+04	1.12E+04	1.51E+04	6.34E-03	1.70E+04	1.56E+03	1.37E+04	1.84E+04	4.30E+04	2.07E+04	1.91E+03
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table C-6: Full Life Cycle Metrics for Offshore Wind Power in Alternate Units (continued)

Category (Units)	Material or Energy Flow	ECF										PT	Total
		Wind Farm Operation					Wind Farm Construction				Landfill Waste	T&D	
		Marine Vessel Idling	Marine Vessel Travel	Electricity	Marine Vessel Construction	Lubricating Oil	Submarine Cable	Gravel	Coating	Steel Plate			
GHG (lb/MWh)	CO_2	1.43E+01	1.37E+01	5.63E-04	8.84E-01	7.79E-03	1.58E-01	1.44E-03	2.96E-04	6.98E+00	2.44E-02	0.00E+00	6.15E+01
	N_2O	4.76E-05	4.58E-05	8.89E-09	2.90E-05	4.09E-05	3.91E-06	0.00E+00	9.50E-10	3.63E-04	2.02E-07	0.00E+00	2.11E-03
	CH_4	1.55E-02	1.49E-02	1.70E-06	4.40E-04	2.14E-03	1.57E-04	0.00E+00	6.50E-07	5.30E-03	7.19E-04	0.00E+00	9.27E-02
	SF_6	4.55E-12	4.37E-12	1.18E-10	1.98E-13	7.64E-14	4.31E-12	7.91E-11	0.00E+00	0.00E+00	6.07E-15	3.16E-04	3.17E-04
	CO_2e (IPCC 2007 100-yr GWP)	1.47E+01	1.41E+01	6.11E-04	9.04E-01	7.34E-02	1.63E-01	1.44E-03	3.13E-04	7.22E+00	4.24E-02	7.20E+00	7.17E+01
Other Air (lb/MWh)	Pb	5.46E-08	5.25E-08	3.73E-12	1.10E-06	2.61E-10	2.52E-06	1.40E-09	2.35E-11	1.38E-05	6.70E-10	0.00E+00	1.80E-05
	Hg	4.53E-09	4.36E-09	1.04E-11	6.92E-08	3.79E-11	6.11E-10	1.23E-10	4.61E-12	8.69E-07	6.76E-11	0.00E+00	1.22E-06
	NH_3	3.09E-05	2.97E-05	5.32E-10	3.42E-08	3.15E-04	6.71E-07	2.68E-07	3.79E-10	0.00E+00	3.82E-08	0.00E+00	7.24E-04
	CO	5.94E-02	3.75E-02	1.09E-07	5.25E-03	6.58E-03	1.94E-04	5.58E-06	1.51E-07	5.89E-02	1.25E-04	0.00E+00	2.32E-01
	NO_X	1.65E-01	1.66E-01	8.62E-07	1.61E-03	1.81E-04	3.40E-04	1.12E-05	7.72E-07	1.17E-02	1.45E-04	0.00E+00	3.96E-01
	SO_2	1.53E-02	1.47E-02	1.80E-06	2.56E-03	5.45E-05	5.77E-04	2.47E-06	2.04E-06	1.59E-02	6.40E-05	0.00E+00	1.01E-01
	VOC	6.78E-03	6.52E-03	1.53E-07	1.62E-06	3.77E-04	3.78E-05	0.00E+00	1.63E-07	-2.71E-11	3.41E-05	0.00E+00	2.66E-02
	PM	4.43E-03	5.35E-05	2.31E-08	4.87E-04	4.14E-04	1.95E-04	0.00E+00	1.77E-07	1.67E-03	4.02E-04	0.00E+00	2.22E-02
Solid Waste (lb/MWh)	Heavy metals to industrial soil	3.88E-05	3.73E-05	3.71E-06	7.37E-08	7.33E-08	6.26E-07	0.00E+00	0.00E+00	0.00E+00	5.26E-07	0.00E+00	4.72E-02
	Heavy metals to agricultural soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.05E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.05E-08
Water Use (gal/MWh)	Withdrawal	1.07E+00	1.03E+00	2.34E-03	6.59E-01	2.73E-03	2.43E-01	0.00E+00	0.00E+00	4.42E+00	6.44E-02	0.00E+00	4.46E+01
	Discharge	2.60E-01	2.50E-01	2.16E-03	3.67E-03	2.84E-03	1.58E-01	0.00E+00	0.00E+00	0.00E+00	1.43E-01	0.00E+00	3.29E+01
	Consumption	8.10E-01	7.79E-01	1.81E-04	6.55E-01	-1.09E-04	8.49E-02	0.00E+00	0.00E+00	4.42E+00	-7.88E-02	0.00E+00	1.16E+01
Water Quality (lb/MWh)	Aluminum	0.00E+00	0.00E+00	7.99E-11	1.26E-06	0.00E+00	2.44E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.52E-06
	Arsenic (+V)	5.03E-05	4.84E-05	8.66E-10	1.64E-10	3.39E-10	3.21E-09	0.00E+00	2.23E-11	0.00E+00	4.13E-10	0.00E+00	1.39E-04
	Copper (+II)	7.37E-05	7.08E-05	1.03E-09	6.36E-10	7.87E-09	6.54E-07	0.00E+00	4.60E-11	0.00E+00	1.16E-08	0.00E+00	1.99E-04
	Iron	3.76E-03	3.61E-03	1.73E-08	2.82E-05	1.22E-06	1.37E-05	0.00E+00	1.04E-08	2.26E-04	7.86E-06	0.00E+00	1.16E-02
	Lead (+II)	1.69E-04	1.63E-04	4.22E-11	2.94E-07	6.64E-08	5.66E-07	0.00E+00	3.86E-11	2.88E-06	6.57E-10	0.00E+00	1.78E-04
	Manganese (+II)	2.26E-07	2.17E-07	1.33E-09	4.08E-07	1.67E-09	1.06E-07	0.00E+00	0.00E+00	0.00E+00	6.94E-09	0.00E+00	2.35E-05
	Nickel (+II)	1.34E-03	1.29E-03	3.96E-08	4.61E-07	6.63E-08	1.69E-07	0.00E+00	1.80E-11	3.90E-07	6.58E-10	0.00E+00	3.91E-03
	Strontium	1.23E-06	1.19E-06	2.88E-11	4.72E-09	7.37E-09	1.24E-07	0.00E+00	4.99E-09	0.00E+00	1.06E-08	0.00E+00	4.84E-05
	Zinc (+II)	2.33E-03	2.24E-03	1.10E-08	3.42E-07	3.32E-08	1.58E-06	0.00E+00	1.27E-10	1.72E-06	4.42E-10	0.00E+00	6.18E-03
	Ammonium/ammonia	4.49E-06	4.32E-06	9.23E-08	3.32E-08	1.87E-06	1.12E-06	0.00E+00	3.26E-11	0.00E+00	1.78E-07	0.00E+00	2.44E-02
	Hydrogen chloride	4.73E-10	4.55E-10	6.75E-15	2.77E-13	2.38E-13	4.81E-12	0.00E+00	0.00E+00	0.00E+00	7.25E-14	0.00E+00	5.00E-09
	Nitrogen (as total N)	0.00E+00	0.00E+00	2.79E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.11E-11	0.00E+00	0.00E+00	0.00E+00	-1.30E-03
	Phosphate	5.59E-08	5.37E-08	3.29E-12	9.17E-10	6.06E-06	1.01E-07	0.00E+00	0.00E+00	0.00E+00	1.68E-08	0.00E+00	3.84E-05
	Phosphorus	1.68E-03	1.62E-03	6.23E-10	2.15E-06	5.72E-10	5.90E-08	0.00E+00	0.00E+00	2.35E-05	1.12E-07	0.00E+00	4.30E-03
Resource Energy (Btu/MWh)	Crude oil	6.61E+04	6.35E+04	8.70E-02	7.20E+02	2.56E+01	4.23E+02	0.00E+00	1.00E-01	6.58E+03	8.64E+01	0.00E+00	1.84E+05
	Hard coal	9.70E+02	9.33E+02	7.65E-01	2.77E+03	4.60E+00	1.58E+02	0.00E+00	1.45E+00	2.87E+04	1.08E+01	0.00E+00	7.16E+04
	Lignite	3.55E+01	3.42E+01	4.03E-04	2.35E+01	2.27E+00	3.47E+01	0.00E+00	0.00E+00	0.00E+00	3.80E+00	0.00E+00	2.04E+03
	Natural gas	7.44E+03	7.15E+03	1.08E+00	7.55E+02	2.09E+01	2.24E+02	0.00E+00	3.37E-01	5.73E+03	3.28E+01	0.00E+00	5.81E+04
	Uranium	4.72E+02	4.54E+02	1.48E-03	1.72E+01	4.21E+00	7.22E+01	0.00E+00	0.00E+00	0.00E+00	5.65E+00	0.00E+00	7.14E+03
	Total resource energy	7.50E+04	7.21E+04	1.94E+00	4.29E+03	5.76E+01	9.13E+02	0.00E+00	1.89E+00	4.10E+04	1.40E+02	0.00E+00	3.22E+05
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10.6:1