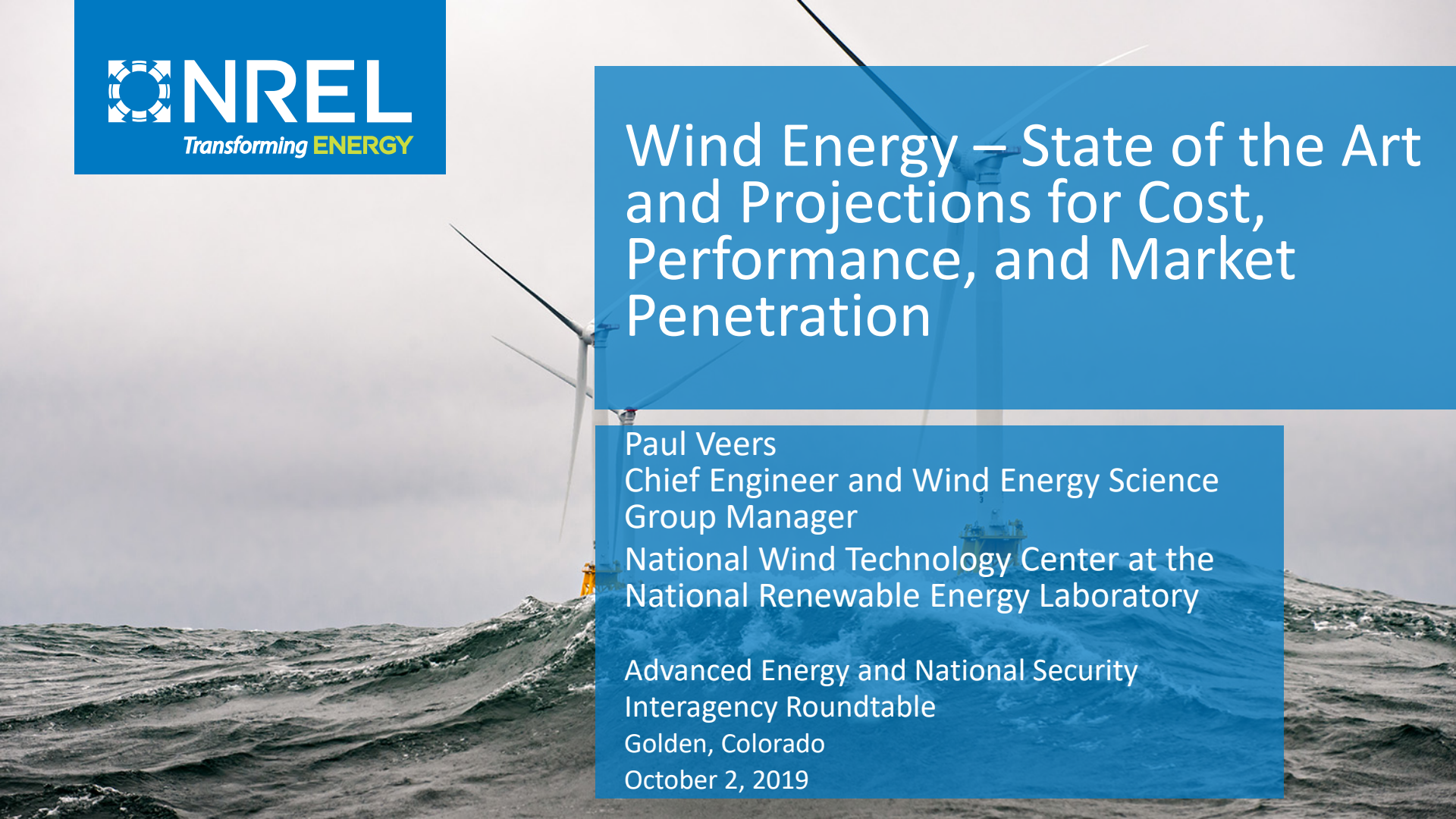


Wind Energy – State of the Art and Projections for Cost, Performance, and Market Penetration

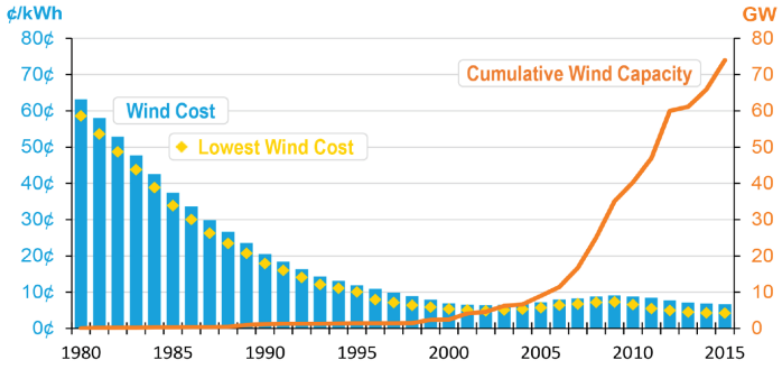
Paul Veers
Chief Engineer and Wind Energy Science Group Manager
National Wind Technology Center at the National Renewable Energy Laboratory

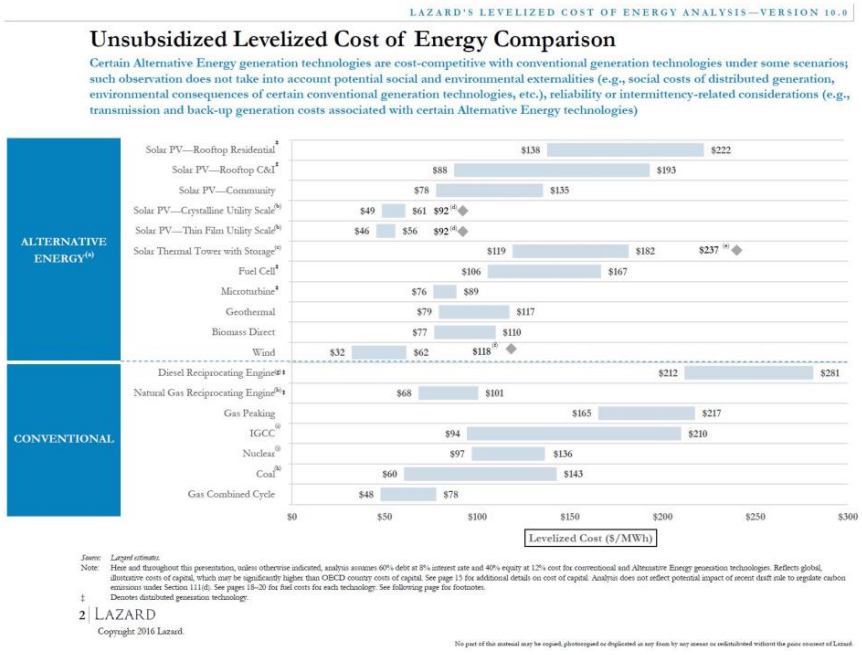
Advanced Energy and National Security Interagency Roundtable
Golden, Colorado
October 2, 2019

Wind Energy: Past and Present

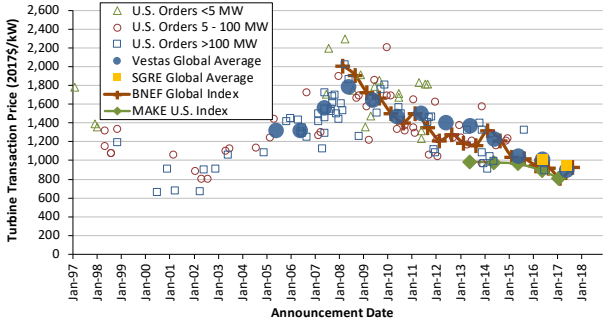
Decreased costs in wind energy have led to exponentially increasing deployment

- Lowest cost electricity available in 2016 (Lazard)
- Current costs: 3-7 cents/kilowatt-hour (kWh)
- Wind provided over 6% of U.S. electricity in 2017
- US Wind capacity (89 gigawatts [GW]) now exceeds hydropower (80 GW).

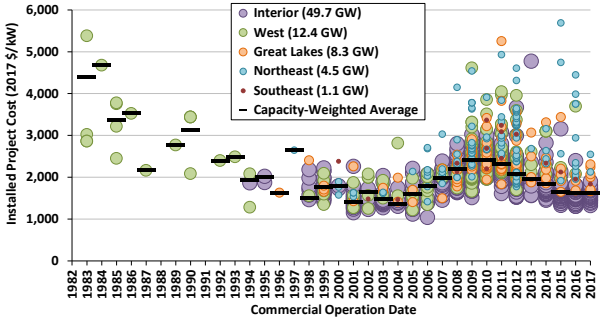




Turbine



Plant

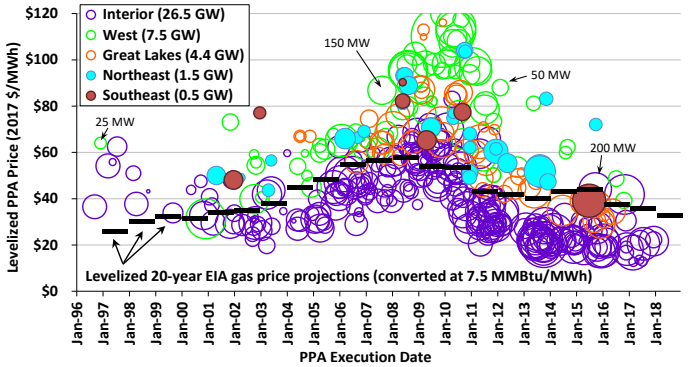


megawatt (MW)
megawatt-hour (MWh)
Million British thermal units (MMBtu)

Wind Turbine Prices Remained Well Below the Levels Seen 10 Years Ago

- Recent turbine orders in the range of $800–950/kilowatt (kW)
- 2017 projects had an average cost of $1,610/kW, down $795/kW since 2009–2010
- Limited sample of under-construction projects suggest somewhat lower costs in 2018.

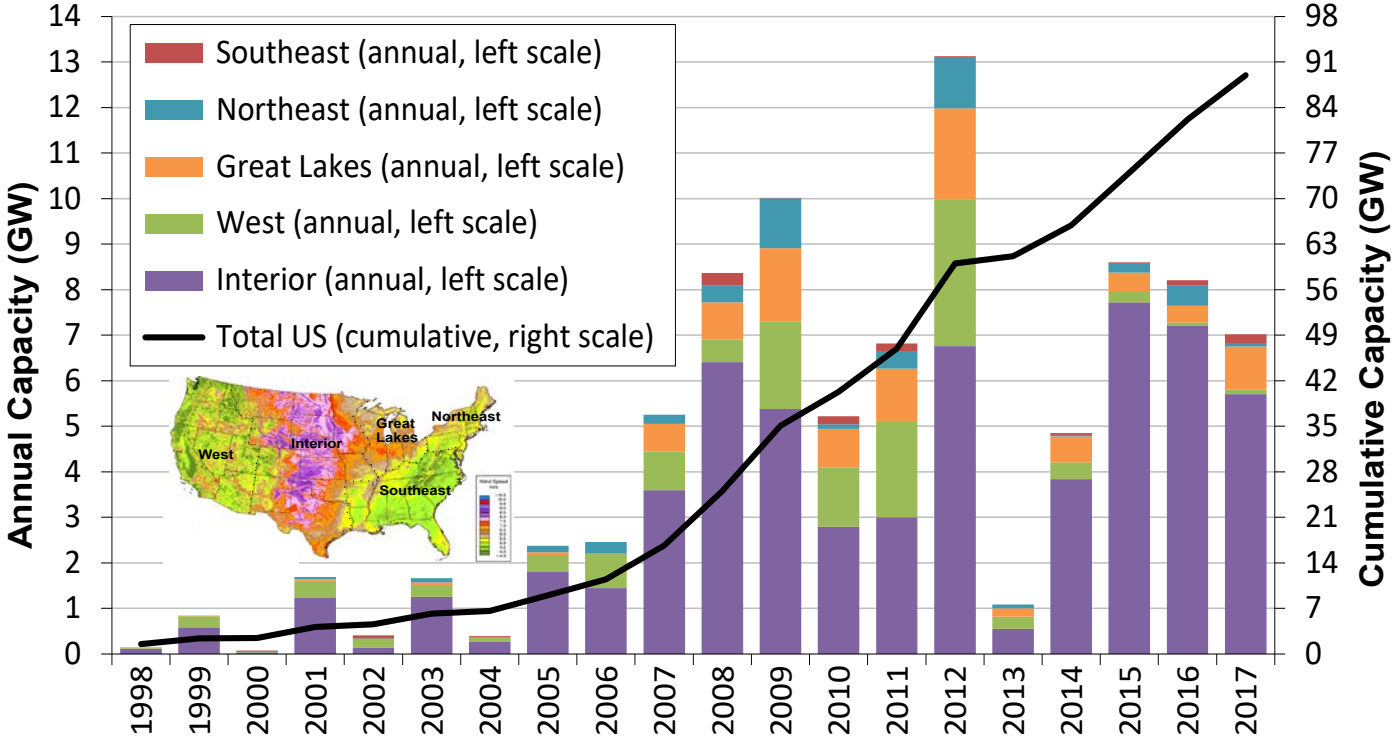
Power Purchase



Gas-powered generation

Wind Power Additions Continued at a Rapid Pace in 2017, with 7,017 MW of New Capacity, Bringing the Total to 88,973 MW

- Investments of $11 billion in wind power project additions in 2017
- Over 80% of new 2017 capacity located in the Interior region
- Partial repowering trend: 2,131 MW of existing plants retrofitted w/longer blades.



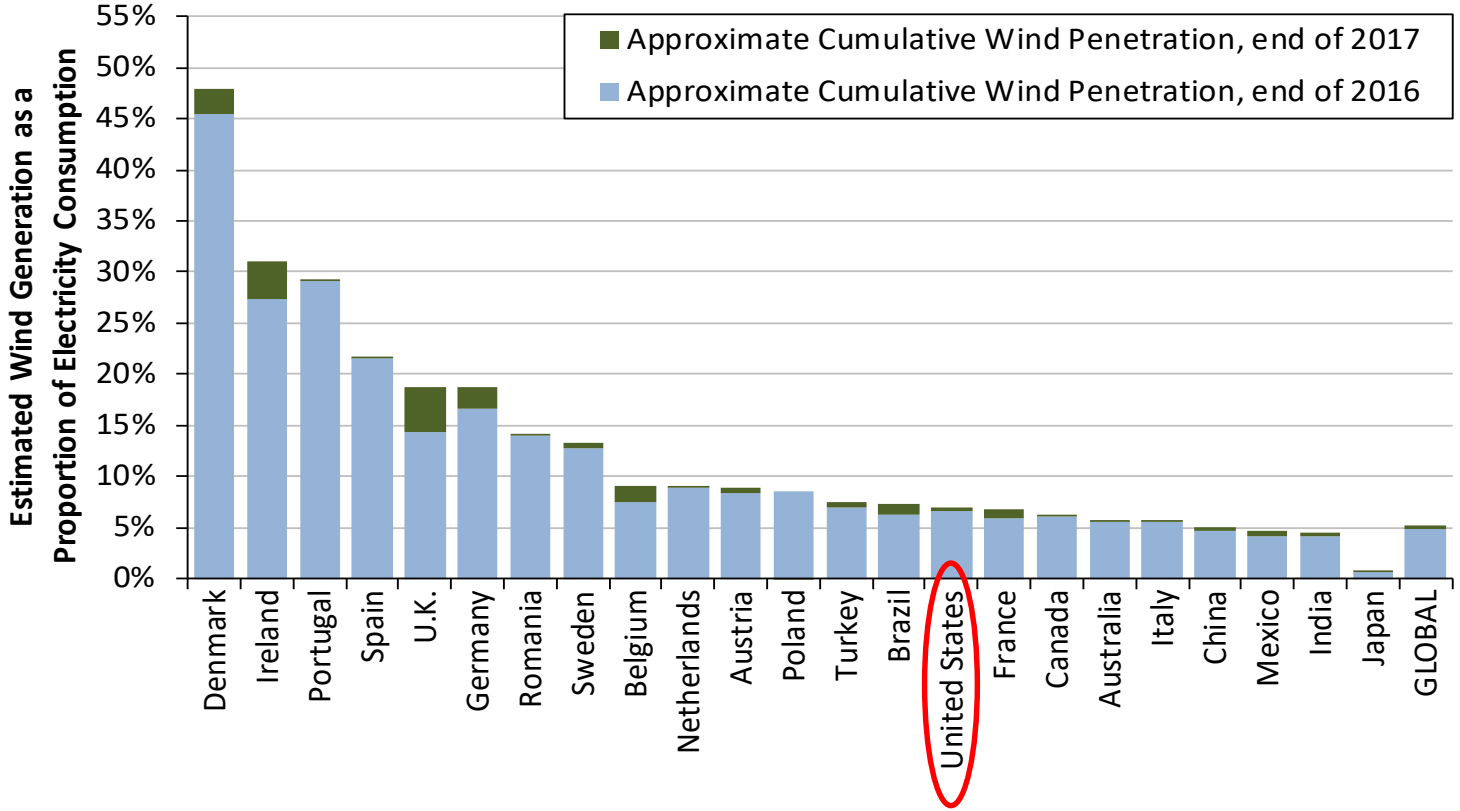
Globally, the United States Placed Second in Annual Wind Power Capacity Additions in 2017 and in Cumulative Wind Power Capacity

Annual Capacity (2017, MW)	
China	19,660
United States	**7,017**
Germany	6,581
United Kingdom	4,270
India	4,148
Brazil	2,022
France	1,694
Turkey	766
South Africa	618
Finland	535
Rest of World	5,182
TOTAL	**52,492**

Cumulative Capacity (end of 2017, MW)	
China	188,392
United States	**88,973**
Germany	56,132
India	32,848
Spain	23,170
United Kingdom	18,872
France	13,759
Brazil	12,763
Canada	12,239
Italy	9,479
Rest of World	82,391
TOTAL	**539,019**

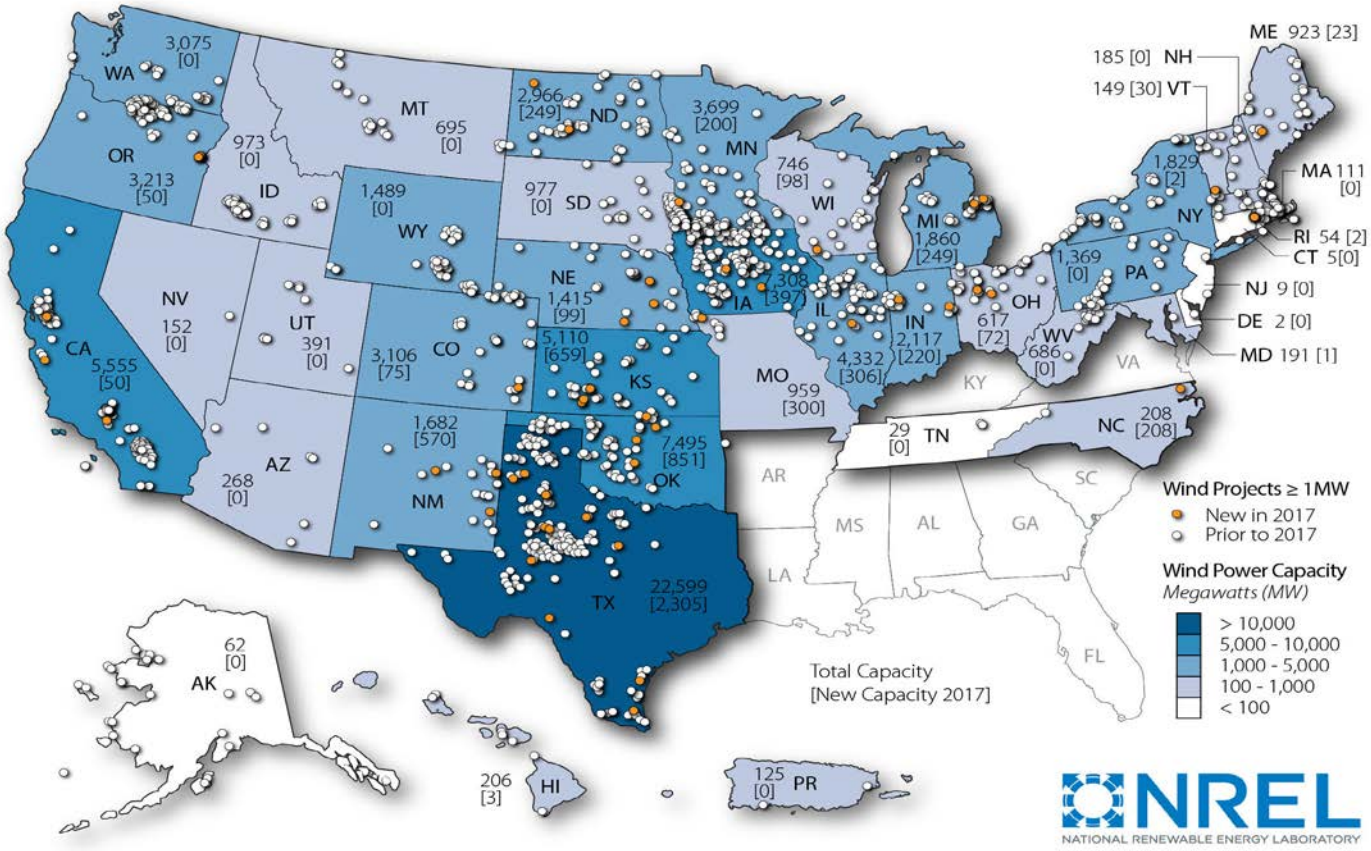
- United States also remains a distant second to China in cumulative capacity
- Global wind additions in 2017 were below the 54,600 MW added in 2016 and the record level of 63,000 MW added in 2015.

The United States is Lagging Other Countries in Wind as a Percentage of Electricity Consumption



Note: Figure only includes the countries with the most installed wind power capacity at the end of 2017.

The Geographic Spread of Wind Power Projects Across the United States Is Broad, with the Exception of the Southeast



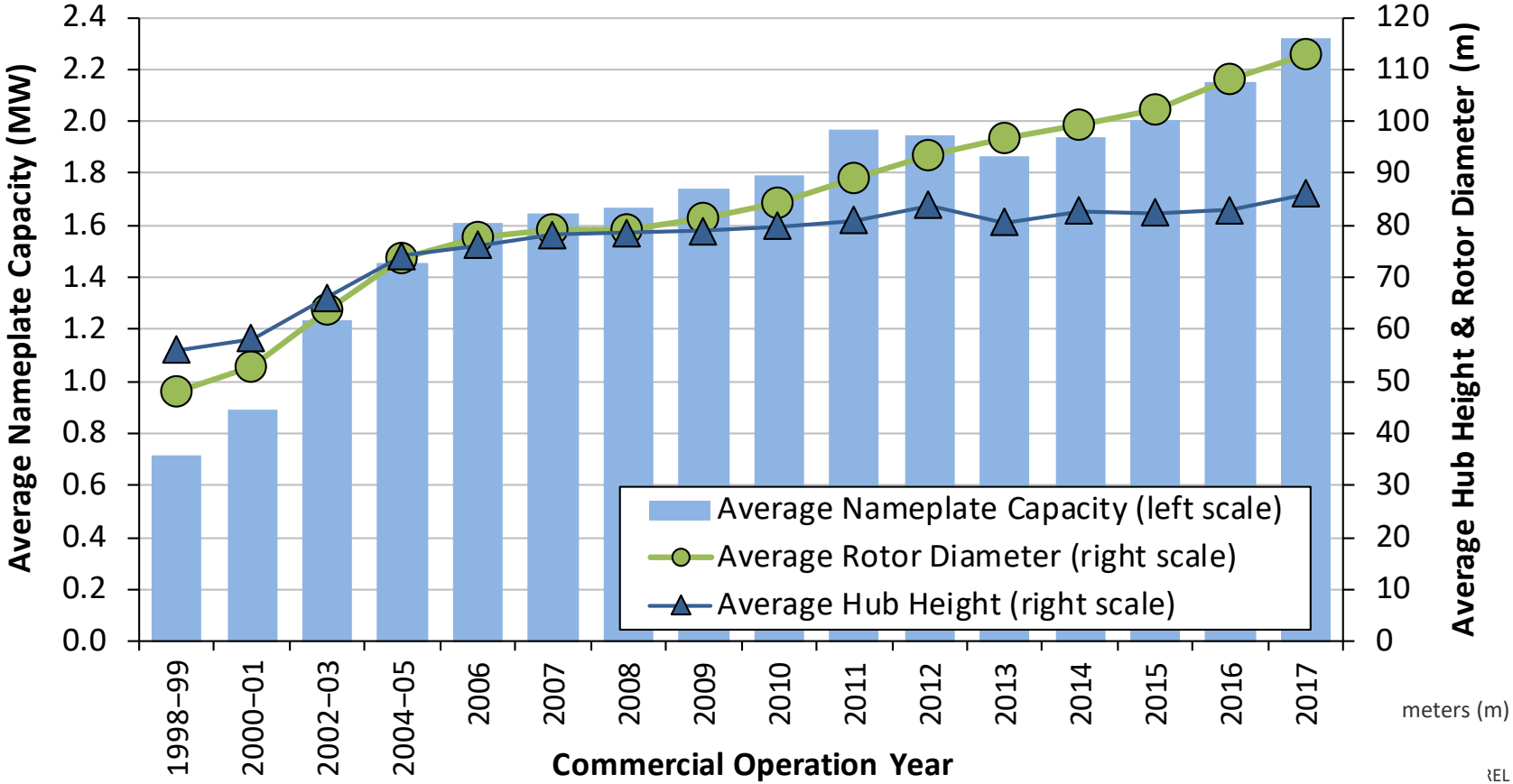
Note: Numbers within states represent cumulative installed wind capacity and, in brackets, annual additions in 2017

Texas Installed the Most Wind Power Capacity in 2017; 14 States Exceed 10% Wind Energy, 4 States Exceed 30%

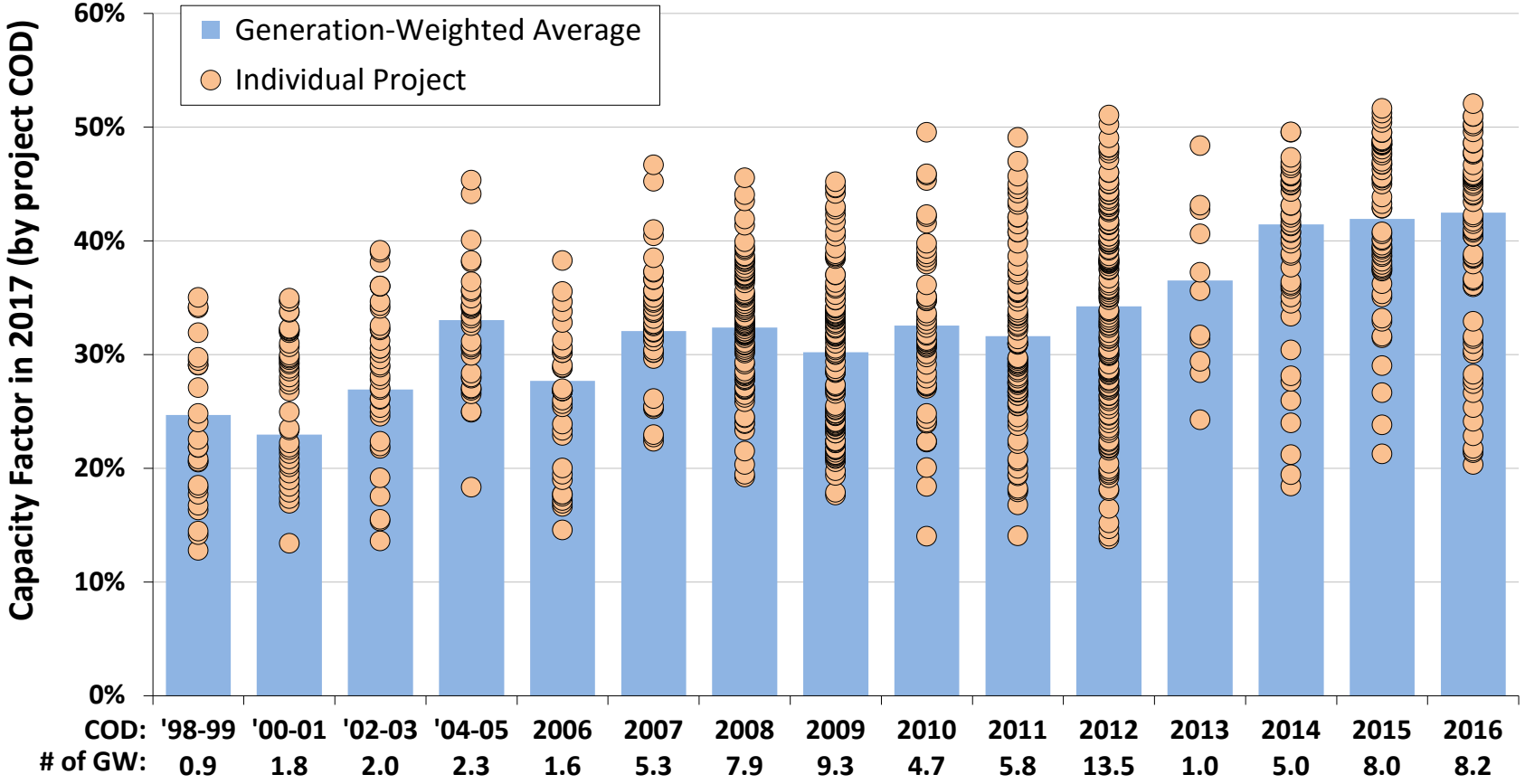
Installed Capacity (MW)				2017 Wind Generation as a Percentage of:			
Annual (2017)		Cumulative (end of 2017)		In-State Generation		In-State Load	
Texas	2,305	Texas	22,599	Iowa	36.9%	North Dakota	58.3%
Oklahoma	851	Oklahoma	7,495	Kansas	36.0%	Kansas	47.1%
Kansas	659	Iowa	7,308	Oklahoma	31.9%	Iowa	43.0%
New Mexico	570	California	5,555	South Dakota	30.1%	Oklahoma	40.9%
Iowa	397	Kansas	5,110	North Dakota	26.8%	Wyoming	26.3%
Illinois	306	Illinois	4,332	Maine	19.9%	South Dakota	25.7%
Missouri	300	Minnesota	3,699	Minnesota	18.2%	New Mexico	19.7%
North Dakota	249	Oregon	3,213	Colorado	17.6%	Maine	19.5%
Michigan	249	Colorado	3,106	Idaho	15.4%	Colorado	17.5%
Indiana	220	Washington	3,075	Texas	14.8%	Nebraska	17.4%
North Carolina	208	North Dakota	2,996	Nebraska	14.6%	Texas	17.3%
Minnesota	200	Indiana	2,117	New Mexico	13.5%	Minnesota	16.7%
Nebraska	99	Michigan	1,860	Vermont	13.4%	Montana	14.8%
Wisconsin	98	New York	1,829	Oregon	11.1%	Oregon	13.5%
Colorado	75	New Mexico	1,682	Wyoming	9.4%	Idaho	10.4%
Ohio	72	Wyoming	1,489	Montana	7.6%	Illinois	8.3%
Oregon	50	Nebraska	1,415	California	6.8%	Washington	8.3%
California	50	Pennsylvania	1,369	Hawaii	6.5%	Hawaii	6.9%
Vermont	30	South Dakota	977	Washington	6.5%	California	5.5%
Maine	23	Idaho	973	Illinois	6.2%	Vermont	5.2%
Rest of U.S.	7	*Rest of U.S.*	6,774	*Rest of U.S.*	1.1%	*Rest of U.S.*	1.2%
TOTAL	7,017	TOTAL	88,973	TOTAL	6.3%	TOTAL	6.9%

2017 wind penetration by independent system operator (ISO): Southwest Power Pool: 23.2%; Electric Reliability Council of Texas: 17.4%; Midcontinent Independent System Operator: 7.7%; California ISO: 6.0%; New York Independent System Operator: 2.7%; PJM: 2.7%; ISO-New England: 2.6%

Turbine Capacity, Rotor Diameter, and Hub Height Have All Increased Significantly Over the Long Term, and in 2017



Capacity Factors Have Increased Significantly Over Time, by Online Date (i.e., Commercial Online Date [COD])

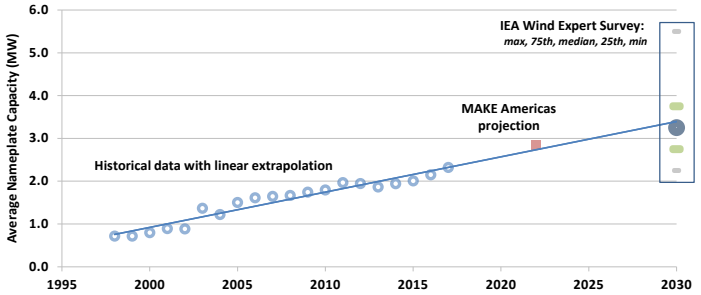


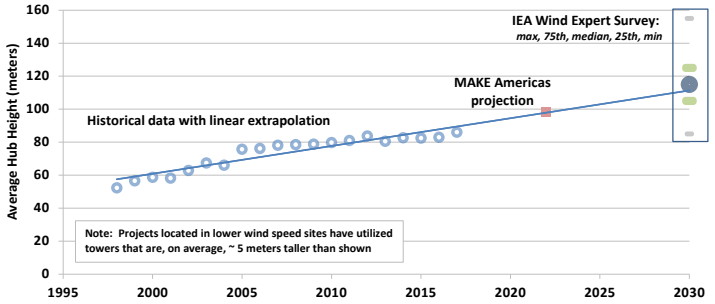
Extrapolation of Turbine Markets in 2030

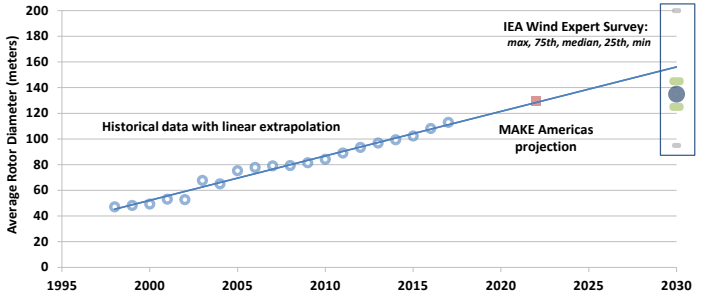
Capacity – 3.3 MW

Hub Height – 111 m

Rotor Diameter – 156 m

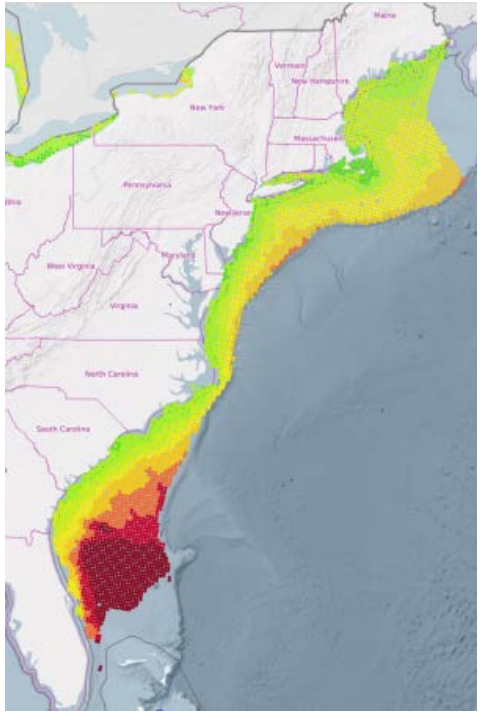




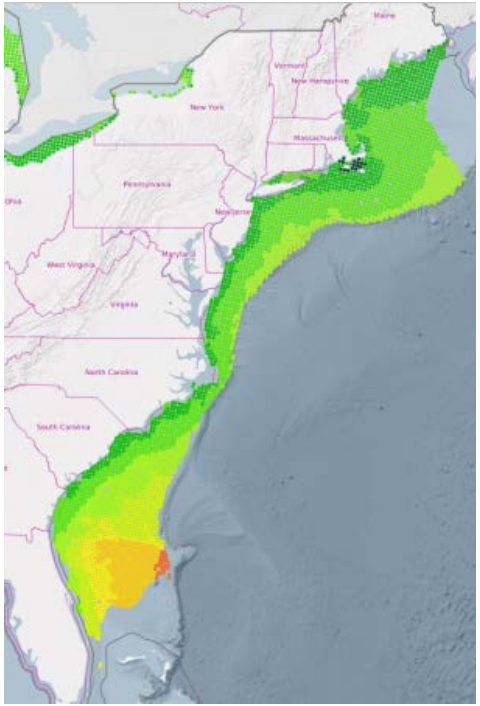


Levelized Cost of Energy for Potential Offshore Wind Projects in the Atlantic Region (Financial Close 2015 to 2025; All Foundation Types)

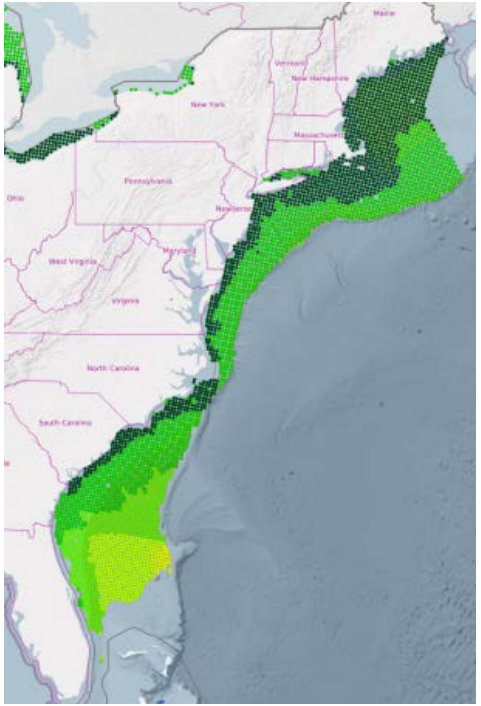
COD 2015 (FC 2013)



COD 2022 (FC 2020)



COD 2027 (FC 2025)

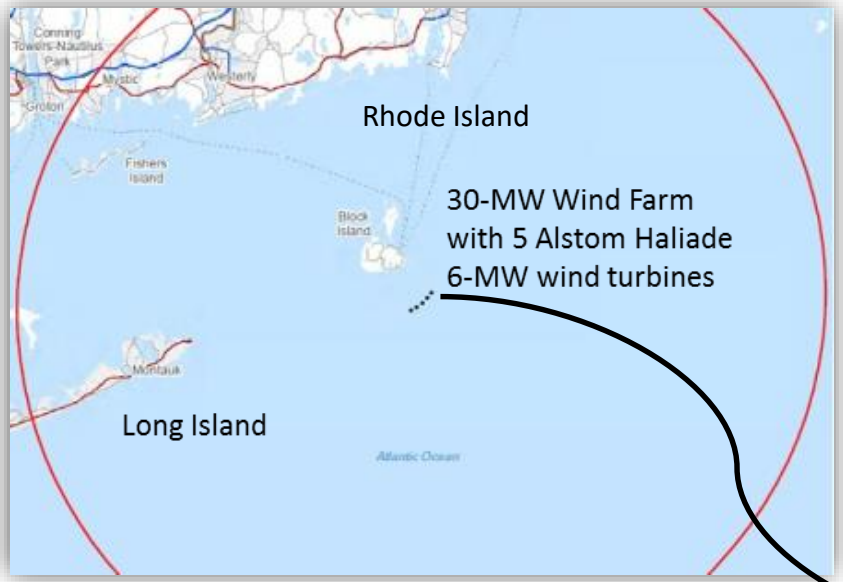


Levelized Cost of Energy (LCOE) (in $/MWh)

Legend

<=100	125 - 150	175 - 200	225 - 250	275 - 300
100 - 125	150 - 175	200 - 225	250 - 275	>300

America's First Offshore Wind Farm



Regional location of Deepwater Wind's Block Island Wind Farm, south of Block Island, Rhode Island

(Map credit: AWS Truepower)

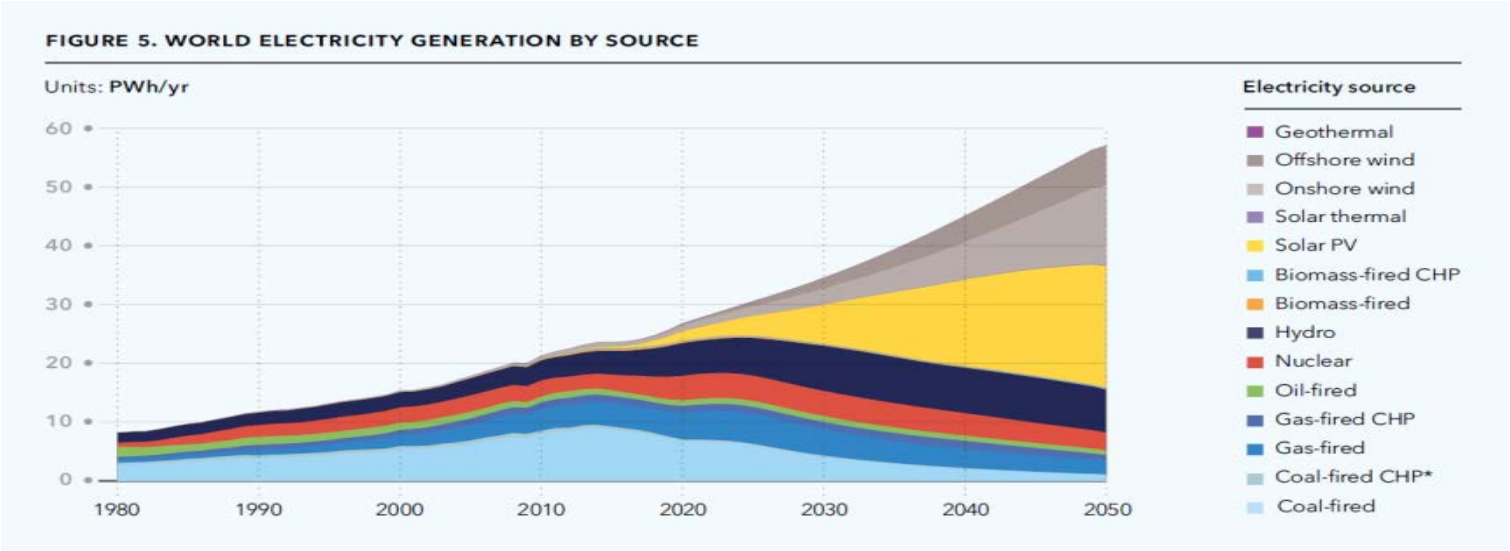
Deepwater Wind's Block Island Wind Farm, the first commercial wind farm in the United States, features five GE Haliade 150-6MW wind turbines to come online by end of 2016.

(*Photo by Dennis Schroeder, NREL 40389*)

DNV GL Energy Transition Outlook 2017 - Electricity

"… a base or 'central' case, … is the aim of this present exercise, which is a forecast, not a scenario." *Remi Eriksen, Group President & CEO DNV GL*

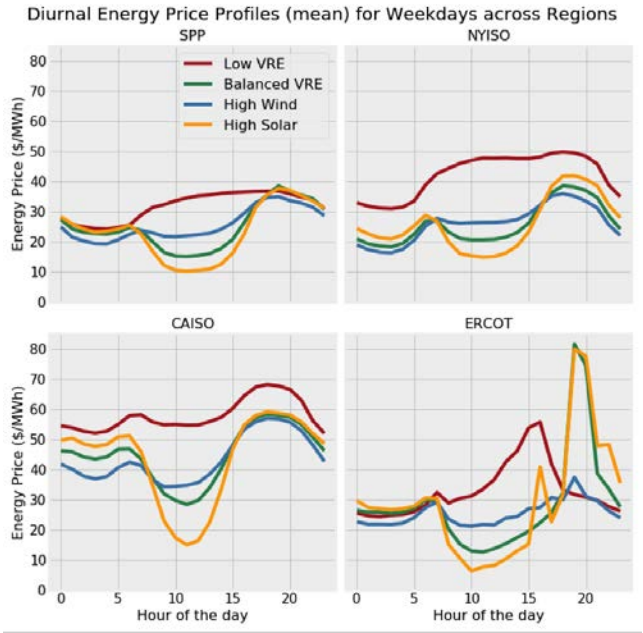
In 2050: one-third wind, one-third solar photovoltaics, one-third everything else. The wind is one-third offshore.



Source: DNV GL. 2017. *Energy Transition Outlook*. https://eto.dnvgl.com/2017/main-report.

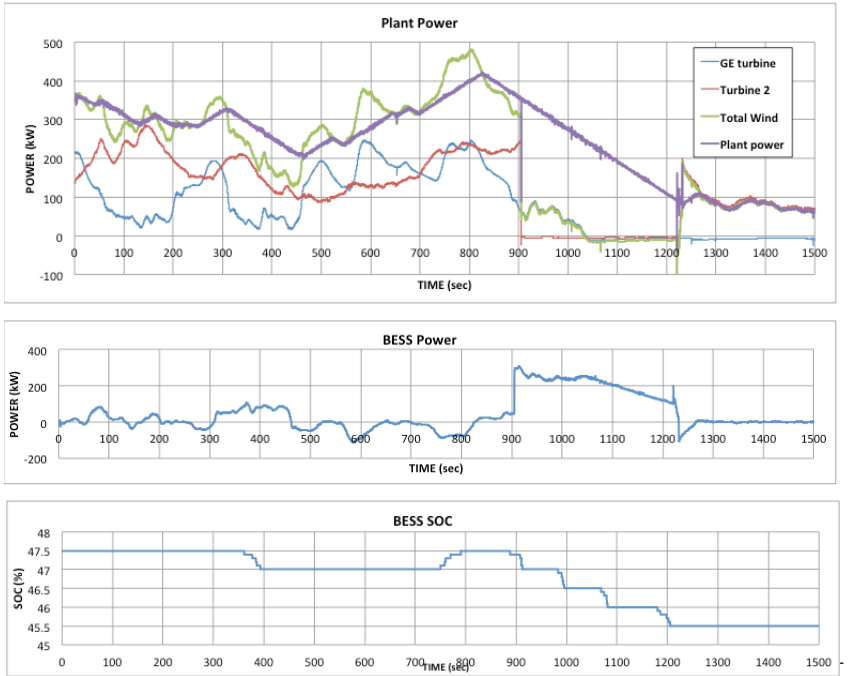
National Deployment of Wind Will Build the Grid Backbone of the Future

- Wind complements solar in diurnal cycles in many places.
- Dynamics of wind energy, once harnessed, will provide many key services for grid reliability and stability.



Balancing Pricing

Providing Grid Services (Ramping)



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Thank You

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NREL/PR-5000-72571

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