NATIONAL ENERGY TECHNOLOGY LABORATORY

Role of Alternative Energy Sources: Wind Technology Assessment

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U.S. DEPARTMENT OF ENERGY

Agenda

- Technology Description
- Resource, Capacity, and Growth
- Environmental Analysis
- Cost Analysis
- Barriers to Implementation
- Risks of Implementation
- Expert Opinions

Technology Description: Wind

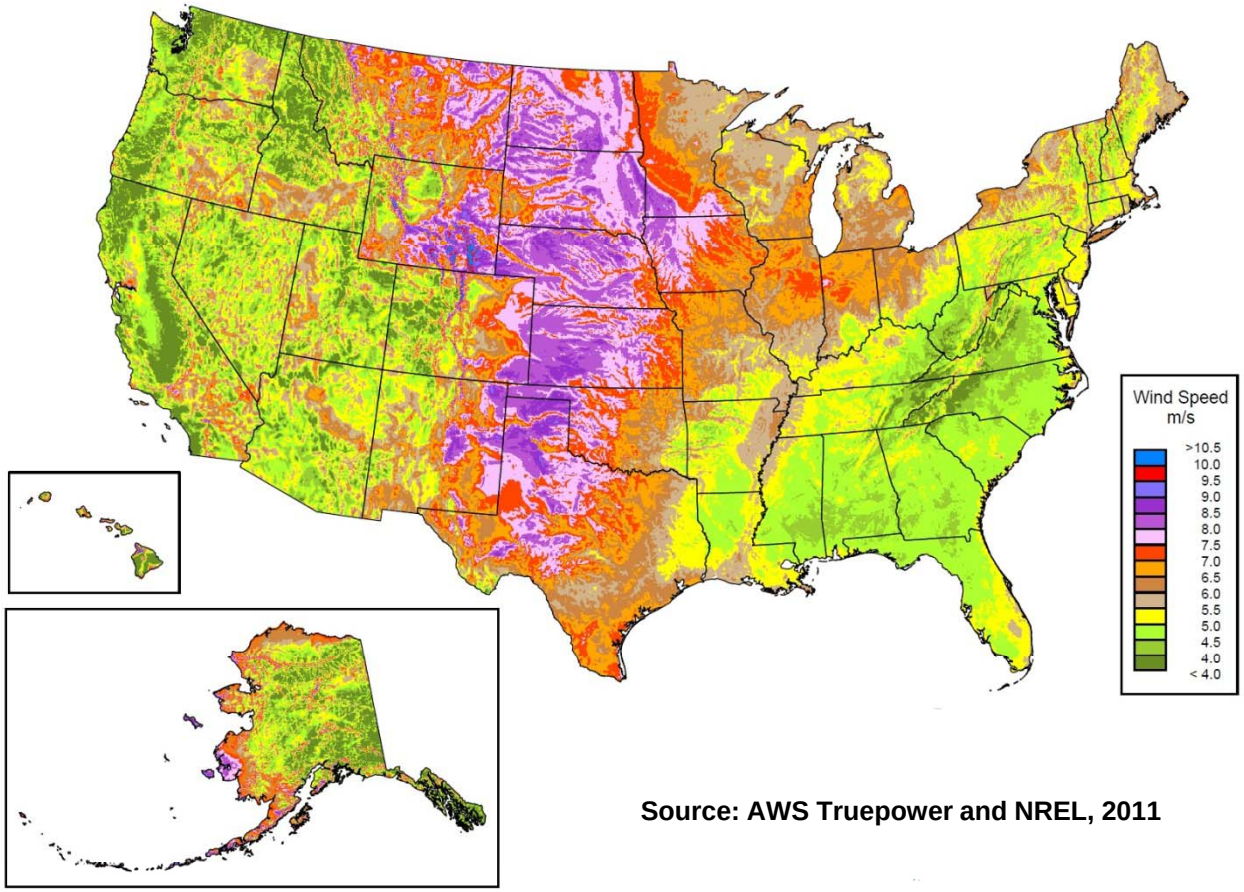
Conventional Onshore Wind Power					
Parameter	**Units**	**Low**	**Expected**	**High**	**Reference**
Total Project Capacity	MW	200			Study Assumption
Single Turbine Capacity	MW	1.5			Wiser & Bolinger, 2011
Total Number of Turbines	count	133			Calculated
Capacity Factor	%	25.0%	30.0%	33.0%	Wiser & Bolinger, 2011
Life	yrs	20	20	30	DOE, 2008

Onshore Advanced Wind Power					
Parameter	**Units**	**Low**	**Expected**	**High**	**Reference**
Total Project Capacity	MW	34			Study Assumption
Single Turbine Capacity	MW	6.0			Wiser & Bolinger, 2011
Total Number of Turbines	count	133			Calculated
Capacity Factor	%	25.0%	30.0%	33.0%	Wiser & Bolinger, 2011
Life	yrs	20	20	30	DOE, 2008

Offshore Wind Power					
Parameter	**Units**	**Low**	**Expected**	**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
Life	yrs	20	20	30	DOE, 2008

- The performance characteristics for *advanced* onshore wind power are the same as for conventional onshore, except the single turbine capacity is 6.0 MW.
- Offshore wind farms have a higher capacity factors than onshore wind farms because wind is more consistent offshore.
- Offshore wind turbines are mounted on large, steel monopiles driven into the ocean floor.
- Offshore wind farms require a sub-marine cable (12 miles in this analysis) to connect to an onshore trunkline.

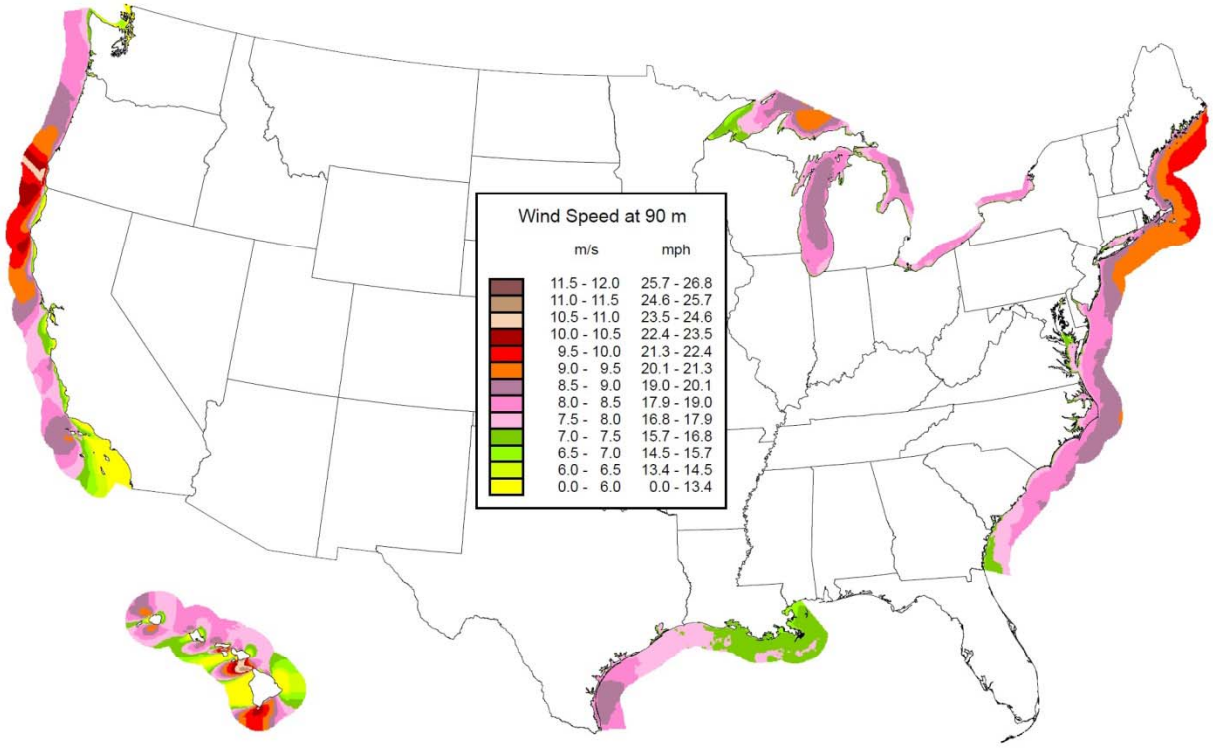
Resource, Capacity, and Growth: Onshore



Source: AWS Truepower and NREL, 2011

- High wind speeds are abundant in the southern, central, and northern plain states; across the lake states; and in southern Texas
- Wind sources are generally lacking in the South
- The U.S. can support an estimated 10,400 GW of onshore wind power, although most of this capacity is in remote areas (DOE, 2011)

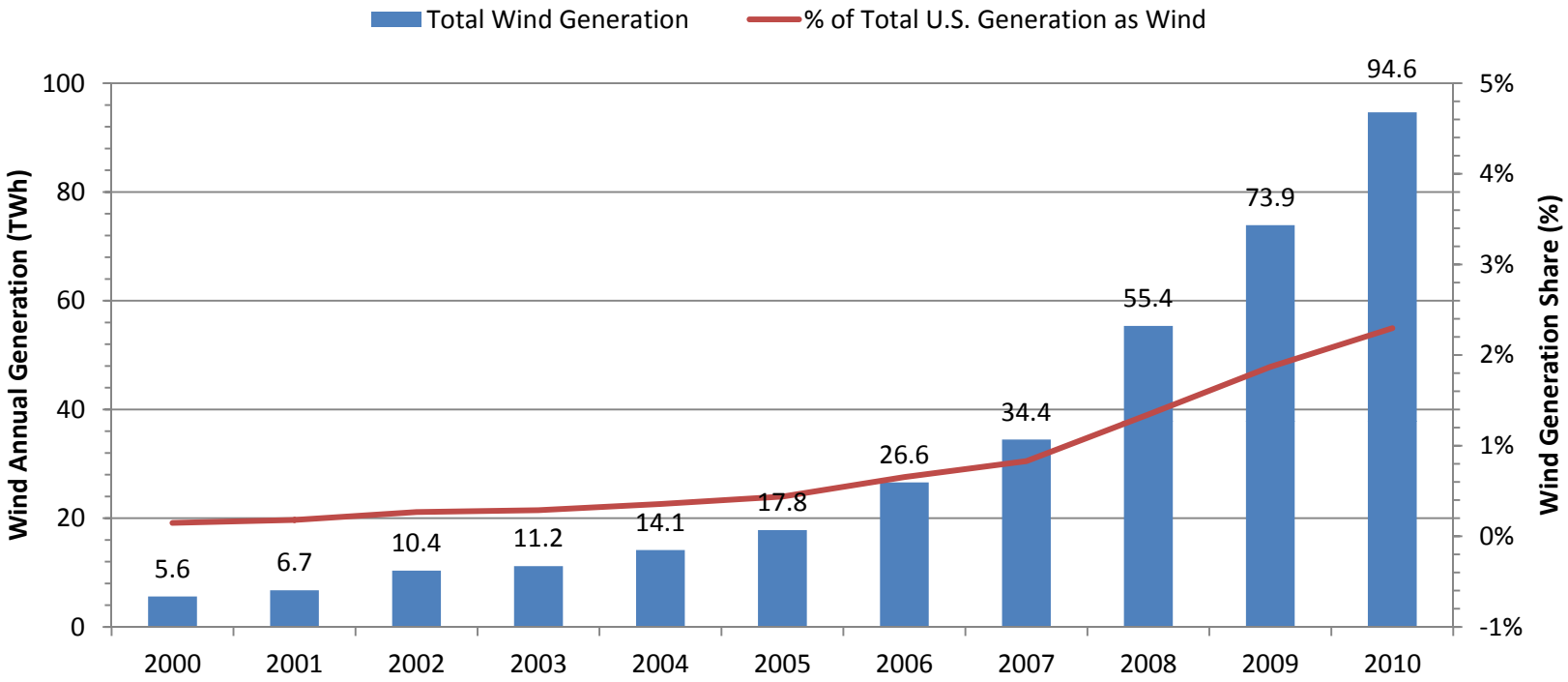
Resource, Capacity, and Growth: Offshore



Source: NREL, 2011

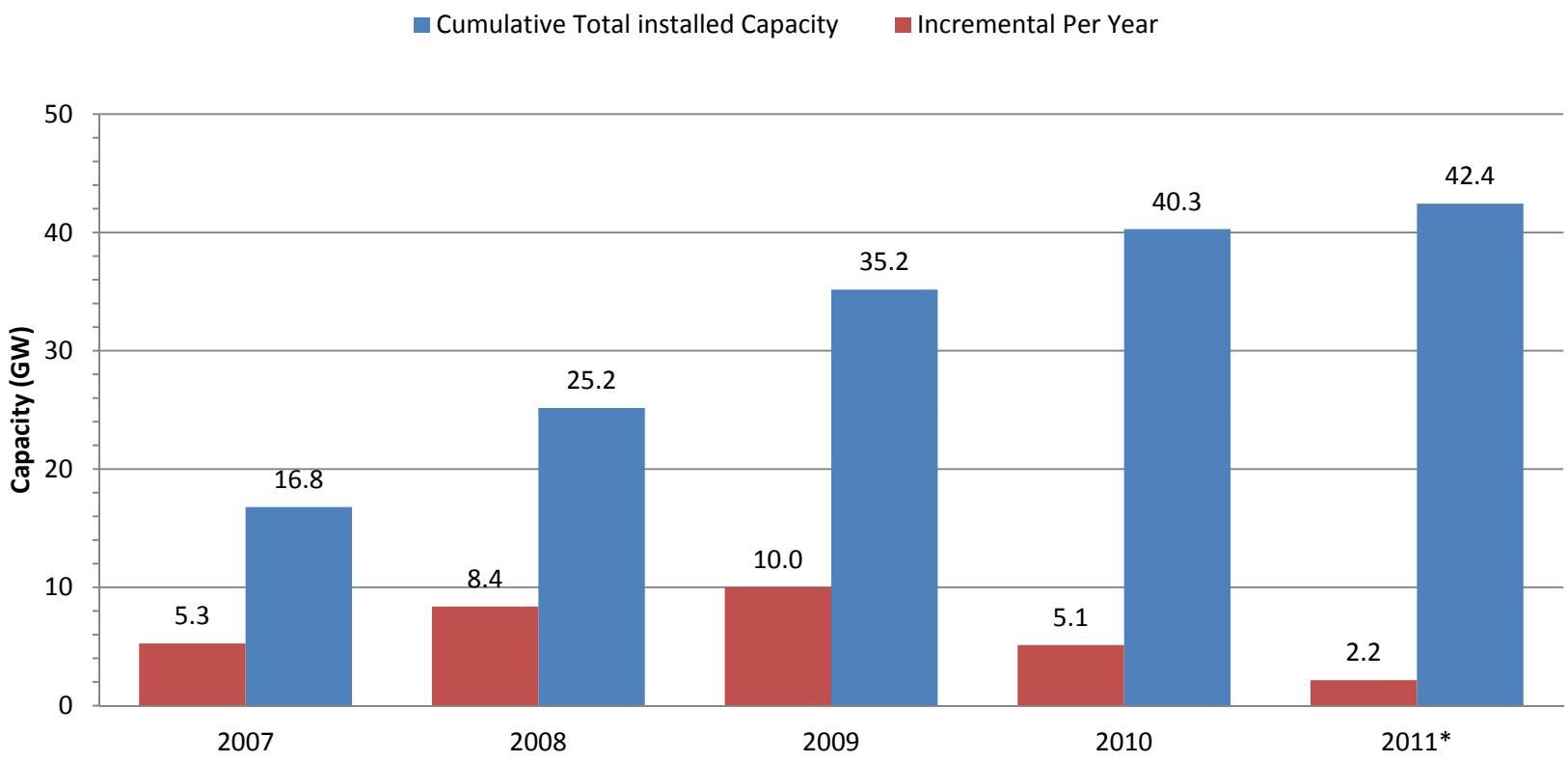
- Offshore wind speeds reach higher persistent velocities than onshore wind
- Strongest offshore wind resources are available off the coast of the U.S. Northeast, the Great Lakes, California, Oregon, and Hawaii
- The U.S. can support an estimated 4,150 GW of offshore wind (Schwartz et al 2010)

Resource, Capacity, and Growth



- The above trend for wind power growth is based on EIA's September 2011 Monthly Energy Review (EIA, 2011)
- Current U.S. wind power expansion is from independently owned power producers. During January through May of 2010 and 2011, independent producers accounted for at least 86% of total wind power production (EIA, 2011)
- 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)

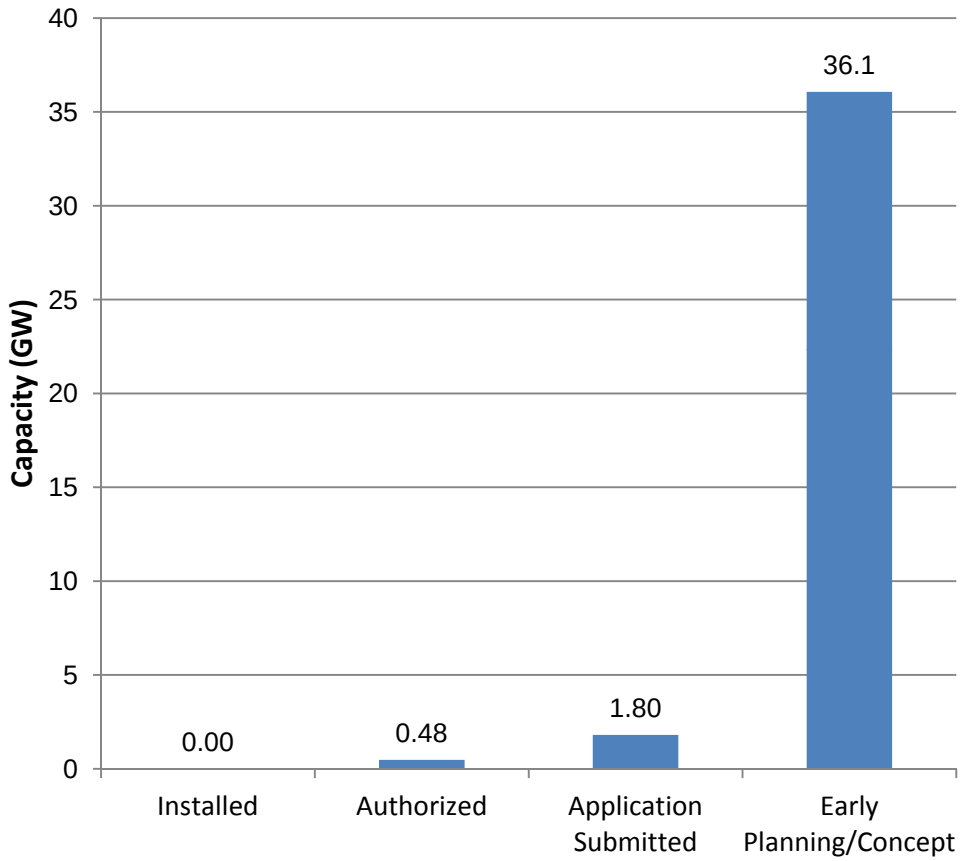
Resource, Capacity, and Growth: Onshore



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

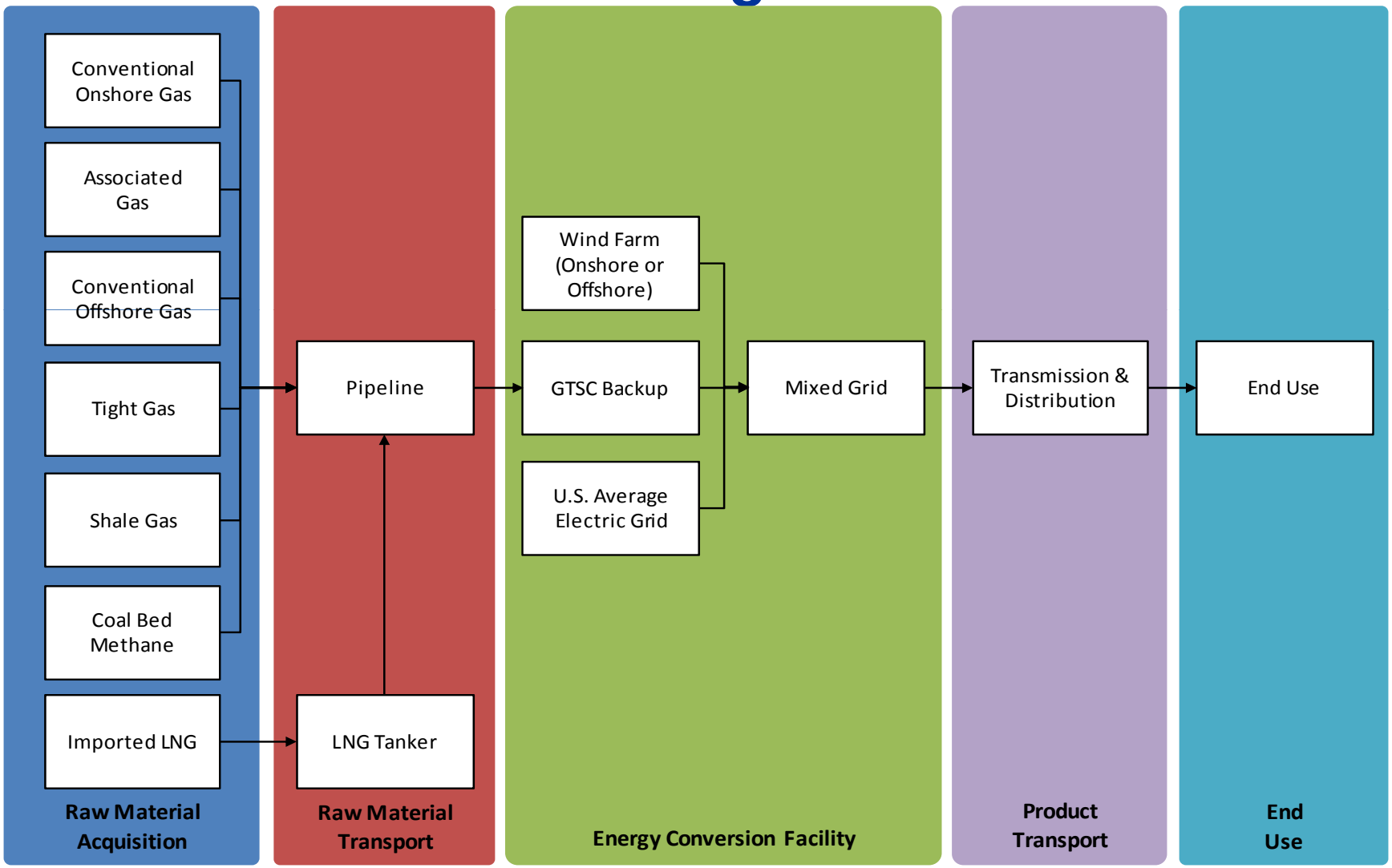
- Newly installed wind power capacity grew from 2007 to 2009, and then declined through 2011 (Schwartz et al 2011)
- While the economic downturn has contributed to a decrease in incremental capacity from 2009 to 2011, the overall wind power capacity has still grown from 2007 to 2011 (Schwartz et al., 2011)

Resource, Capacity, and Growth: Offshore

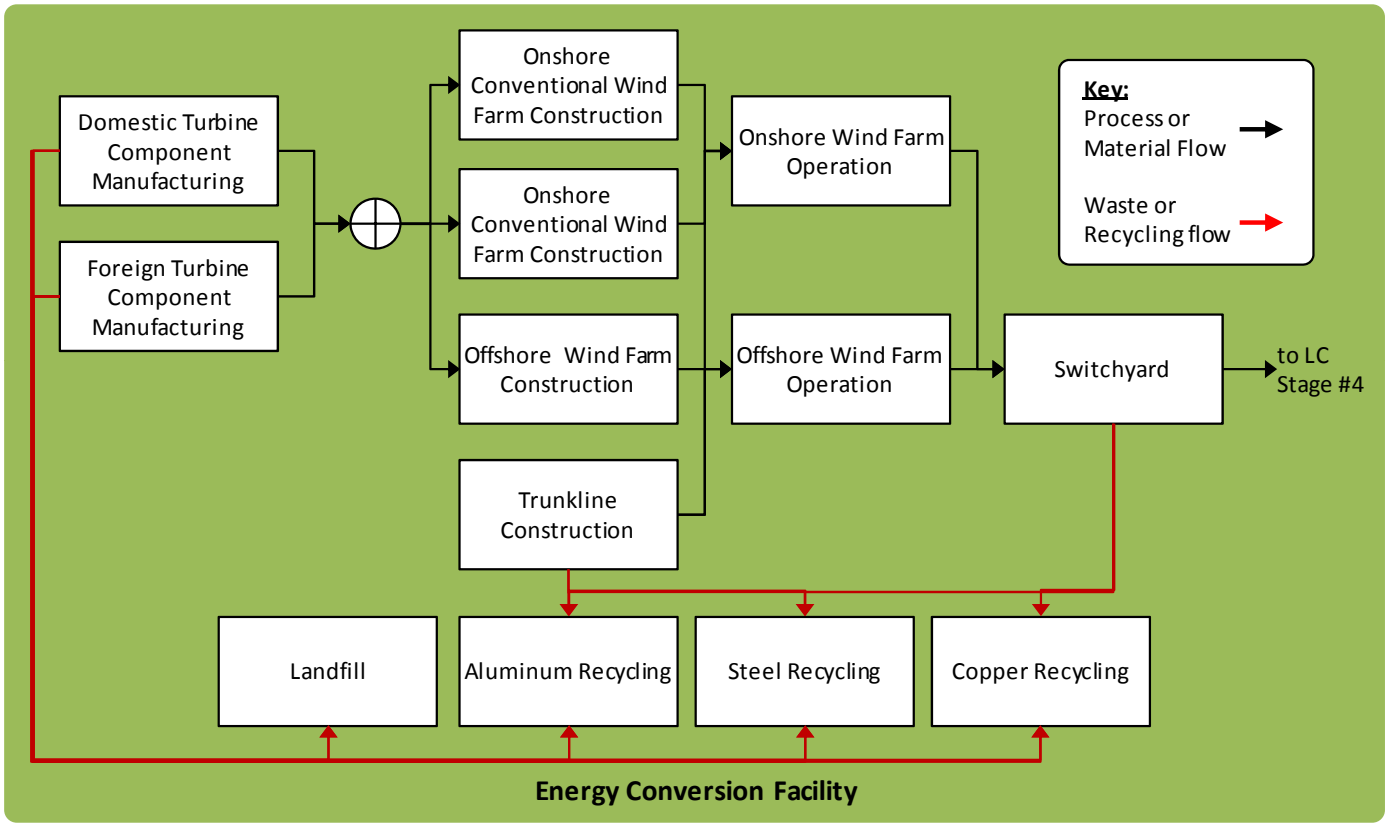


- There is a high degree of uncertainty for offshore wind power development
- Recent federal announcements have supported offshore wind power, including *The National Offshore Wind Strategy* (EERE, 2011)
- No offshore wind projects have been installed, but 475 MW has been authorized (representing Cape Wind and a small installation offshore of Texas), 1.8 GW are moving forward with applications, and 36.1 GW are in early planning (4C Offshore, 2011)

Environmental Analysis of Wind: LCA Modeling Structure



Environmental Analysis of Wind: LCA Modeling Structure of the ECF for Wind



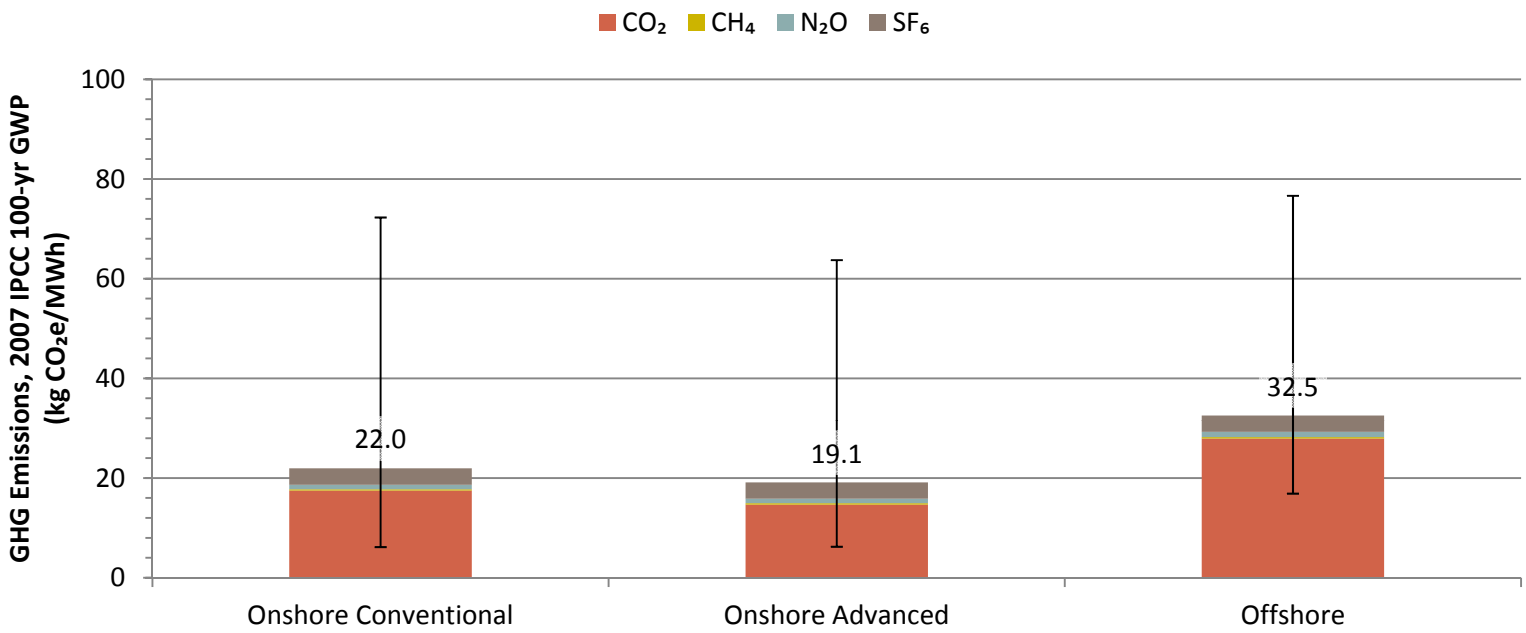
- As of 2008, 55% of wind turbine components were imported
- Wind turbines have an expected life of 20 years, with individual components having variable service lives
- 90% of recyclable metals are recovered for recycling during decommissioning
- System expansion is used to model recycling of scrap metal

Environmental Analysis: Modeling Parameters for Wind Power

Parameter	Conventional Onshore	Onshore Advanced	Offshore
Net Capacity (MW)	200	200	468
Capacity Factor (%)	30.0%	30.0%	39.0%
Individual Wind Turbine Capacity (MW)	1.5	6.0	3.6
Trunkline Distance (miles)	100	100	100
Turbine Lifetime (years)	20	20	20
Rotor Diameter(m)	63	125	111
Submarine Cable Length (miles)	N/A	N/A	12

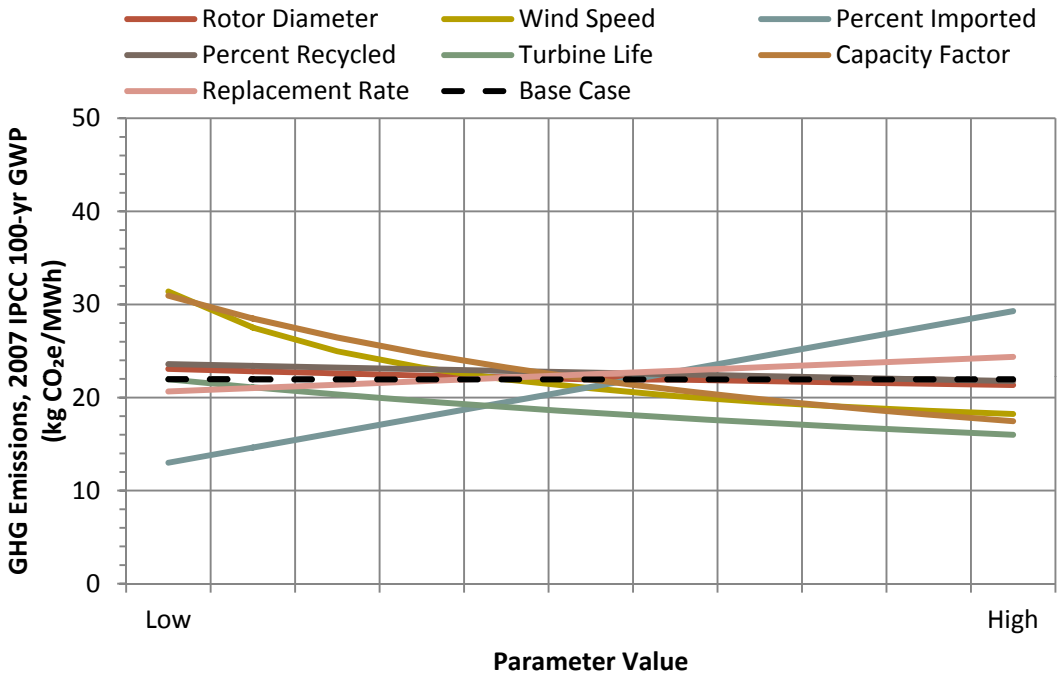
- Offshore wind farm net capacity is larger than onshore, and reflects proposed capacity of the Cape Wind project
- Rotor diameter is variable based on turbine capacity, wherein higher capacity wind turbines require a larger rotor diameter
- Trunkline distance and turbine lifetime were estimated to be the same across all three modeled cases

Environmental Analysis: GHG Results for Wind Power



- Results above do not include GHG emissions from land use change (calculated separately)
- GHG profile for wind power is dominated by carbon dioxide, which is attributable to material and installation requirements for wind farms, SF_6 (from T&D equipment) contributes 10-17% of emissions
- Manufacturing of wind turbines is largest single-category contributor to life cycle GHG emissions of onshore wind power
- Efficiency of scale for offshore turbines reduces contribution of turbine manufacturing to life cycle GHG emissions of offshore wind power, but construction emerges as a key driver to life cycle GHG emissions of offshore wind power

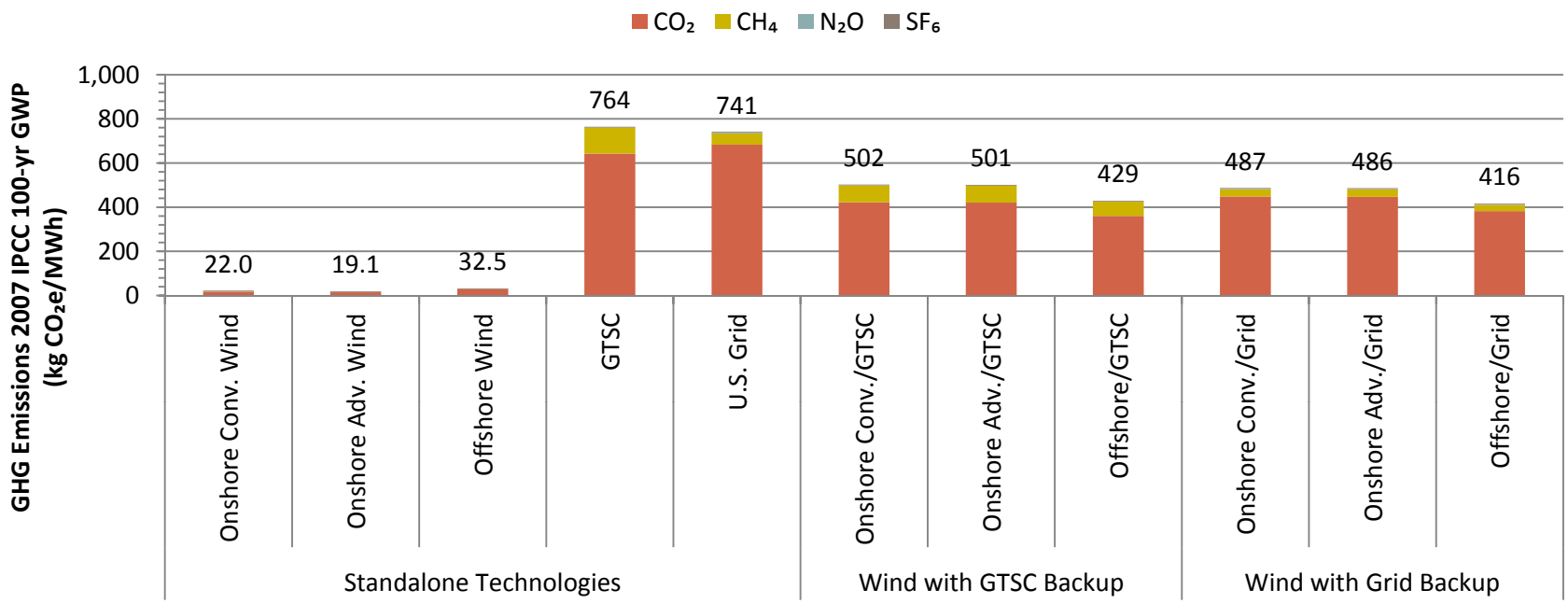
Environmental Analysis: Sensitivity and Uncertainty



Parameter	Low	Expected	High	Units
Rotor Diameter	57	63	69	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	20	30	40	%

- Expected base case result of 22.0 kg CO_2e/MWh (conventional onshore) is shown by the dashed line
- Possible range of GHG results for conventional wind power is 6 to 72 kg CO_2e/MWh when accounting for interaction between model parameters
- Slopes of the lines show that wind speed and capacity factor are not only the most sensitive, but also add the most uncertainty in the overall GHG emissions
- Relationships between many parameters and GHG emissions are nonlinear – for instance there is a cubic relationship between wind speed and GHG emissions

Environmental Analysis: Wind and Backup Power

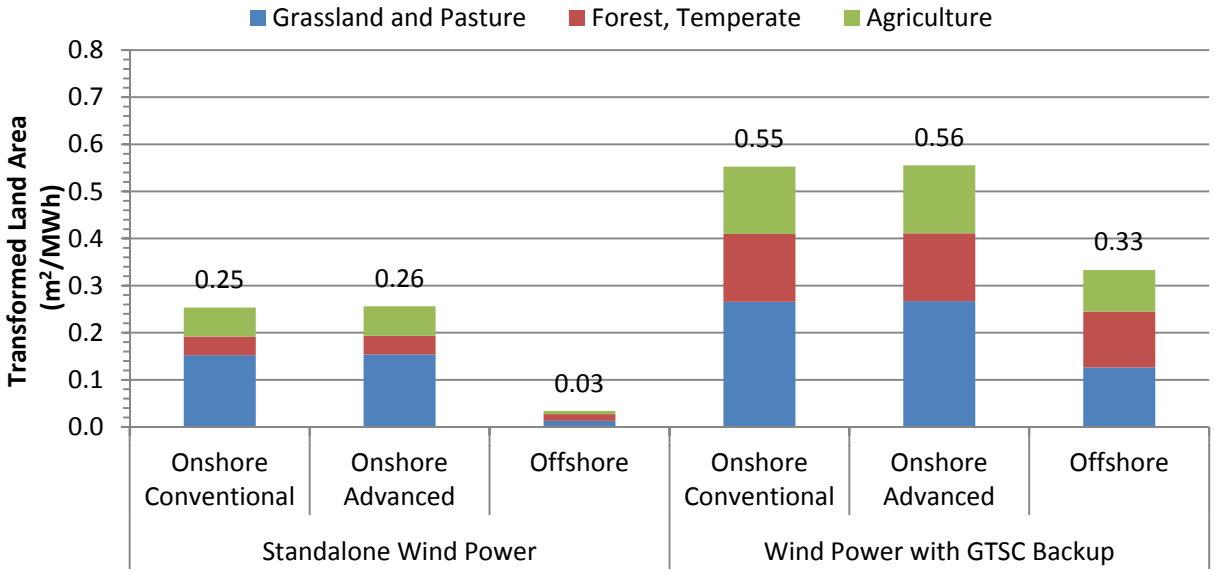


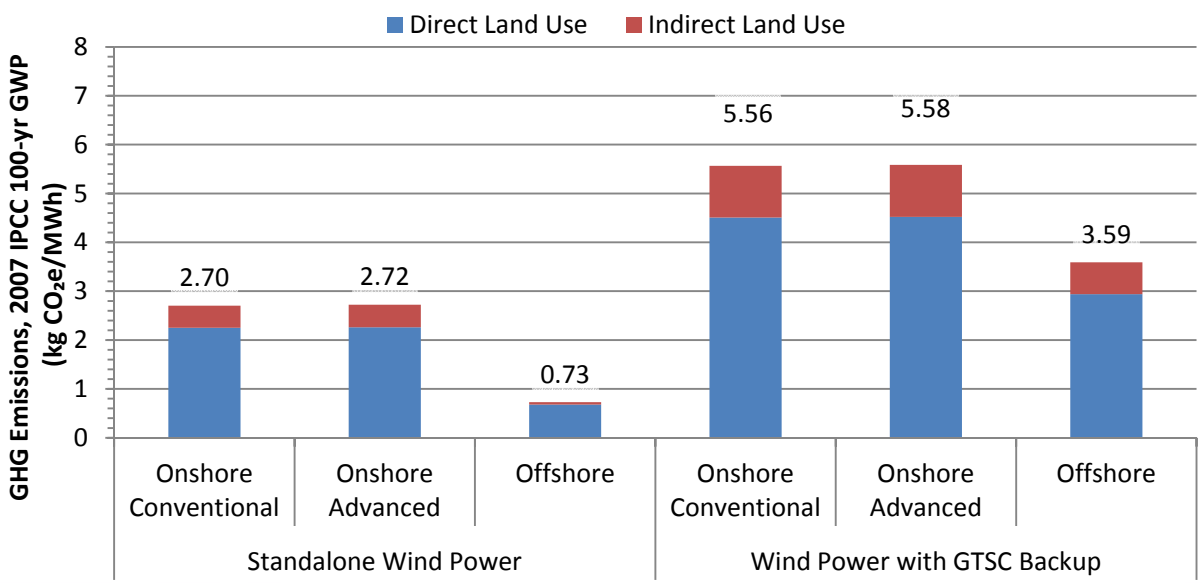
- Results above do not include GHG emissions from land use change (calculated separately)
- It is not necessary to back up wind farm to a combined capacity factor of 100%; combined capacity factor is 85%
- At a combined capacity factor of 85%, an onshore wind farm with a capacity factor of 30% represents a 35.3% contribution to the power mix, and the backup represents a 64.7% contribution to the power mix
- At a combined capacity factor of 85%, an offshore wind farm with a capacity factor of 39% represents a 45.9% contribution to the mix of wind and backup power, and the backup represents a 54.1% contribution to the power mix

Environmental Analysis: Land Use

- **Transformed Land Area - Facility sizes for Onshore and Offshore**
  - Data from NREL's Land Use Requirements of Modern Wind Power Plants in the U.S. (2009)
    - Onshore considers wind farm, trunkline, and NG facilities
    - Offshore considers trunkline and NG facilities
- **Direct GHG Emissions**
  - Existing land use type evaluated based on state level land use data available from USDA
  - GHG emissions calculated based on U.S. EPA's method for the quantification of GHG emissions, in support of current RFS2
- **Indirect GHG Emissions**
  - Indirect GHG emissions quantified only for the displacement of agriculture (not for other uses)
    - Assumes 30% of lost agriculture indirectly converted from existing use to new agriculture
  - Emissions calculated based on EPA's GHG emission factors for land use conversion

Environmental Analysis: Land Use Results





- Standalone offshore wind power has lowest transformed land at approximately 0.034 m^2/MWh, followed by onshore wind farm (0.25 to 0.26 m^2/MWh), offshore wind with GTSC backup (0.33 m^2/MWh), and finally onshore wind with GTSC backup (0.55 to 0.56 m^2/MWh)
- Direct land use emissions comprise at least 80% of all land use emissions
- Land use GHG emissions from onshore conventional wind power increase the total life cycle GHG from 22.0 to 24.7 kg CO_2e/MWh
- Land use GHG from offshore wind power represent 2.2% of the total life cycle emissions of 33.2 kg CO_2e/MWh

Environmental Analysis: Other Emissions

Airborne Emission	Onshore Conventional (kg/MWh)	Onshore Advanced (kg/MWh)	Offshore (kg/MWh)
Lead (Pb)	-9.51E-06	7.91E-07	9.38E-06
Mercury (Hg)	1.45E-07	1.69E-07	6.54E-07
Ammonia (NH_3)	8.16E-04	6.42E-04	2.90E-04
Carbon Monoxide (CO)	4.97E-02	4.39E-02	1.05E-01
Nitrogen Oxides (NO_X)	4.45E-02	3.20E-02	1.76E-01
Sulfur Dioxide (SO_2)	2.85E-02	3.09E-02	4.33E-02
Volatile Organic Carbons (VOC)	8.76E-03	8.24E-03	1.06E-02
Particulate Matter (PM)	2.72E-02	1.68E-02	9.66E-03

- These results reflect mass emissions of pollutants – results cannot be compared across emission categories (e.g., CO and NO_X emissions are not directly comparable)
- Variability in non-GHG emissions among cases is generally within one order of magnitude
- Offshore wind emissions are higher than onshore for most emissions except ammonia and particulate matter due to combination of greater fuel combustion during operations and construction for offshore wind farm
- For onshore wind, most emissions result from turbine manufacturing

Cost Analysis: Financial and Cost Parameters

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), $/MW-yr.	24,050	24,050	24,050
Turbine Life, Years	**30**	**20**	**20**
Total Project Capacity, MW	200	200	200
Single Turbine Capacity, MW	1.0	1.5	1.75
Capacity Factor, %	**33.0%**	**30.0%**	**25.0%**
Construction Period, Years	2	2	2
Onshore Advanced Wind Power (All Costs in 2007$)			
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), $/MW-yr.	24,050	24,050	24,050
Turbine Life, Years	**30**	**20**	**20**
Total Project Capacity, MW	200	200	200
Single Turbine Capacity, MW	2.5	2.75	3.0
Capacity Factor, %	**33.0%**	**30.0%**	**25.0%**
Construction Period, Years	2	2	2
Offshore Wind Power (All Costs in 2007$)			
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
Turbine 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

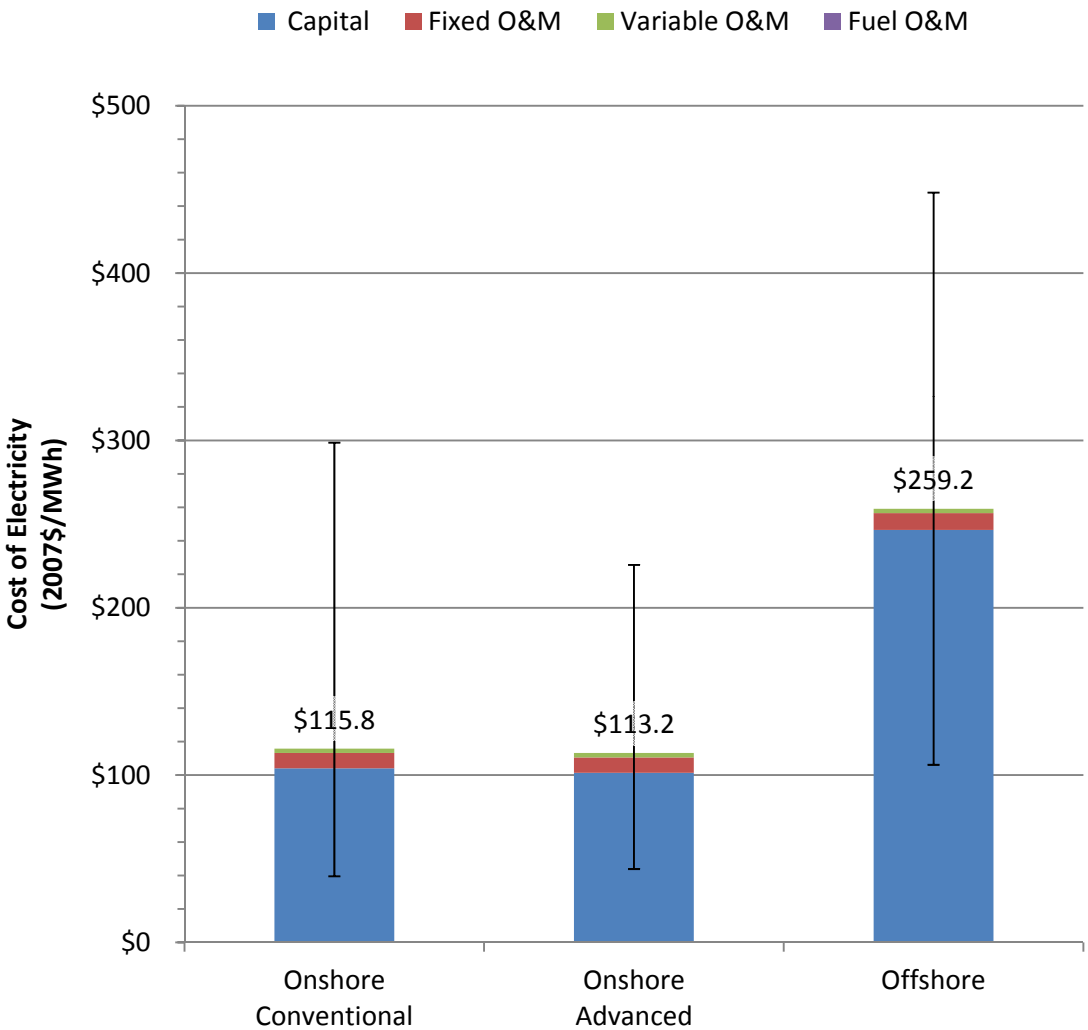
- Capital costs, turbine life, and capacity factors (shown in bold) introduce the most uncertainty
- Capital costs dominate the COE for wind power, comprising between 89.6% and 95.1% of the COE of wind power
- Offshore wind power has higher capital costs due to larger foundations (monopiles) and measures for corrosion resistance
- Offshore wind power has higher fixed O&M costs due to the extra costs of marine vessels and other equipment necessary for offshore operations

Cost Analysis: Financial and Cost Parameters

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 (%)	4.5%	4.5%	4.5%
Debt Term (years)	15	15	15
Plant Lifetime (years)	30	20	20
Depreciation Period (MACRS) (years)	7	7	7
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)	6.0%	12.0%	18.0%

- Plant lifetime and return on equity (IRROE) are the only financial parameters that vary among cases
- Return on equity (IRROE) is used to evaluate different investment risk scenarios
- Tax incentives for renewable energy were not modeled because subsidies have not been considered in other NETL LCC models
- The LCC data and financial assumptions were modeled in NETL's Power Systems Financial Model (PSFM)

Cost Analysis: Life Cycle Cost Results for Standalone Wind Power



- Expected cost results show that onshore wind power has lower COE than offshore wind power, and that onshore advanced wind power has a slightly lower COE than other technologies, but there is overlap of uncertainties for all cases
- Figure shows COE, which is the cost for the *first* year of operation
- 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 wind projects

Other Issues

Barriers to Implementation

- Uncertain construction schedules, especially for offshore projects
- Grid integration

Risks of Implementation

- Wildlife impacts (e.g., bird and bat strikes or aquaculture disturbance)
- Offshore wind power may interfere with marine navigation
- Noise and visual aesthetics

Expert Opinions

- Wind developers are fearful of entering a boom-bust scenario (AWEA, 2011)
- In the Obama Administration's *A National Offshore Wind Strategy* (EERE, 2011), economists anticipate a surge in offshore wind installations

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