ME/ESE 4470
Wind and Tidal Power
Economics

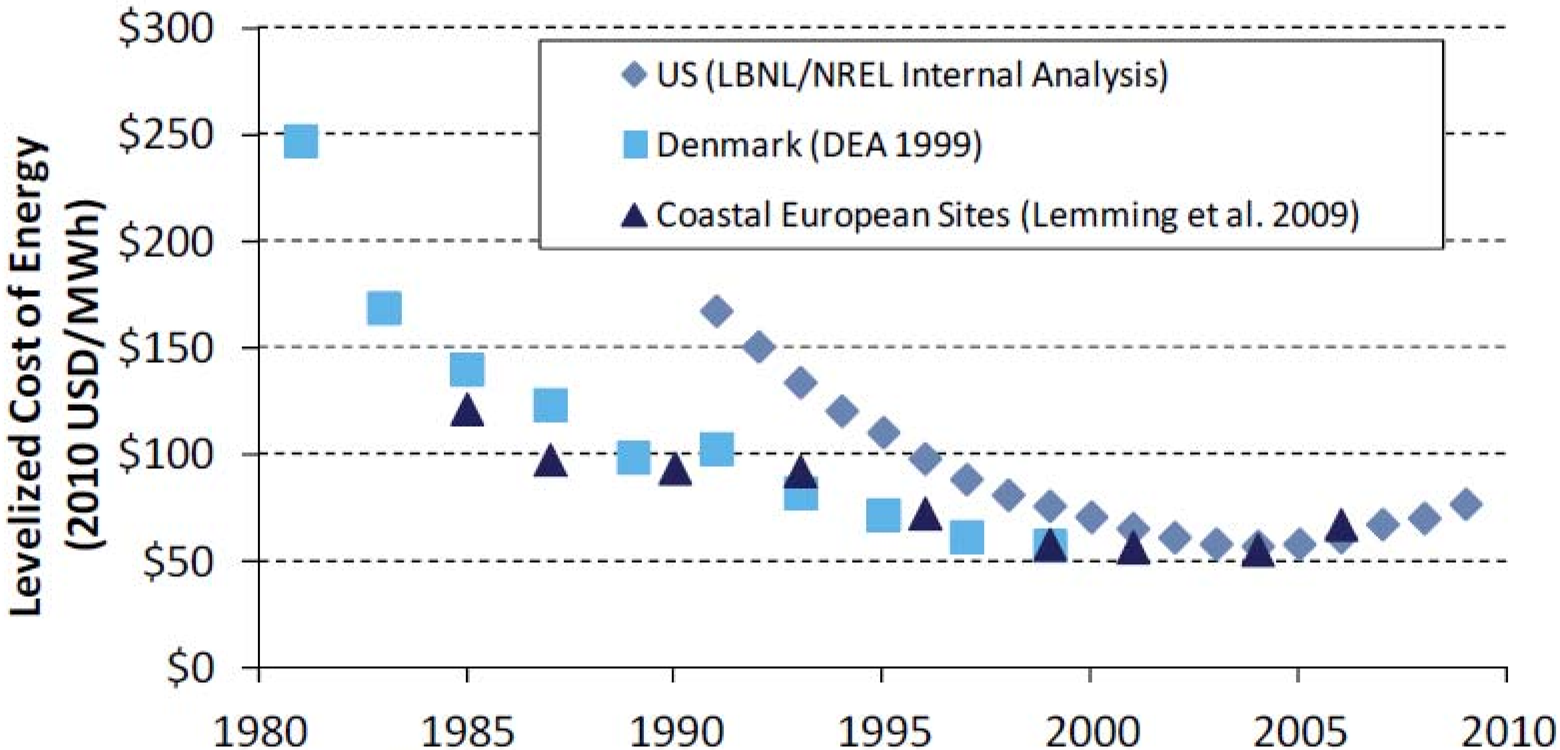
Wind Energy Economics

A. What issues affect the economics of wind turbine?
   - Cost of Energy (COE), Cost of Energy, Cost of Energy
   - Wind Turbine Cost and Installation Costs
   - Operations – Reliability
   - Design & Operations – Capacity Factor
   - Policy and Incentives
   - Transmission (or lack thereof) and Grid Operation

   - Economic Impact on Installation

Wind Energy Economics

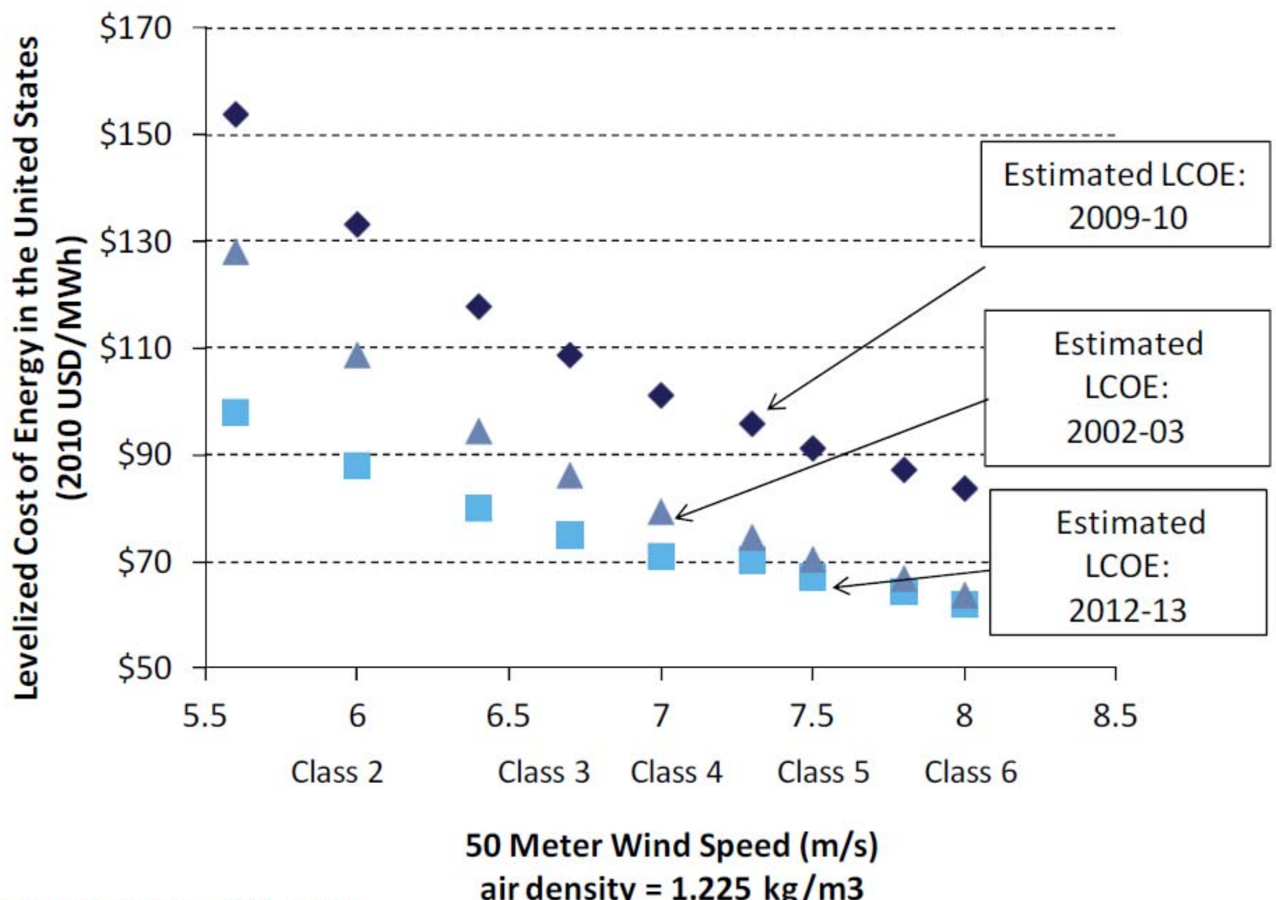
B. Cost of Energy



Source: Lantz et al. 2012

Wind Energy Economics

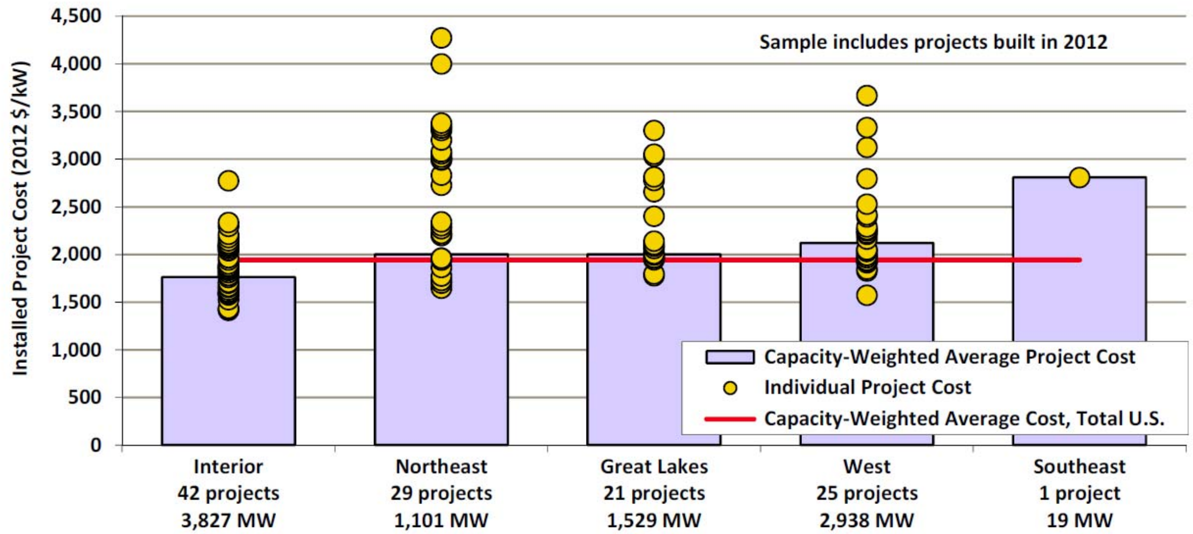
B. Cost of Energy



Source: Lantz et al. 2012

Wind Energy Economics

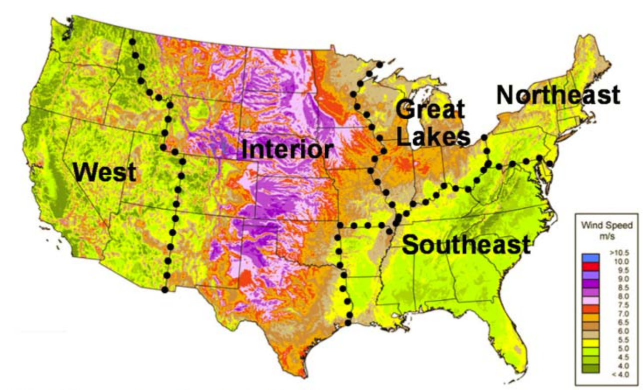
B. Cost of Energy



Source: Berkeley Lab

Figure 23. Installed Wind Power Project Costs by Region: 2012 Proje

2012 Wind Technologies Market Report
Ryan Wiser, Mark Bolinger



Source: AWS Truepower, National Renewable Energy Laboratory

Figure 24. Regional Boundaries Overlaid on a Map of Average Annual Wind Speed at 80 Meters

Wind Energy Economics

B. Cost of Energy

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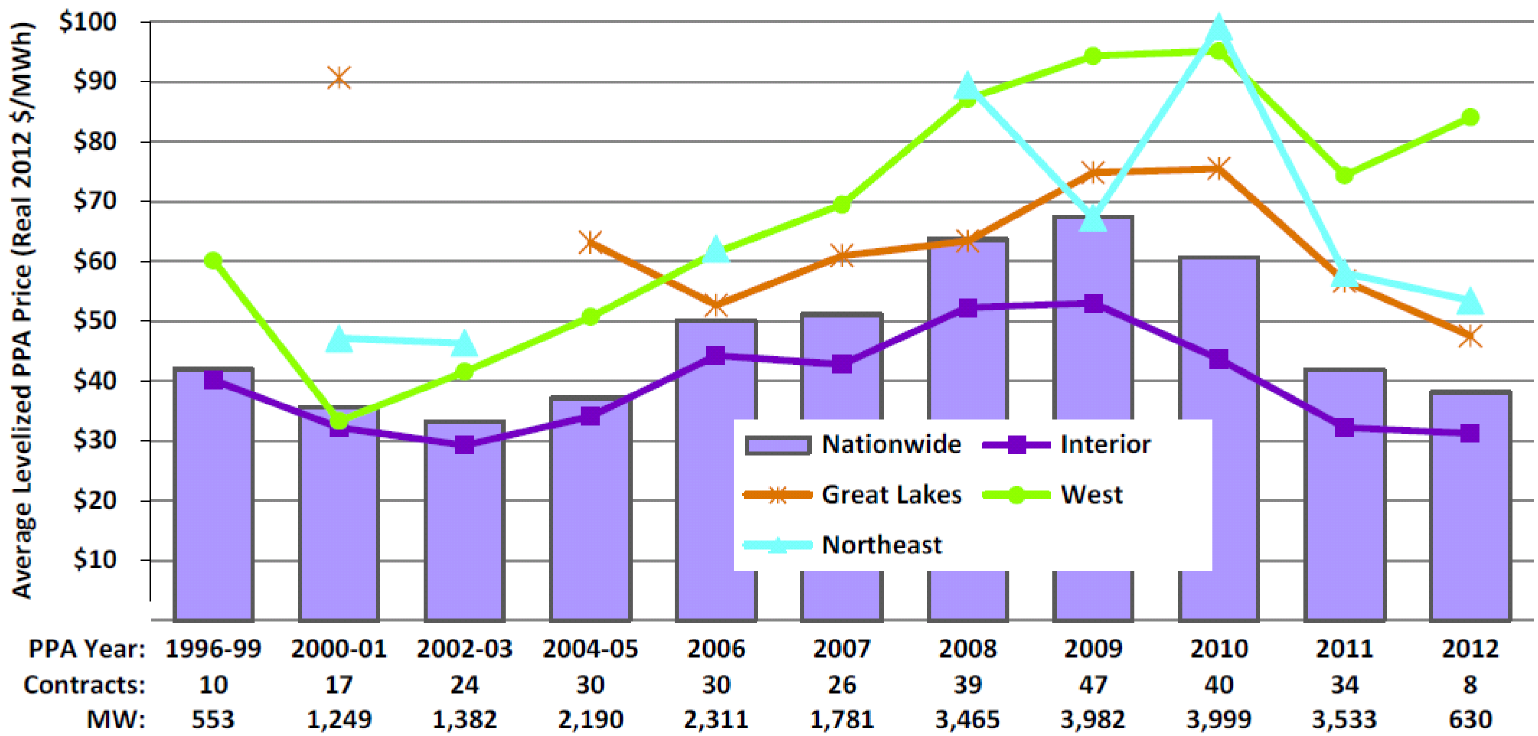


Figure 33. Generation-Weighted Average Levelized Wind PPA Prices by PPA Execution Date and Region

Wind Energy Economics

B. Cost of Energy

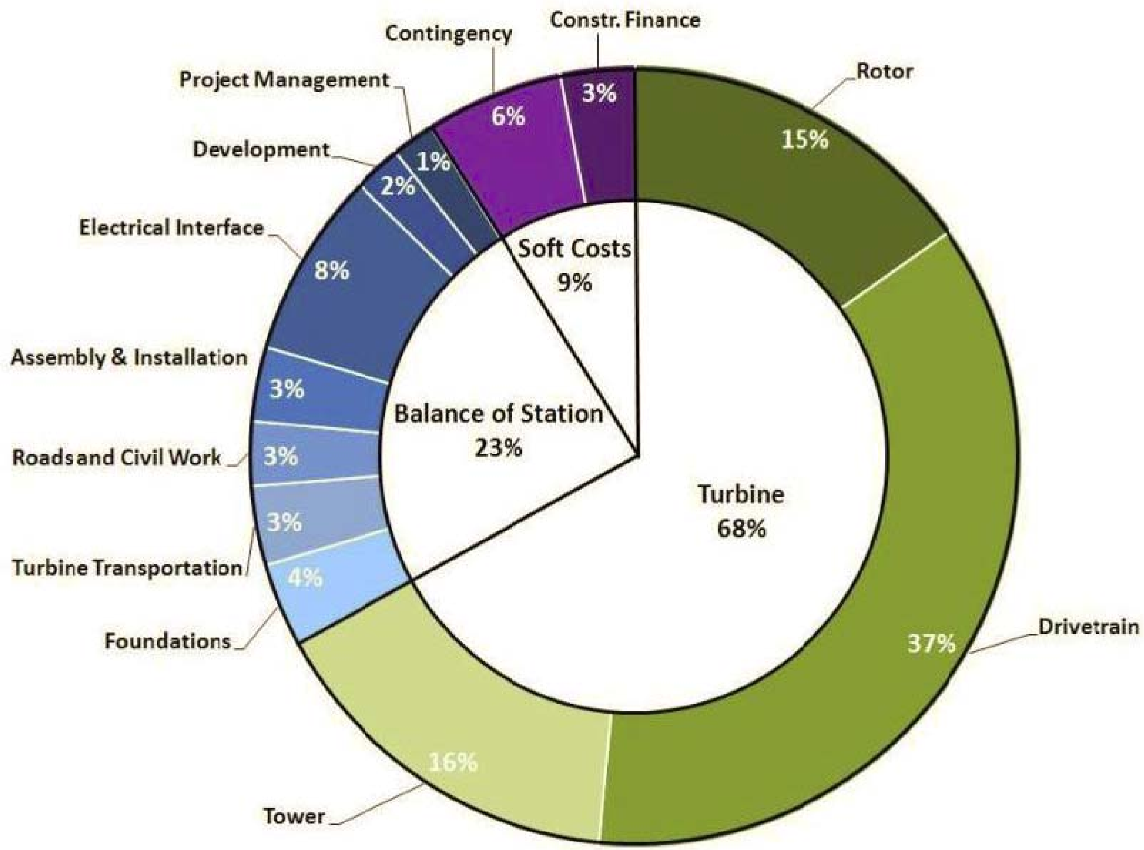
U.S. Energy Information Administration
Annual Energy Outlook 2013

Table 1. Estimated levelized cost of new generation resources, 2018

Plant type	Capacity factor (%)	U.S. average levelized costs (2011 $/megawatthour) for plants entering service in 2018				
		Levelized capital cost	Fixed O&M	Variable O&M (including fuel)	Transmission investment	Total system levelized cost
Dispatchable Technologies						
Conventional Coal	85	65.7	4.1	29.2	1.2	100.1
Advanced Coal	85	84.4	6.8	30.7	1.2	123.0
Advanced Coal with CCS	85	88.4	8.8	37.2	1.2	135.5
Natural Gas-fired						
Conventional Combined Cycle	87	15.8	1.7	48.4	1.2	67.1
Advanced Combined Cycle	87	17.4	2.0	45.0	1.2	65.6
Advanced CC with CCS	87	34.0	4.1	54.1	1.2	93.4
Conventional Combustion Turbine	30	44.2	2.7	80.0	3.4	130.3
Advanced Combustion Turbine	30	30.4	2.6	68.2	3.4	104.6
Advanced Nuclear	90	83.4	11.6	12.3	1.1	108.4
Geothermal	92	76.2	12.0	0.0	1.4	89.6
Biomass	83	53.2	14.3	42.3	1.2	111.0
Non-Dispatchable Technologies						
Wind	34	70.3	13.1	0.0	3.2	86.6
Wind - Offshore	37	193.4	22.4	0.0	5.7	221.5
Solar PV[1]	25	130.4	9.9	0.0	4.0	144.3
Solar Thermal	20	214.2	41.4	0.0	5.9	261.5
Hydro[2]	52	78.1	4.1	6.1	2.0	90.3

Wind Energy Economics

C. Wind Turbine Cost and Installation Costs



2011 Cost of Wind Energy Review
S. Tegen, E. Lantz, M. Hand, B. Maples, A. Smith, and P. Schwabe
National Renewable Energy Laboratory

Wind Energy Economics

C. Wind Turbine Cost and Installation Costs

2011 Cost of Wind Energy Review

S. Tegen, E. Lantz, M. Hand, B. Maples, A. Smith, and P. Schwabe

National Renewable Energy Laboratory

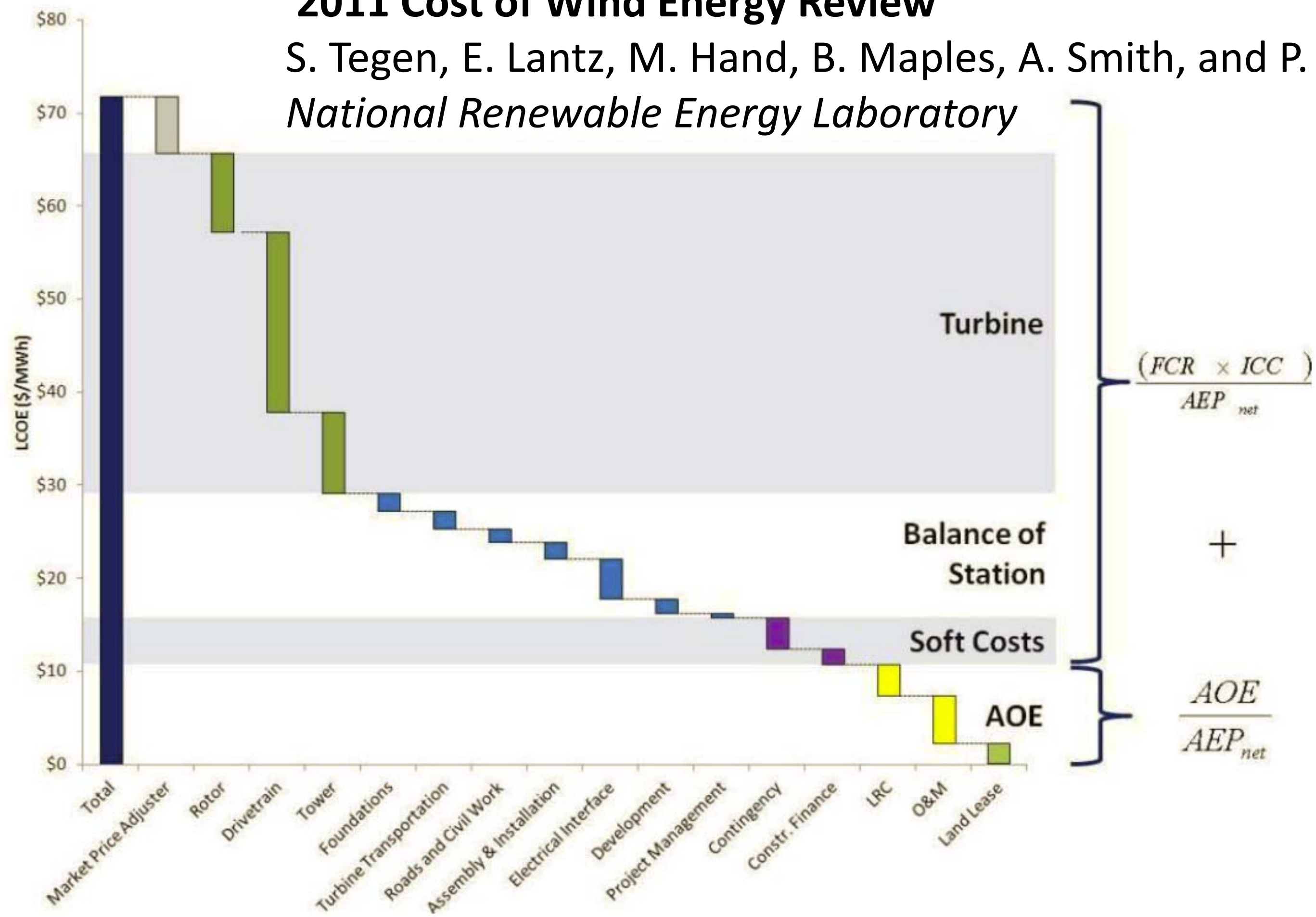


Figure 2. Line item cost breakdown for the 2011 land-based wind reference project

Wind Energy Economics

C. Wind Turbine Cost and Installation Costs

Table ES1. Summary Description of the Land-Based Wind Reference Project, Using 1.5-MW Turbines

Data Source		1.5-MW Land-Based $/kW	1.5-MW Land-Based $/MWh
Model	Turbine capital cost	1,286	37
Model	Balance-of-station	446	13
Model	Soft costs	172	5
Market	Market price adjustment*	195	6
Market	**INSTALLED CAPITAL COST**	**2,098**	**61**
Market	Annual operating expenses ($/kilowatt/yr)	35	11
Market	Fixed charge rate (%)	9.5	
Model	Net annual energy production (megawatt-hour/MW/yr)	3,263	
Model	Capacity factor (%)	37	
	TOTAL LCOE ($/MWh)	**72**	

*The market price adjustment is the difference between the modeled cost and the actual price paid for the typical project in the 2011 market.

2011 Cost of Wind Energy Review

S. Tegen, E. Lantz, M. Hand, B. Maples, A. Smith, and P. Schwabe

National Renewable Energy Laboratory

Wind Energy Economics

C. Wind Turbine Cost and Installation Costs

Table ES2. Summary Description of the Fixed-Bottom Offshore Wind Reference Project, Using 3.6-MW Turbines

Data Source		3.6-MW Offshore $/kW	3.6-MW Offshore $/MWh
Literature	Turbine capital cost	1,789	62
Market	Balance-of-station costs	2,918	101
Literature	Soft costs	893	31
Market	**INSTALLED CAPITAL COST**	**5,600**	**194**
Market	Annual operating expenses ($/kilowatt/yr)	136	40
Market	Fixed charge rate (%)	11.8	
Model	Net annual energy production (megawatt-hour/MW/yr)	3,406	
Model	Capacity factor (%)	39	
	TOTAL LCOE ($/MWh)	**225**	

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National Renewable Energy Laboratory

Wind Energy Economics

C. Wind Turbine Cost and Installation Costs

Table 14. Ranges of LCOE and LCOE Elements for Land-Based and Offshore Wind in 2011

	Land-Based	Offshore
Installed capital cost	$1,400–$2,900/kW	$4,500–$6,500/kW
Annual operating expenses	$9–$18/MWh	$15–$55/MWh
Capacity factor	18%–53%	30%–55%
Discount rate	6%–13%	8%–15%
Operational life	20–30 years	20–30 years
Range of LCOE	<$60–>$100/MWh	<$168–>$292/MWh

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S. Tegen, E. Lantz, M. Hand, B. Maples, A. Smith, and P. Schwabe
National Renewable Energy Laboratory

Wind Energy Economics

D. Operations - Reliability

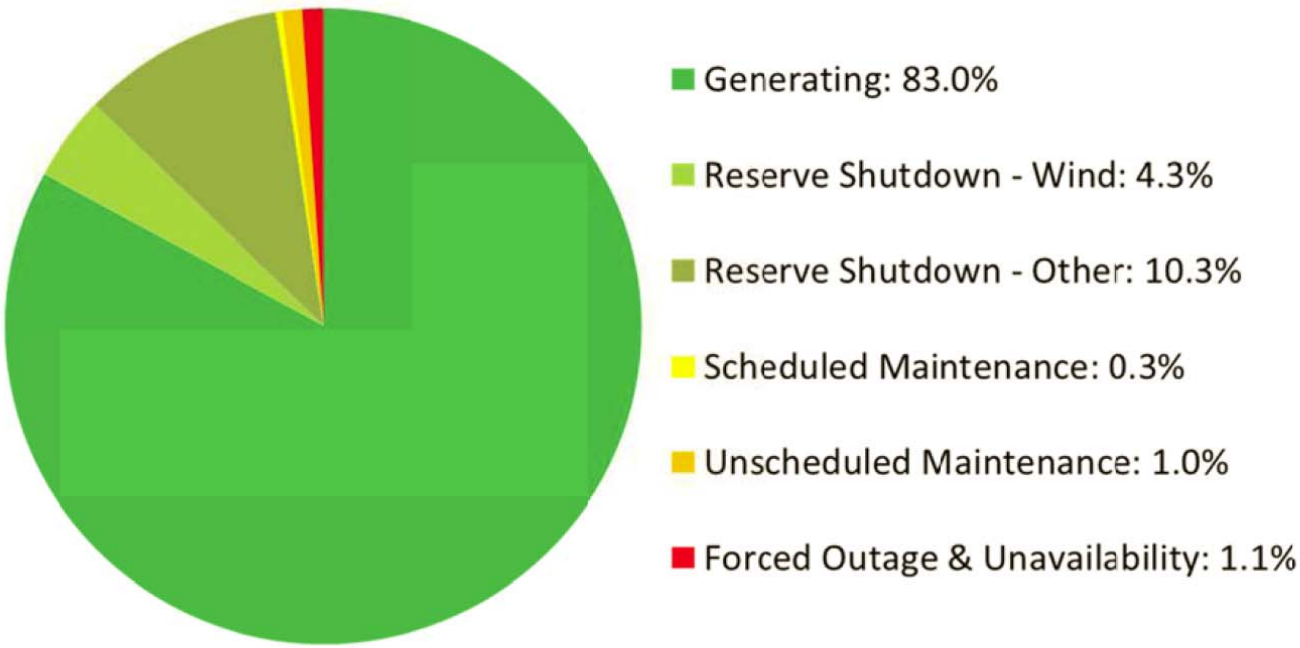

Figure 1. Availability Time Accounting.

Continuous Reliability Enhancement for Wind (CREW) Database: Wind Plant Reliability Benchmark.
Valerie A. Hines, Alistair B. Ogilvie, and Cody R. Bond
Sandia2013-7288

Wind Energy Economics

D. Operations - Reliability

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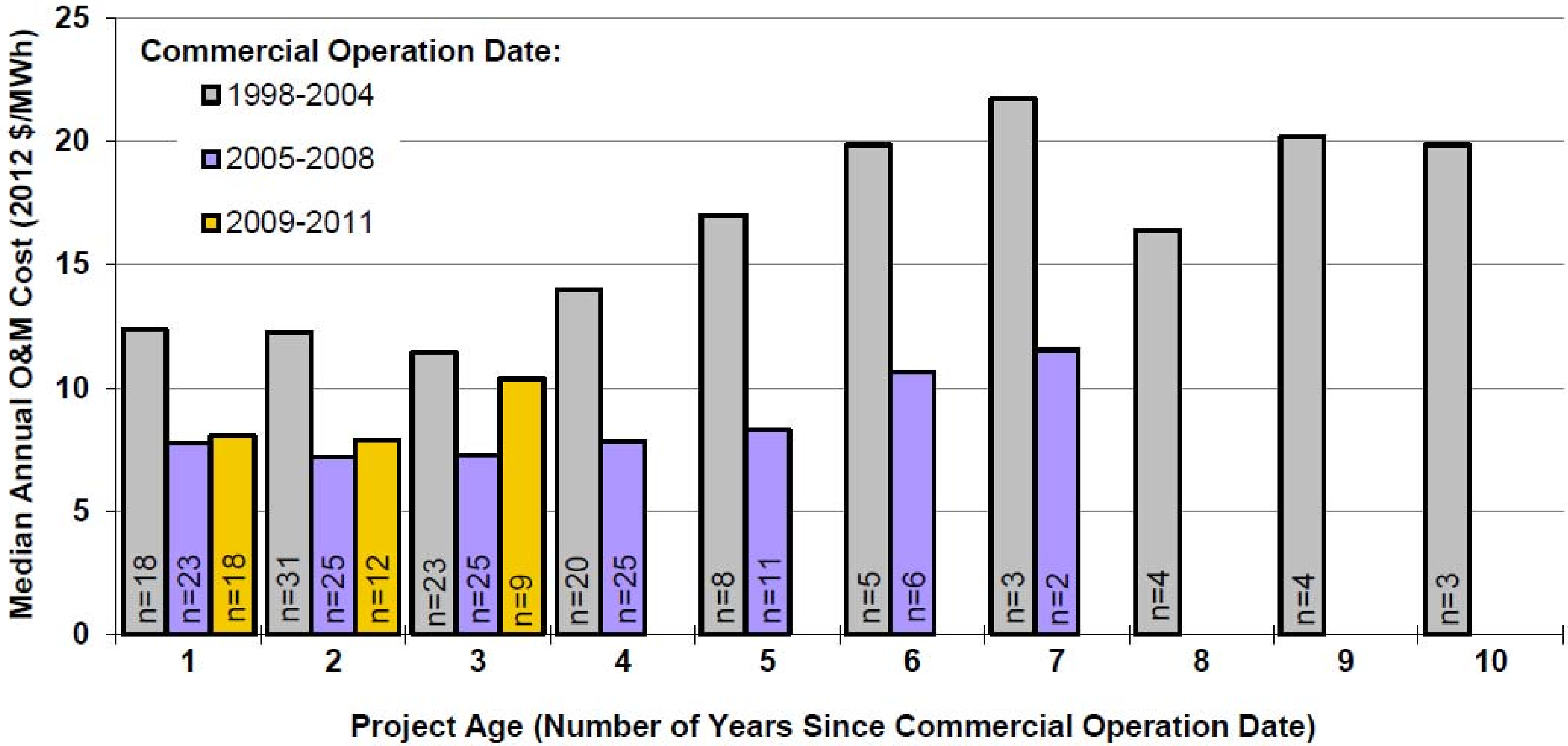


Source: Berkeley Lab; medians shown only for groups of two or more projects, and only projects >5 MW are included

Figure 26. Median Annual O&M Costs by Project Age and Commercial Operation Date

Wind Energy Economics

D. Operations - Reliability

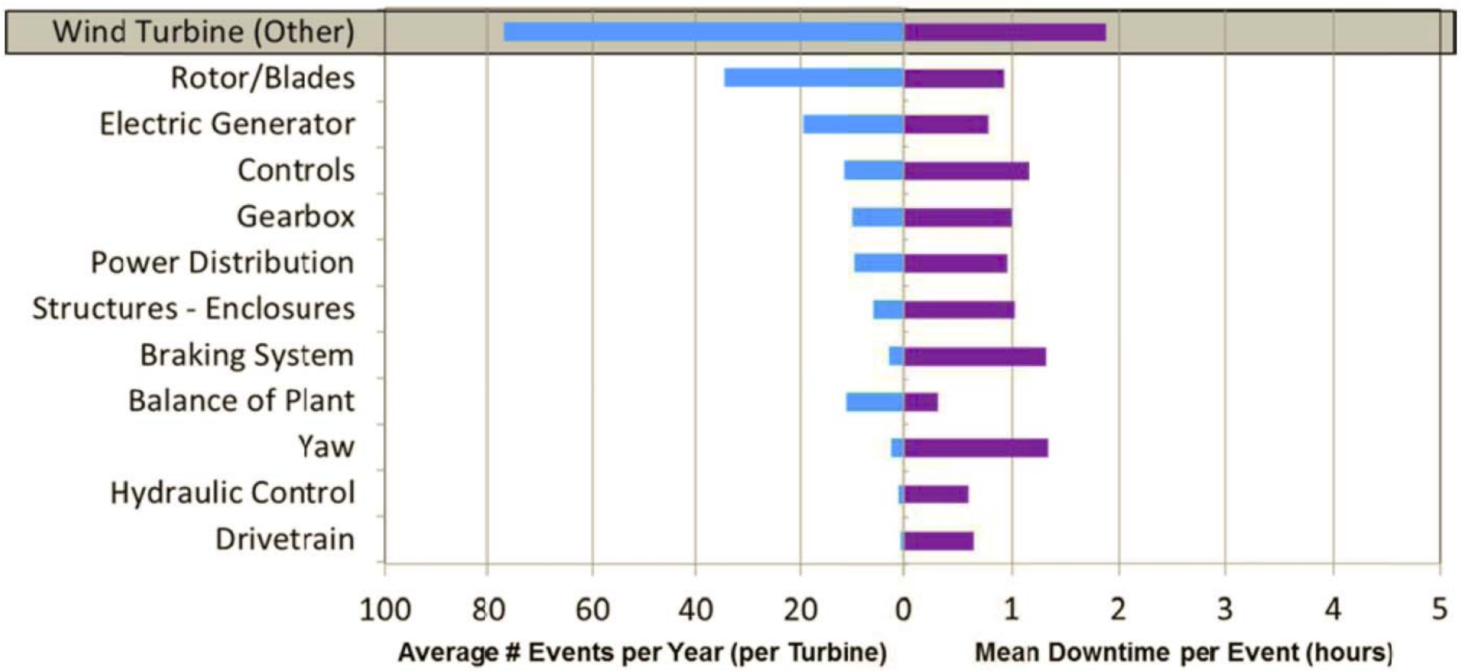


Figure 2. Event Frequency versus Downtime.

Continuous Reliability Enhancement for Wind (CREW) Database: Wind Plant Reliability Benchmark.
Valerie A. Hines, Alistair B. Ogilvie, and Cody R. Bond
Sandia2013-7288

Wind Energy Economics

D. Operations - Reliability

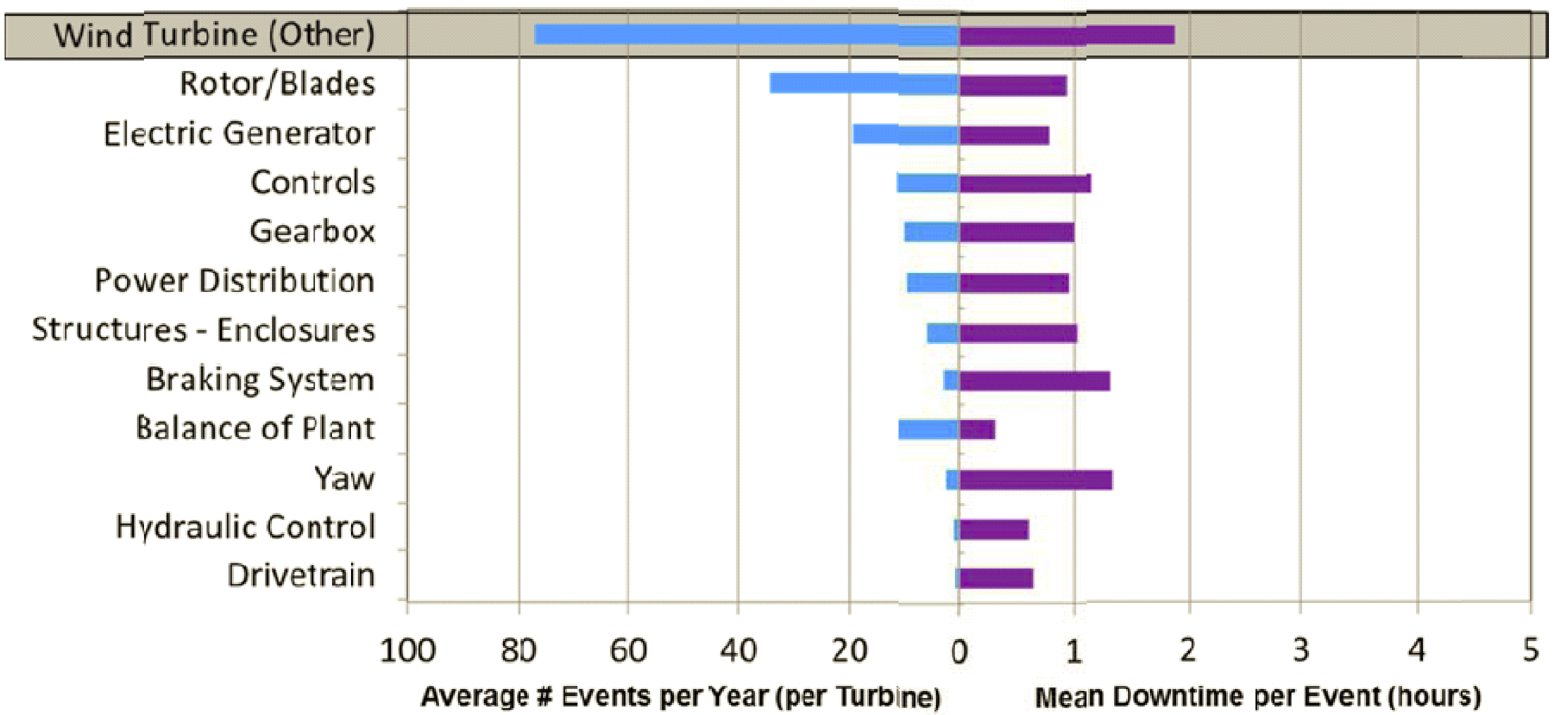
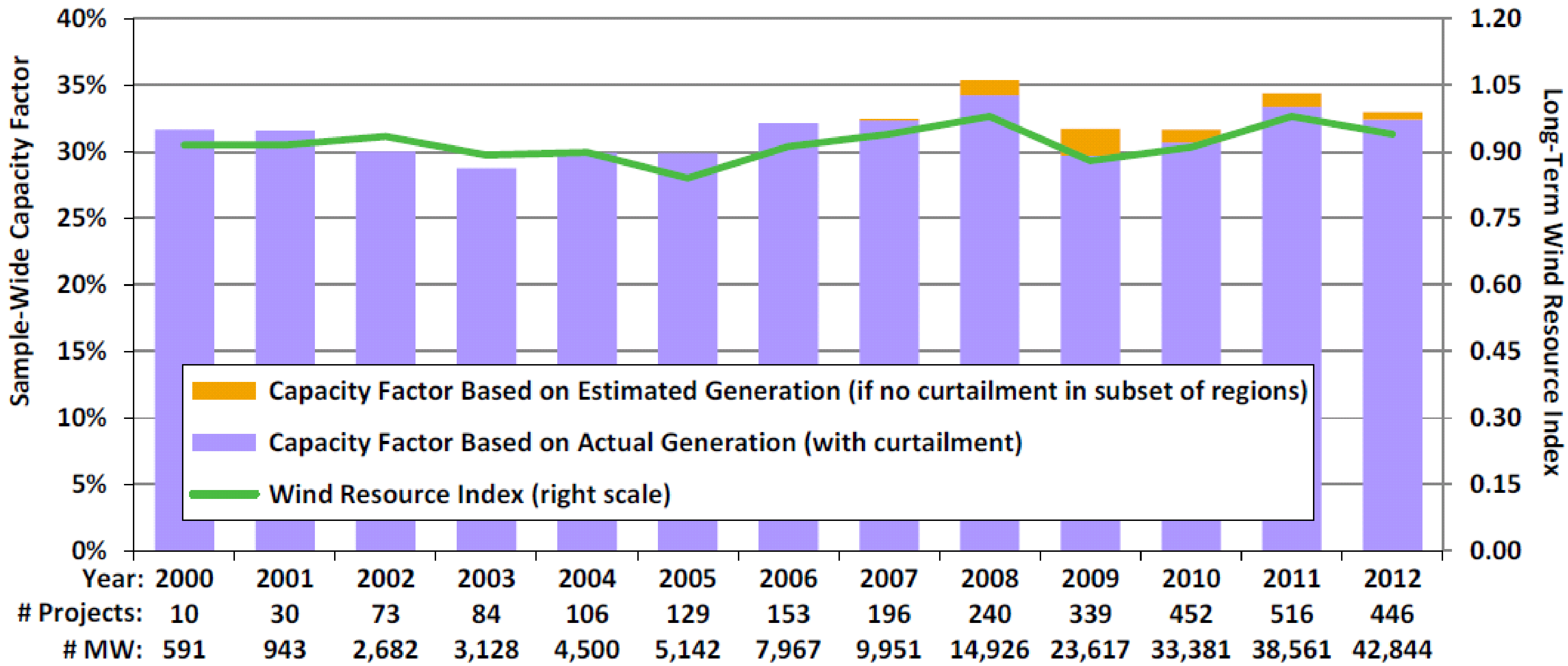


Figure 10. Unavailability Contributors, System Event Frequency and Downtime.

Continuous Reliability Enhancement for Wind (CREW) Database:
Wind Plant Reliability Benchmark.
Valerie A. Hines, Alistair B. Ogilvie, and Cody R. Bond
Sandia2013-7288

Wind Energy Economics

E. Design & Operations – Capacity Factor



Source: Berkeley Lab

Figure 27. Average Cumulative Sample-Wide Capacity Factor by Calendar Year

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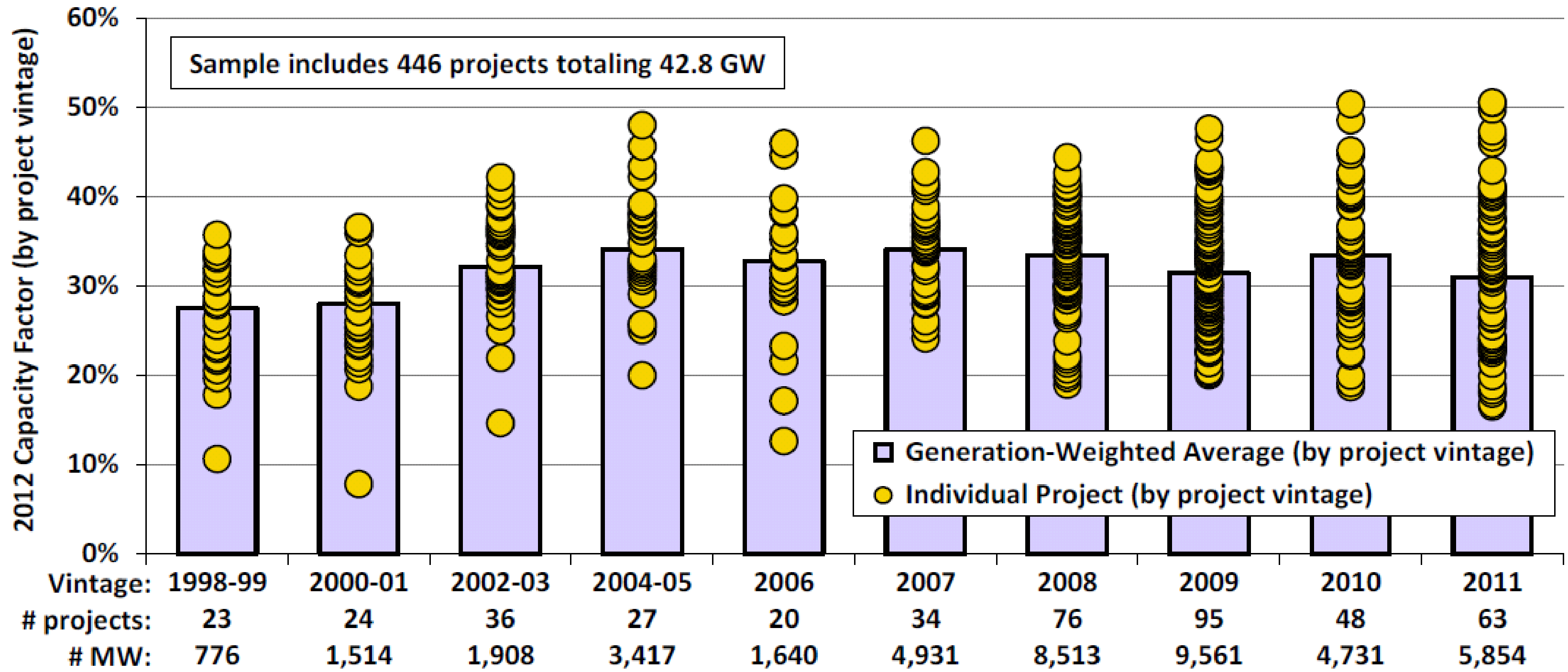
Ryan Wiser, Mark Bolinger

Wind Energy Economics

E. Design & Operations – Capacity Factor



Source: Berkeley Lab

Figure 28. 2012 Project Capacity Factors by Commercial Operation Date

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E. Design & Operations – Capacity Factor

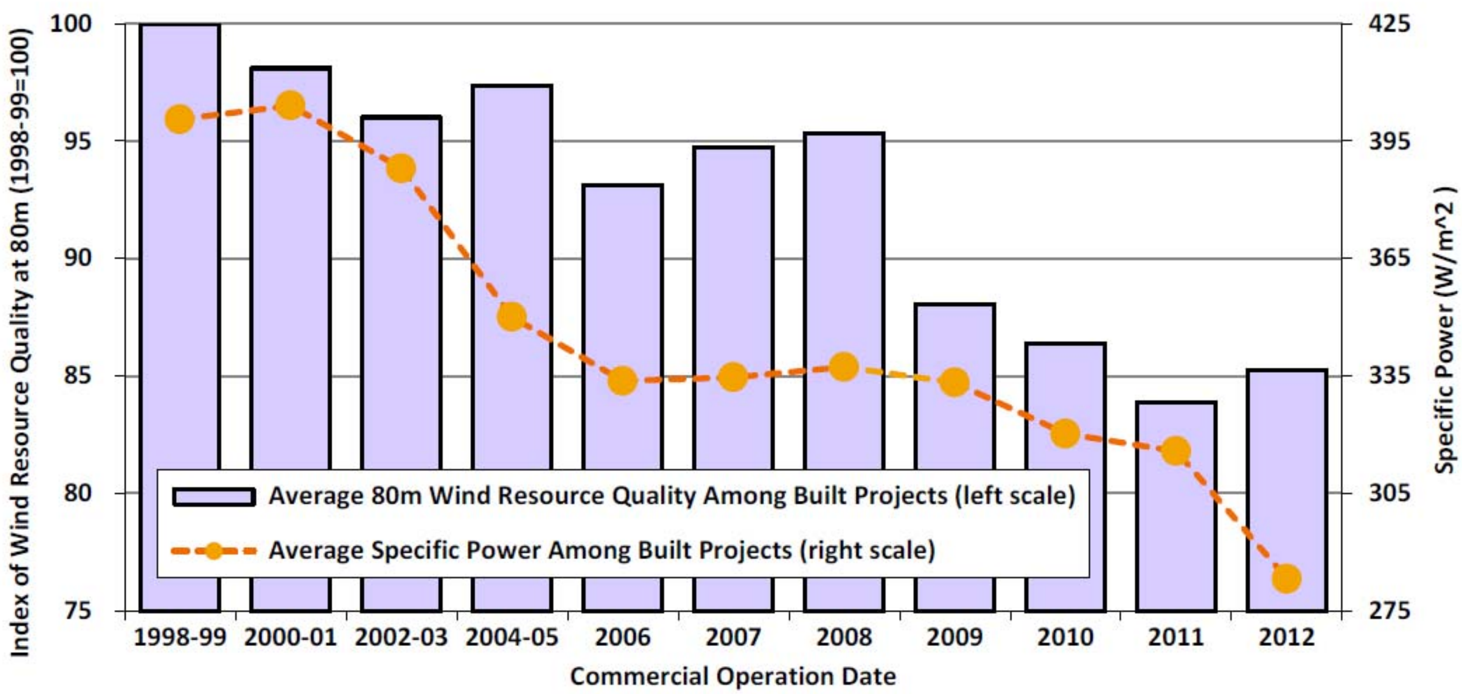

Figure 29. Index of Wind Resource Quality at 80 Meters vs. Specific Power

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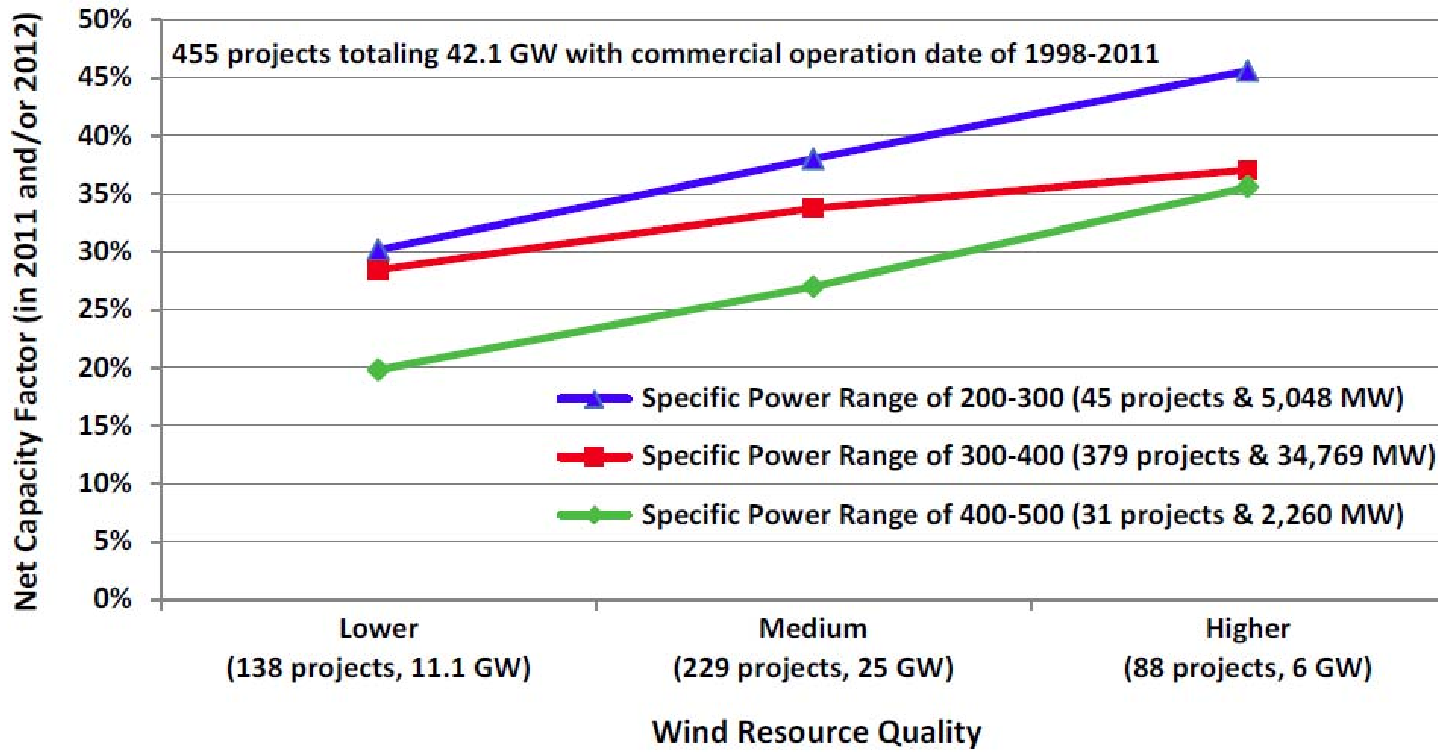
E. Design & Operations – Capacity Factor



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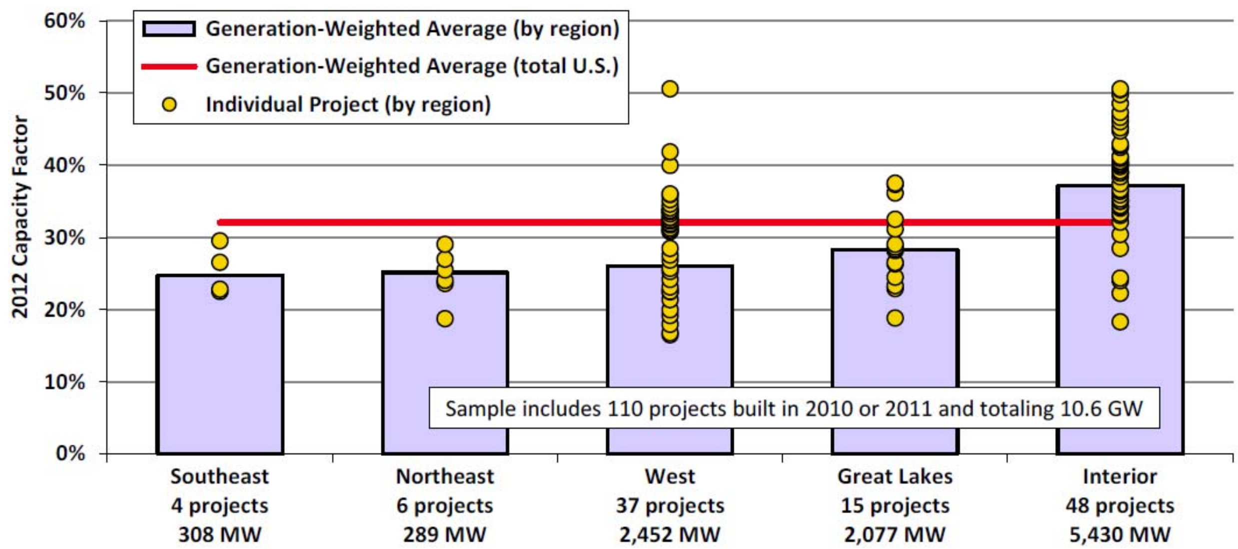
E. Design & Operations – Capacity Factor



Source: Berkeley Lab

Figure 31. 2012 Capacity Factors by Region: 2010–2011 Projects Only

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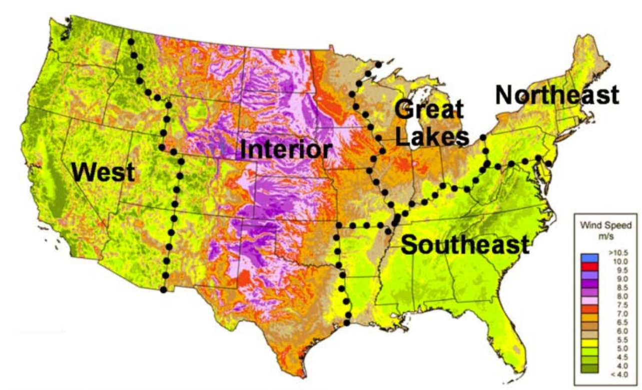


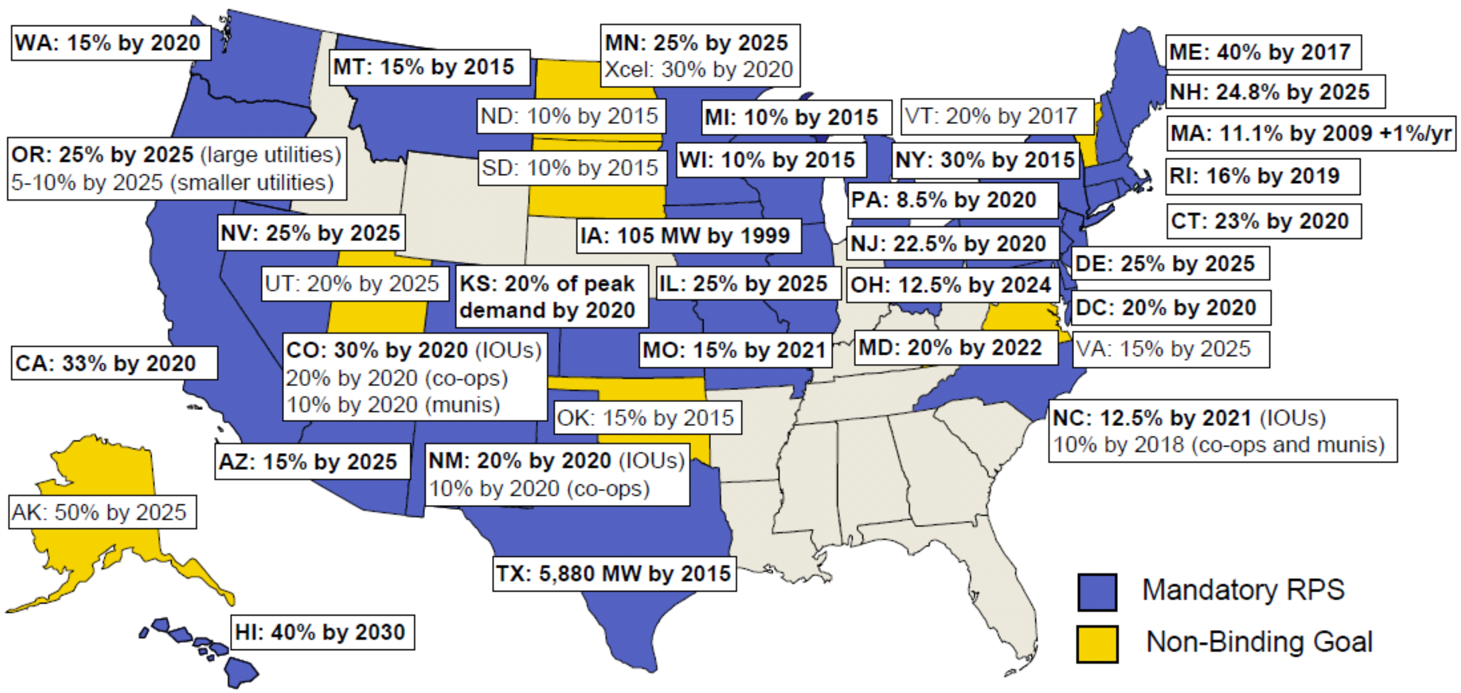
Source: AWS Truepower, National Renewable Energy Laboratory

Figure 24. Regional Boundaries Overlaid on a Map of Average Annual Wind Speed at 80 Meters

Wind Energy Economics

F. Policy and Incentives

2012 Wind Technologies Market Report
Ryan Wiser, Mark Bolinger



Source: Berkeley Lab

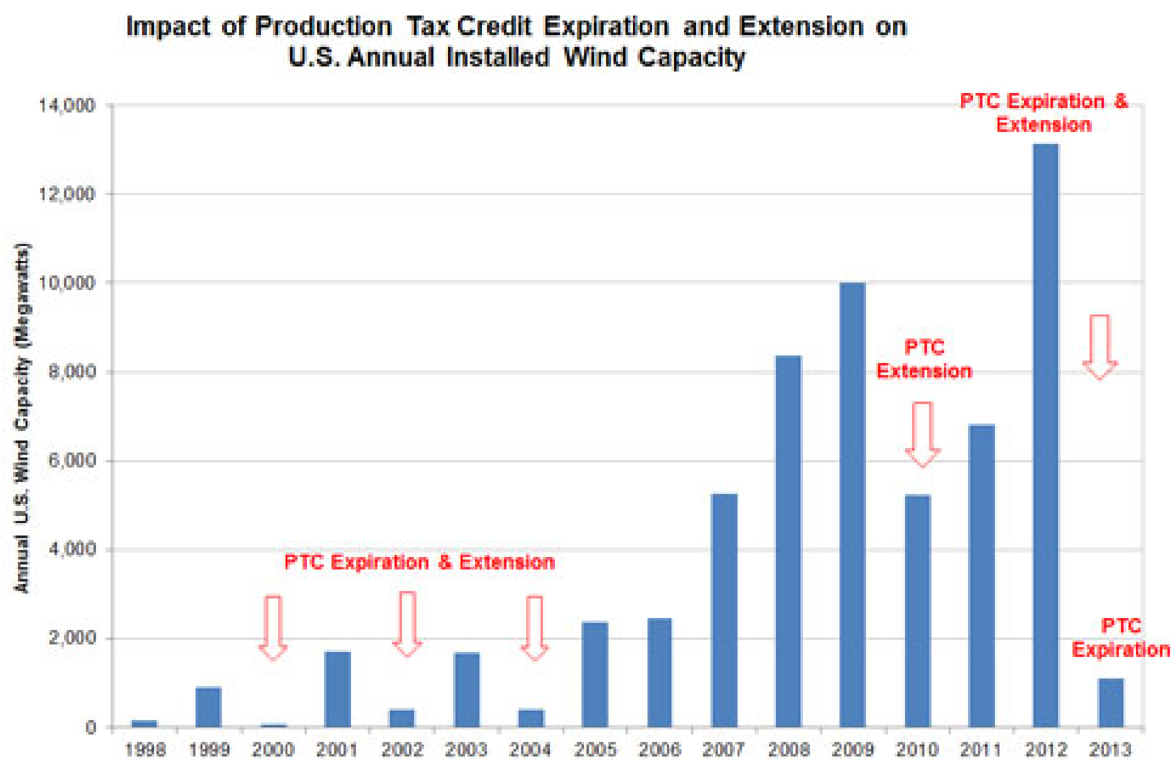
Note: The figure does not include West Virginia's mandatory "alternative and renewable energy portfolio standard" or Indiana's voluntary "clean energy standard." Under these two states' policies, both renewable and non-renewable energy resources may qualify, but neither state specifies any minimum contribution from renewable energy. Thus, for the purposes of the present report, these two states are not considered to have enacted mandatory RPS policies or non-binding renewable energy goals. Also not included in the figure are the mandatory RPS and non-binding renewable energy goals established in U.S. territories.

Figure 36. State RPS Policies and Non-Binding Renewable Energy Goals (as of June 2013)

Wind Energy Economics

F. Policy and Incentives
  1. 1.7 cents/kW-h in 1993 dollars
  2. Currently 2.3 cents/kW-h

Source: Union of Concerned Scientists



Wind Energy Economics

G. Cost of Delivered Renewable Electricity

1. Includes cost of generation, transmission and other costs

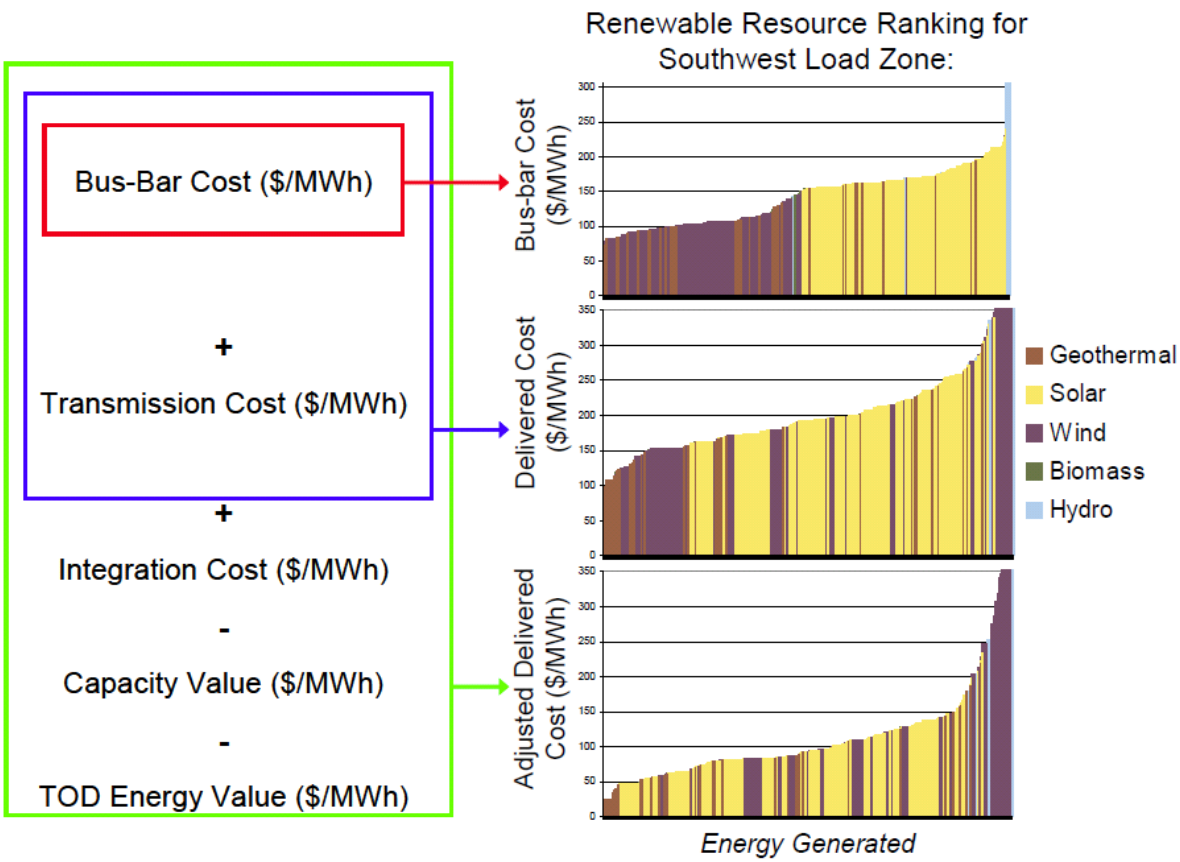


Figure ES-1. Framework for evaluating the economic attractiveness of renewable resources to load zones in the WREZ model

Exploration of Resource and Transmission Expansion Decisions in the Western Renewable Energy Zone Initiative

Andrew Mills, Amol Phadke, and Ryan Wiser

Wind Energy Economics

G. Cost of Delivered Renewable Electricity

1. Includes cost of generation, transmission and other costs

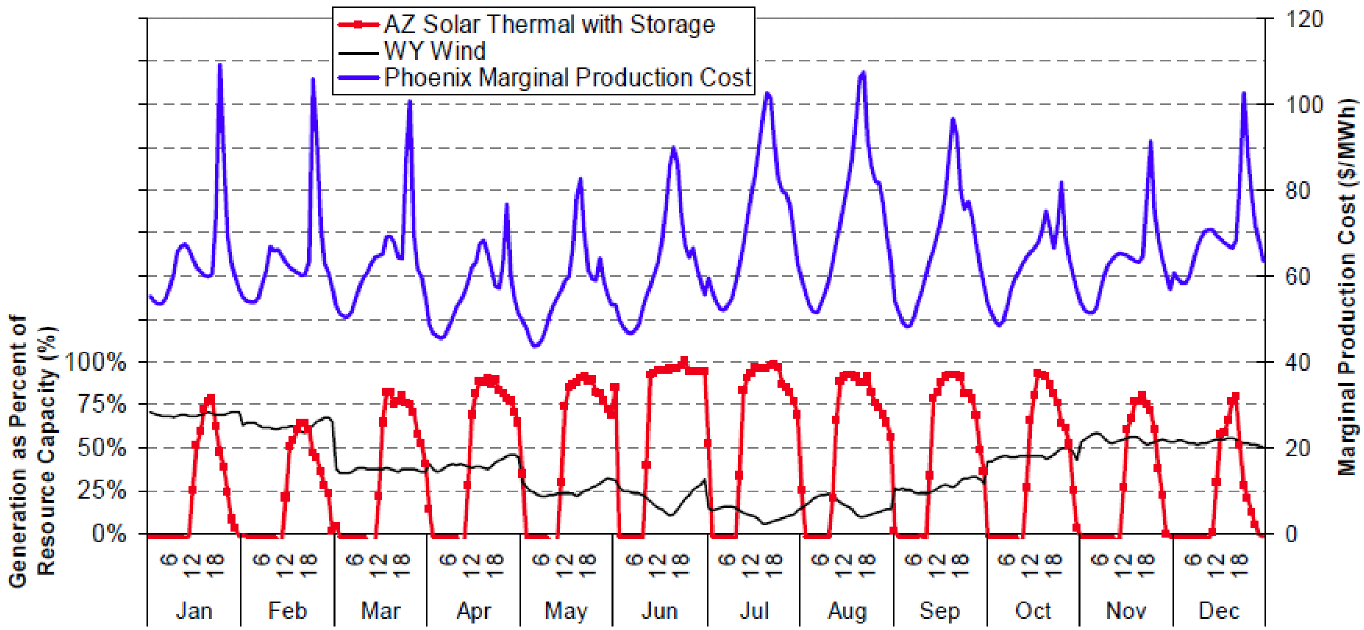
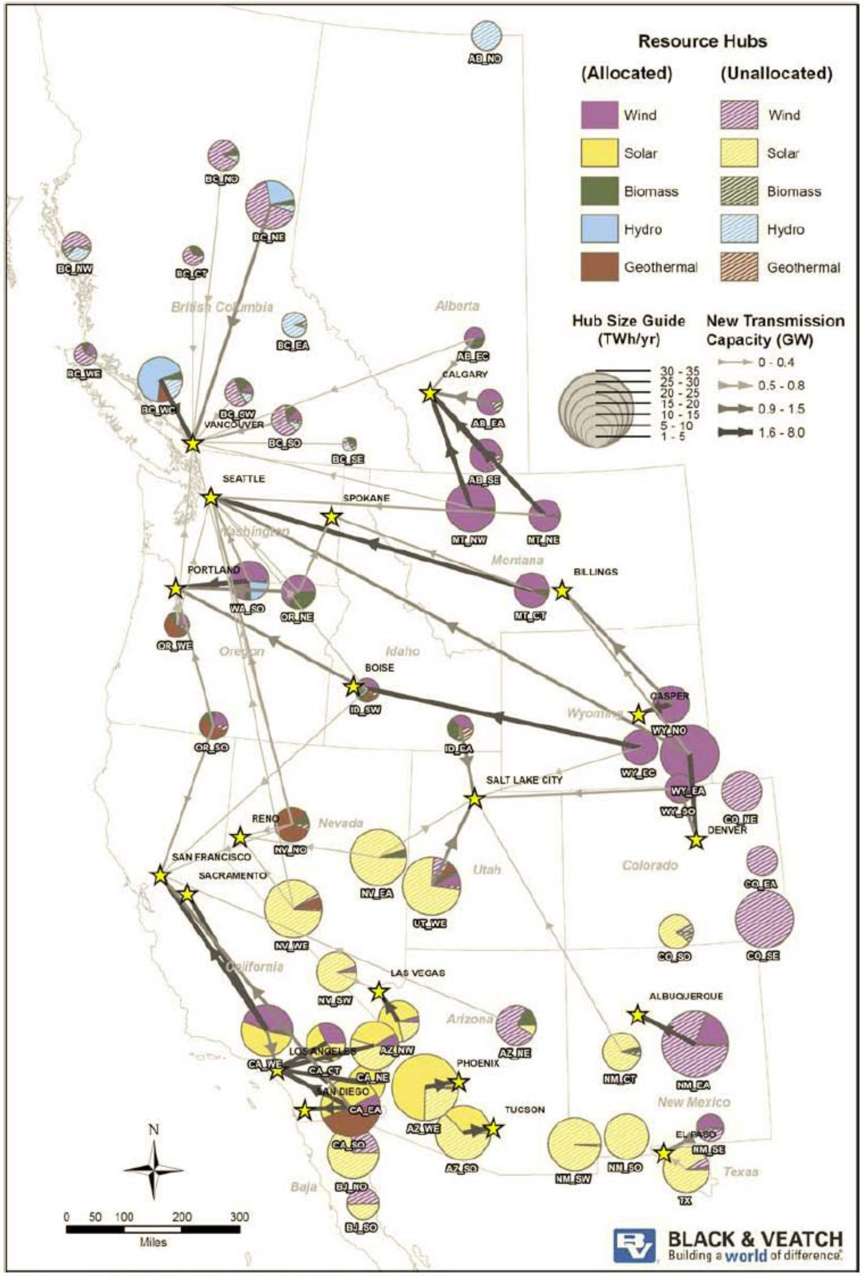


Figure 3. Example of TOD energy value comparison for WY wind and AZ solar thermal with storage for the Phoenix load zone

Exploration of Resource and Transmission Expansion Decisions in the Western Renewable Energy Zone Initiative

Andrew Mills, Amol Phadke, and Ryan Wiser



Map created 11/03/2009 by Sally Maki and Josh Finn

Note: The size of the WREZ hub reflects the total resource potential. The portion that is filled-in represents the resource that is procured by a load zone.

Figure ES-2. Transmission and resource selection in the WECC-wide 33% Base case

Exploration of Resource and Transmission Expansion Decisions in the Western Renewable Energy Zone Initiative

Andrew Mills, Amol Phadke, and Ryan Wiser

Wind Energy Economics

G. Cost of Delivered Renewable Electricity

Table ES-1. WECC-wide impact of increasing renewable energy levels on resource composition, costs, and transmission expansion

Impact		12% Renewables		25% Renewables		33% Renewables	
		(TWh/yr)	(GW)	(TWh/yr)	(GW)	(TWh/yr)	(GW)
Resource Composition	Geothermal	22.7	3.0	28.6	3.9	28.6	3.9
	Biomass	7.9	1.1	17.2	2.3	20.7	2.8
	Hydro	6.5	1.5	12.0	2.7	16.7	3.7
	Wind	42.2	13.2	108.5	36.1	144.3	48.2
	Solar	0.0	0.0	47.1	13.7	85.5	25.0
Costs	Average Adjusted Delivered Cost ($/MWh)		23.6		37.2		43.2
	Marginal Adjusted Delivered Cost ($/MWh)		33.9		54.7		61.5
Transmission Expansion	New Capacity (GW-mi)		4,123		11,958		18,510
	Transmission Investment ($ Billion)		5.9		17.0		26.3
	Transmission and Losses Cost as Percentage of Delivered Cost		16%		14%		15%

Exploration of Resource and Transmission Expansion Decisions in the Western Renewable Energy Zone Initiative

Andrew Mills, Amol Phadke, and Ryan Wiser

Wind Energy Economics

G. Cost of Delivered Renewable Electricity

Exploration of Resource and Transmission Expansion Decisions in the Western Renewable Energy Zone Initiative

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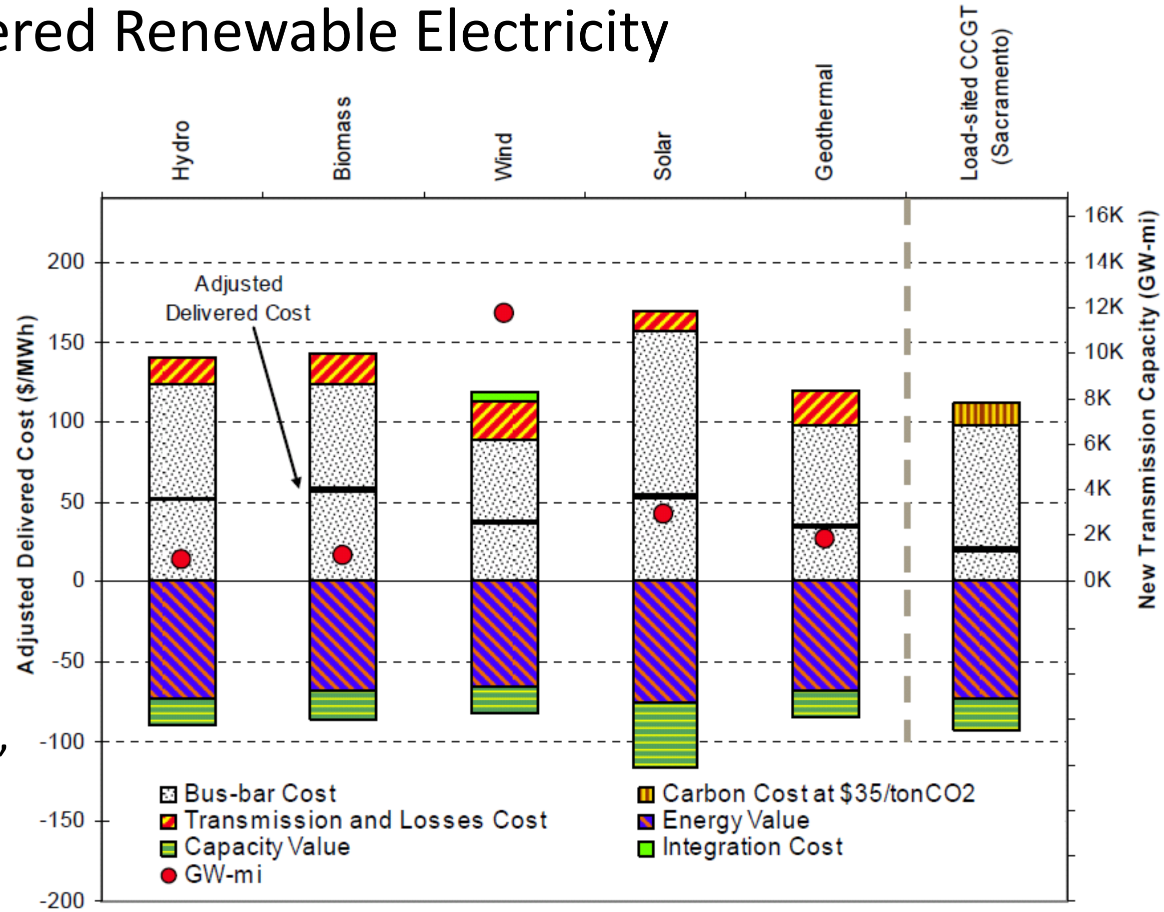

Note: The cost and value components of a load-sited combined-cycle gas turbine (CCGT) in Sacramento assuming an $8/MMBTU natural gas price and a carbon cost adder are provided for reference.

Figure 10. Average cost and value components of the adjusted delivered cost for the various RE technologies and required transmission expansion in the Base case.

Wind Energy Economics

G. Cost of Delivered Renewable Electricity

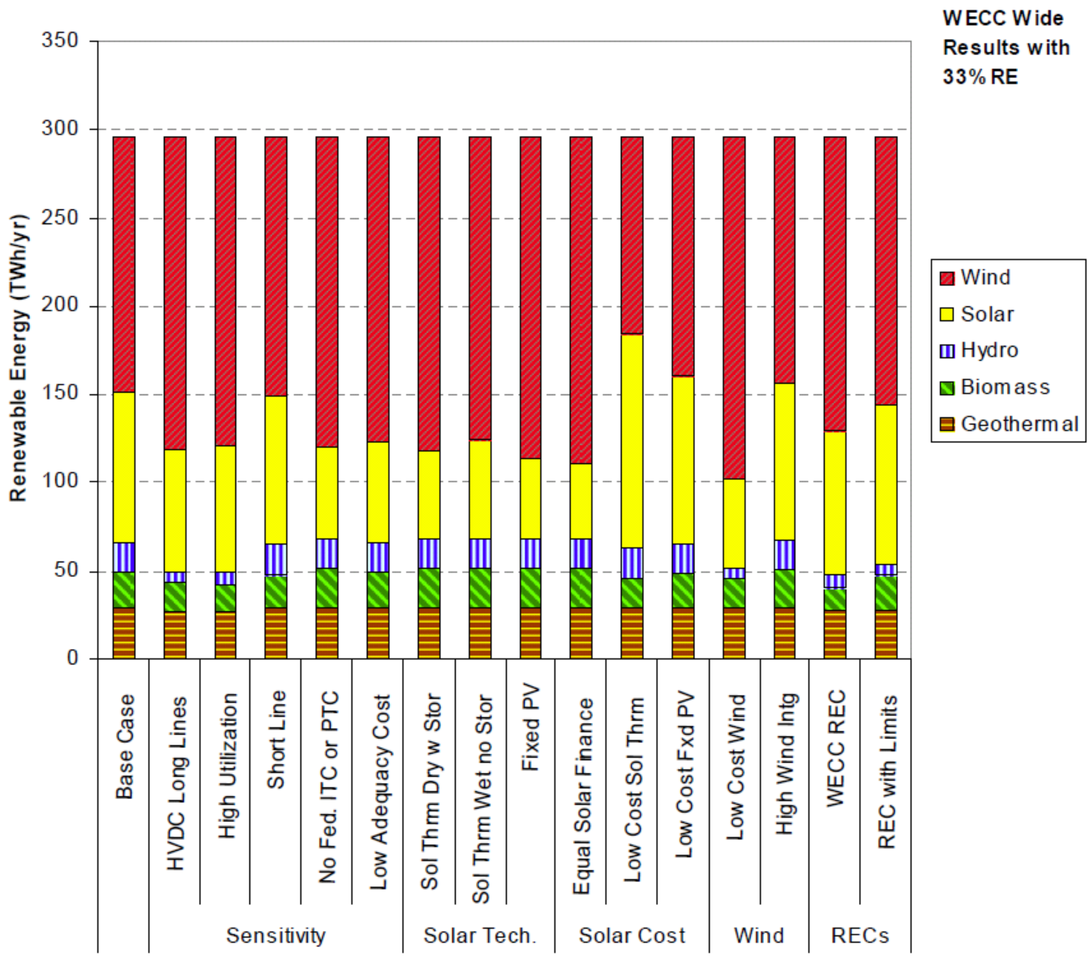

Figure 11. Resource composition in 33% renewable energy scenarios

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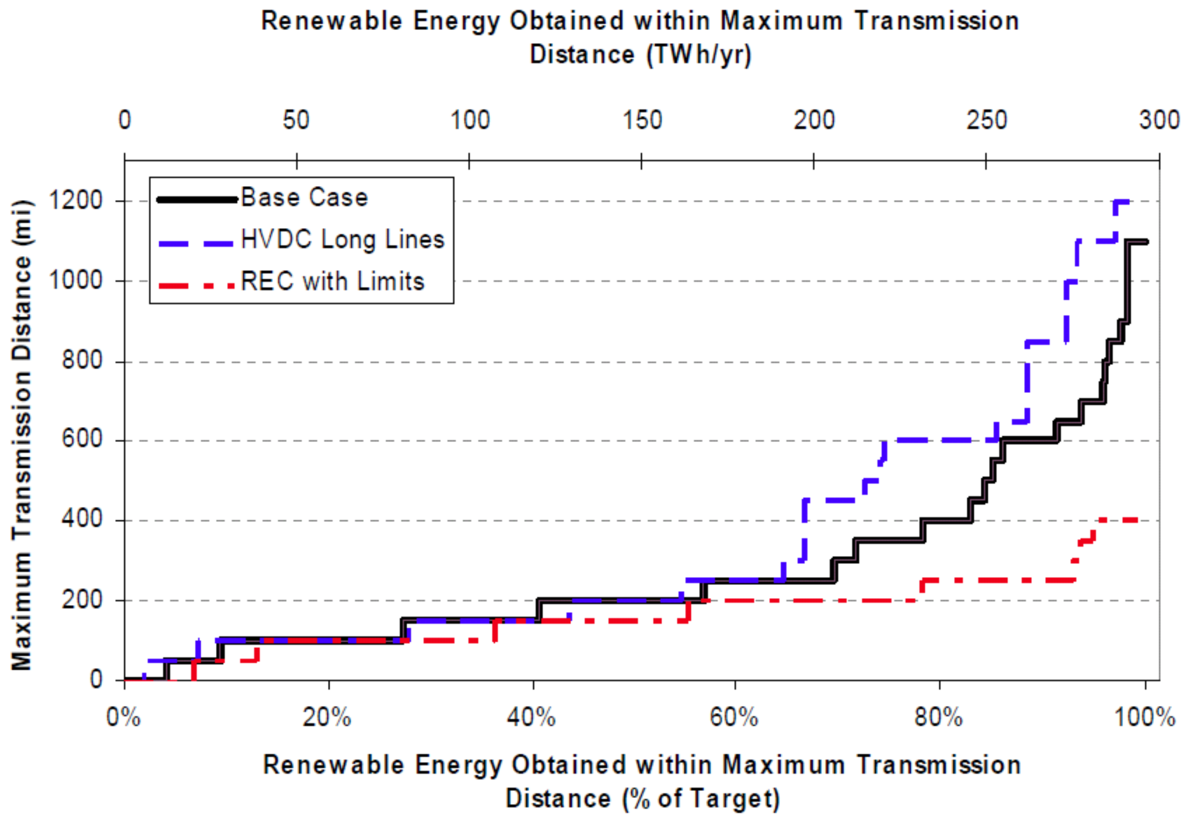
G. Cost of Delivered Renewable Electricity



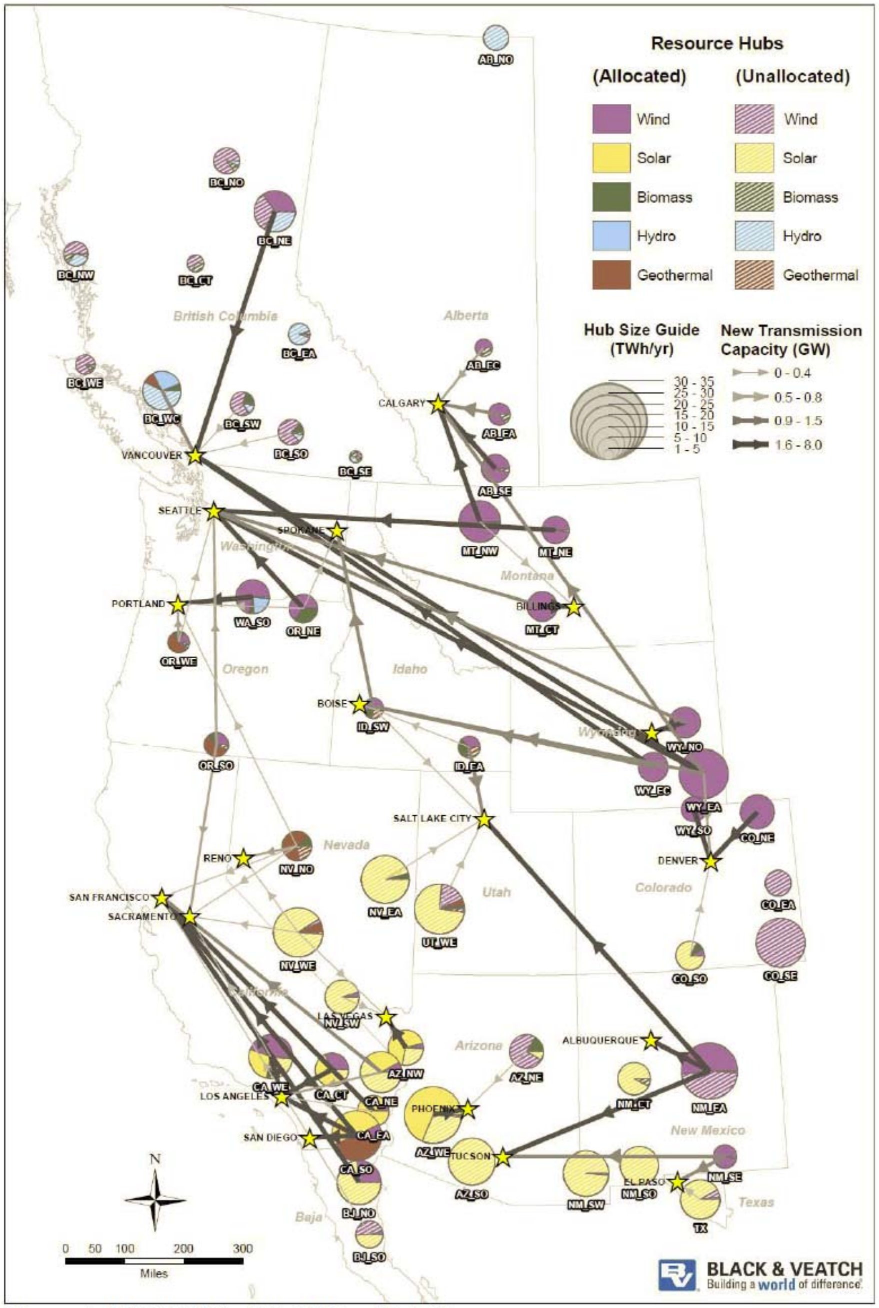
Note: Each step increases the maximum transmission distance by 50 miles.

Figure ES-6. Quantity of RE procured within a maximum transmission distance from each load zone in the Base case, the HVDC Long Lines case, and the REC with Limits case.

Value of Diversity?

Exploration of Resource and Transmission Expansion Decisions in the Western Renewable Energy Zone Initiative

Andrew Mills, Amol Phadke, and Ryan Wiser



Map created 11/03/2009 by Sally Maki and Josh Finn

Figure 16. Transmission and resource selection to meet 33% RE WECC-wide in the HVDC Long Lines case

HVDC case

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Value of Diversity?

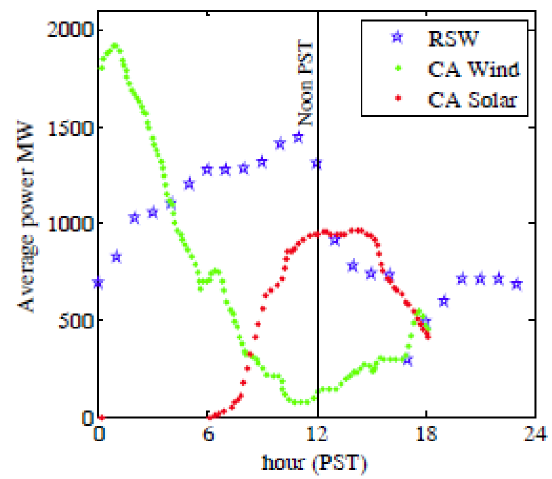
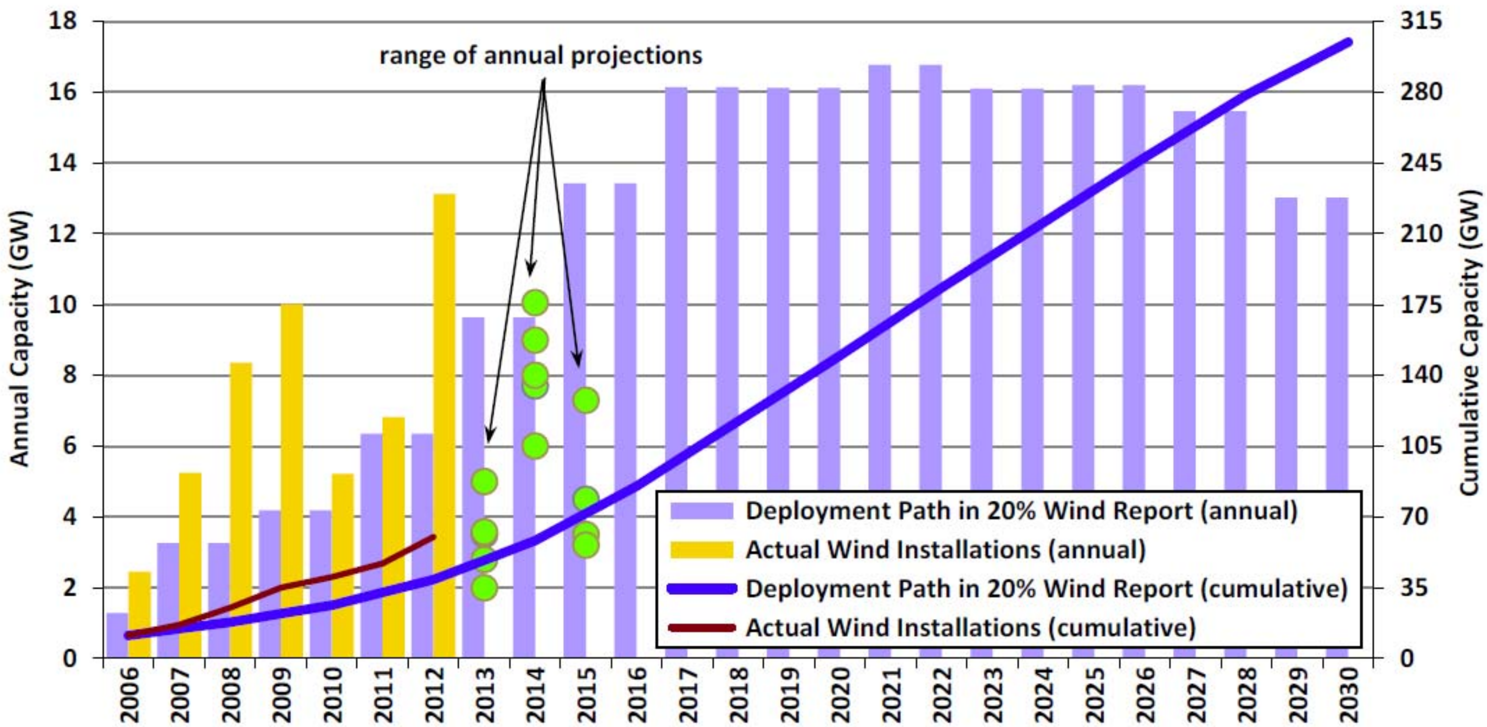


Figure 14- California wind and solar production on August 9, 2012 along with the summer diurnal output from 3000 MW of installed capacity in Rawlins, WY (RSW). The summer diurnal output for the Wyoming sites has been determined by averaging over the period June-September.

Wind Diversity Enhancement of Wyoming/California Wind Energy Projects
Naughton et al.

Wind Energy Economics

H. Economic Impact on Installation



Source: DOE 2008 (20% wind scenario), AWEA (historical additions), Table 6 (projected additions)

Figure 39. Wind Power Capacity Growth: 20% Wind Report, Actual Installations, Projected Growth

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