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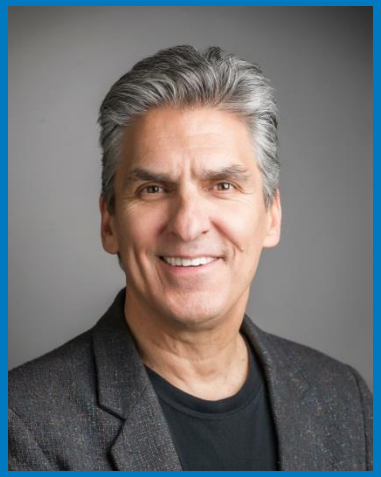
Offshore Wind Energy Briefing



Walt Musial
Principal Engineer
Manager Offshore Wind
National Renewable Energy Laboratory

California Energy Commission
Integrated Energy Policy Workshop
Offshore Renewable Energy

May 25, 2016

Outline

- Brief NREL Background
- Floating Offshore Wind Technology Update
- Floating Offshore Wind Market Update
- California Offshore Wind Resource Characteristics
- Future Cost and Performance Potential of Floating Offshore Wind through 2030

National Renewable Energy Laboratory (NREL)

NREL Program Portfolio

Strategic Analysis

Efficient Energy Use

- Vehicle Technologies
- Buildings Technologies

Renewable Resources

- Wind and Water
- Solar
- Biomass
- Hydrogen
- Geothermal

Delivery & Storage

- Smart Grid and RE Grid Integration
- Battery and Thermal Storage

- Federal Energy Management
- Integrated Deployment
- International
- Other Intergovernmental

Foundational Science

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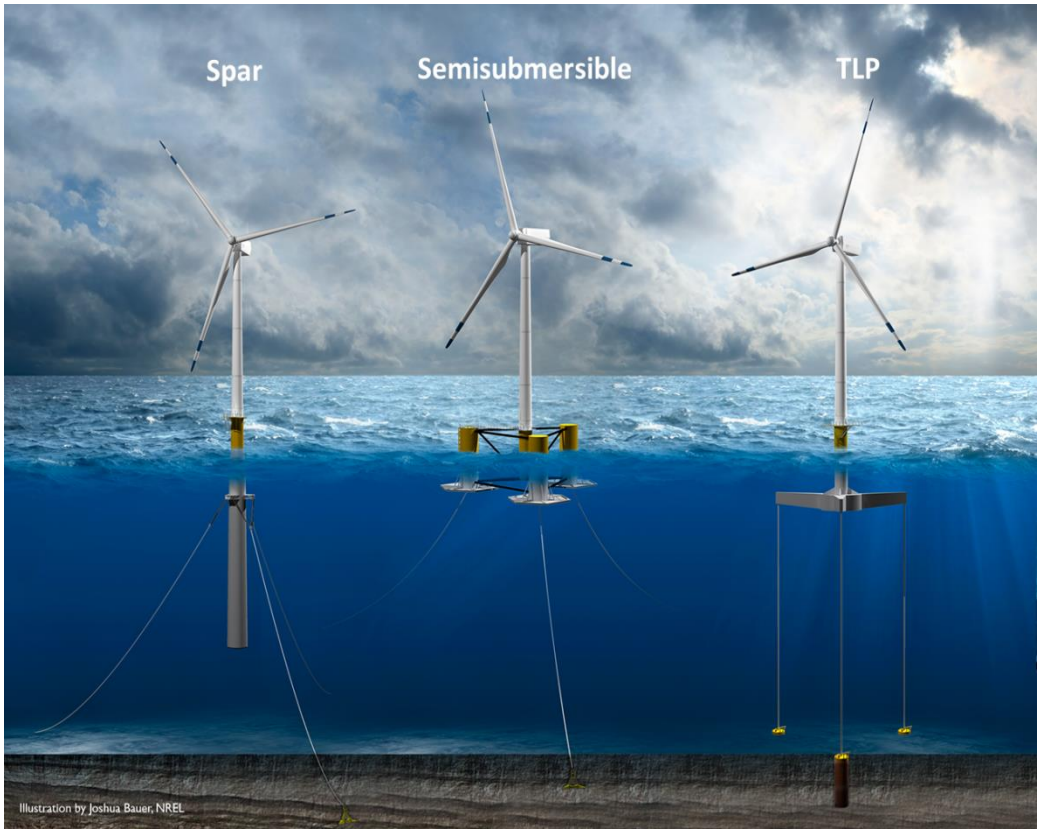
Floating Offshore Wind Technology Update

Floating Offshore Wind Energy Status

- Evolving from fixed-bottom wind turbines, marine operations, siting, regulatory
- Larger resource and lower siting conflicts relative to fixed-bottom offshore wind
- Higher costs with potential to achieve cost parity
- Reduced marine operations can offset higher CapEx of platforms/moorings/anchors
- Further system optimization benefits may come after market develops.



Three Types of Floating Platform Technologies are Evolving from Offshore Oil and Gas
(Figure Source: Josh Bauer, NREL)

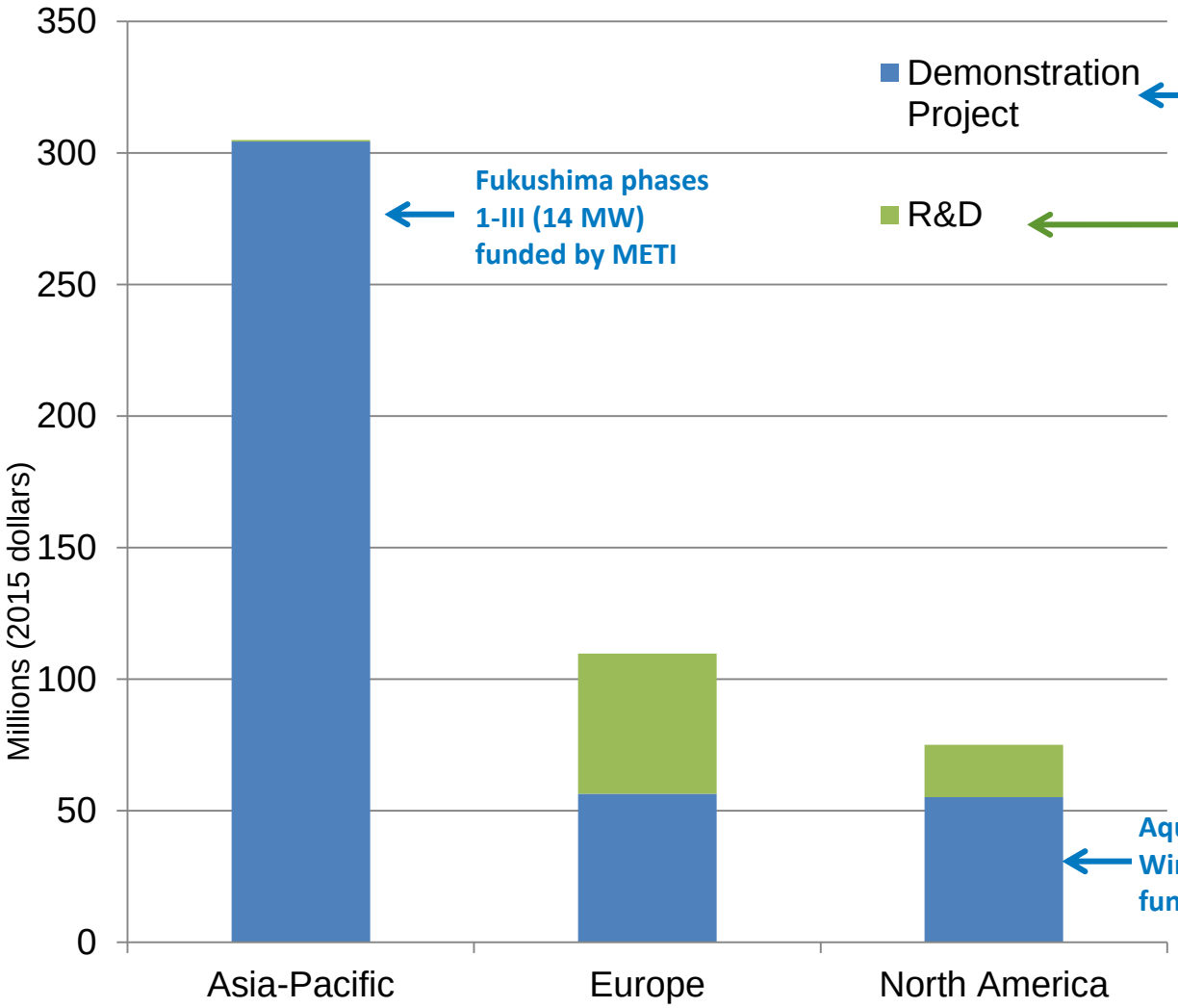
Floating Offshore Wind Challenges

- Levelized cost of energy must be reduced
- Designs depend on fixed-bottom practices
- Floating wind design standards are not mature
- Experience with dynamic electric cables and moorings from oil and gas and fixed bottom wind turbines
- Higher Pacific sea states may increase operating costs in California

Photos: Above Statoil Hywind I – First offshore wind turbine 2009 Credit NREL PIX 27845

Left: Kabashima Spar Buoy – 2 MW Hitachi Turbine 2014 Credit: Walt Musial

Floating Wind R&D Activities



$416 million including 9 demonstration projects with available funding figures

$74 million encompassing 19 R&D projects with available funding figures

Research areas include: floating wind project design, foundation design, foundation testing and evaluation, operations and maintenance of floating wind turbines, materials for floating foundations, environmental studies and surveying, and simulation of floating wind projects.

Source: NREL Offshore R&D Activities Database.
Note: Project list consists of active projects (as of end of 2015 and projects finished after 2013). It does not comprehensively encompass all R&D projects for floating wind technology in all regions. Certain projects without available funding amounts are not accounted for in the above figure.

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Offshore Wind Market Update

NREL 2014-2015 Offshore Wind Technologies Market Report

2014-2015 Market Report Covers Global and Domestic Offshore Wind

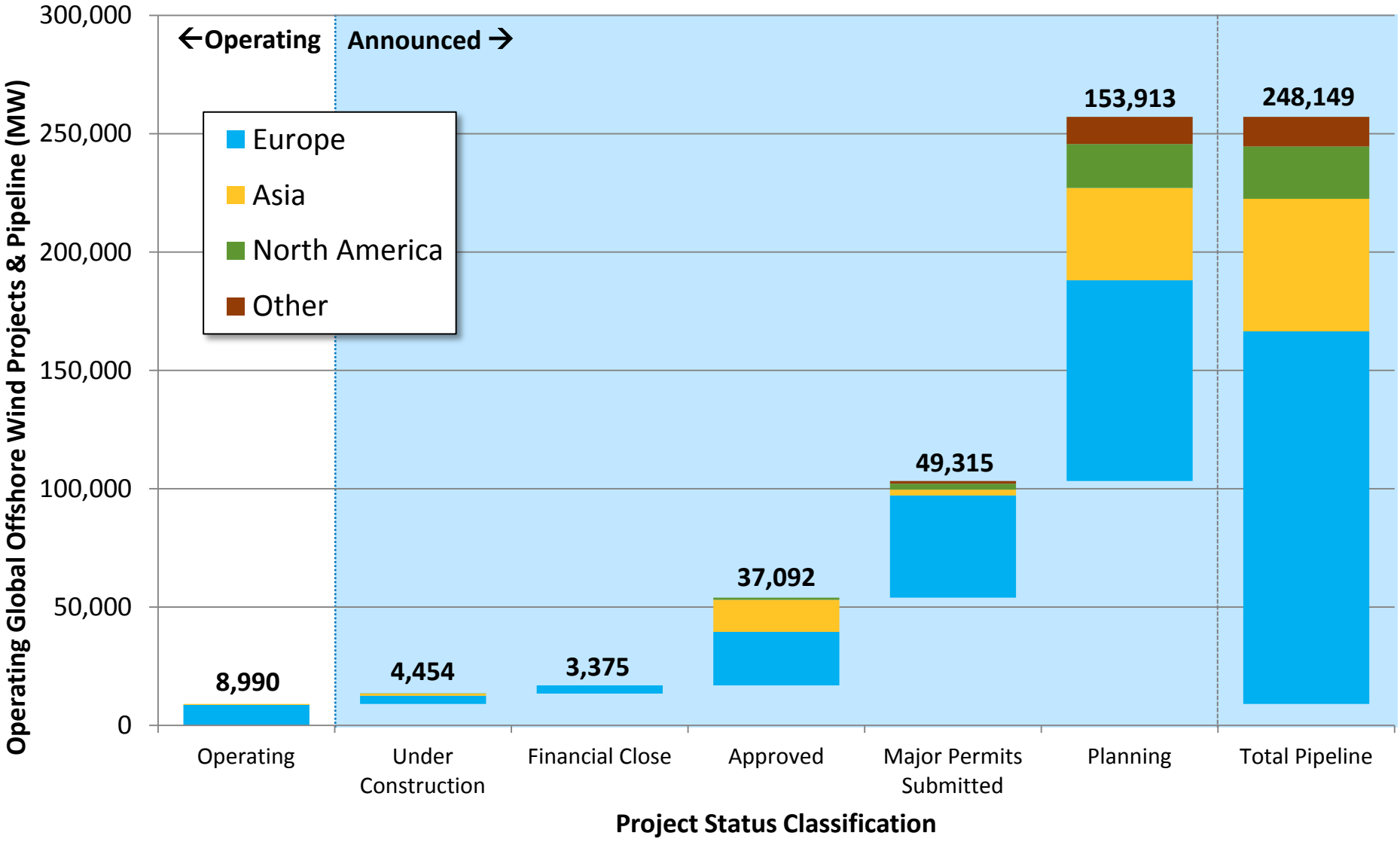
- Published Sept 25, 2015
- Recent Market Developments and Drivers
- Deployment Status and Projections
- Technology Trends
- Economic Trends
  - Cost
  - Performance
  - Finance
- LCOE Reduction Progress

Reference: A. Smith, T. Stehly, and W. Musial; "2014-2015 Offshore Wind Technologies Market Report", Sept 2015, NREL Report, Golden CO.

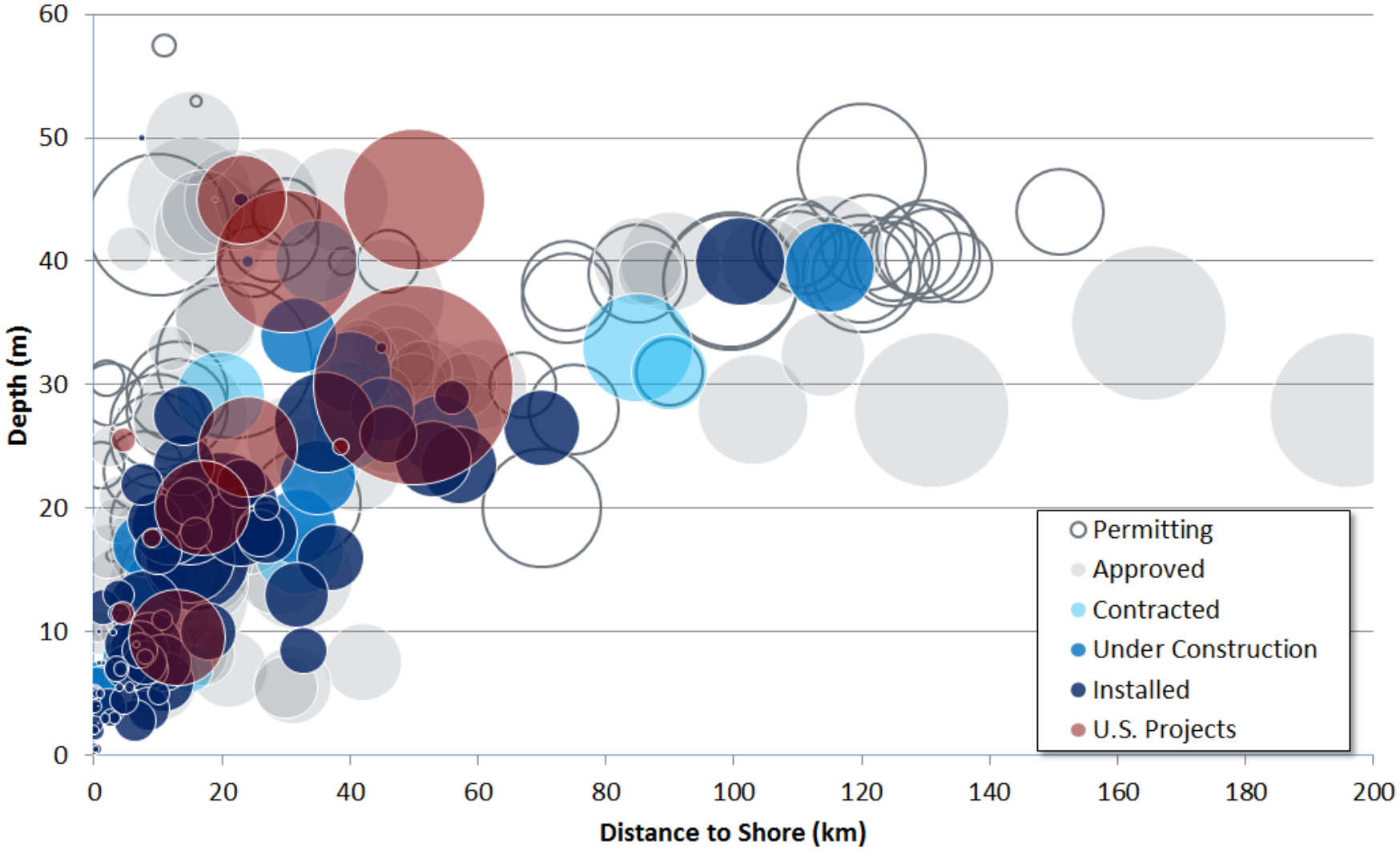
http://www.nrel.gov/docs/fy15osti/64283.pdf

NREL Market Report is the Basis for Near-term Trends and Projections

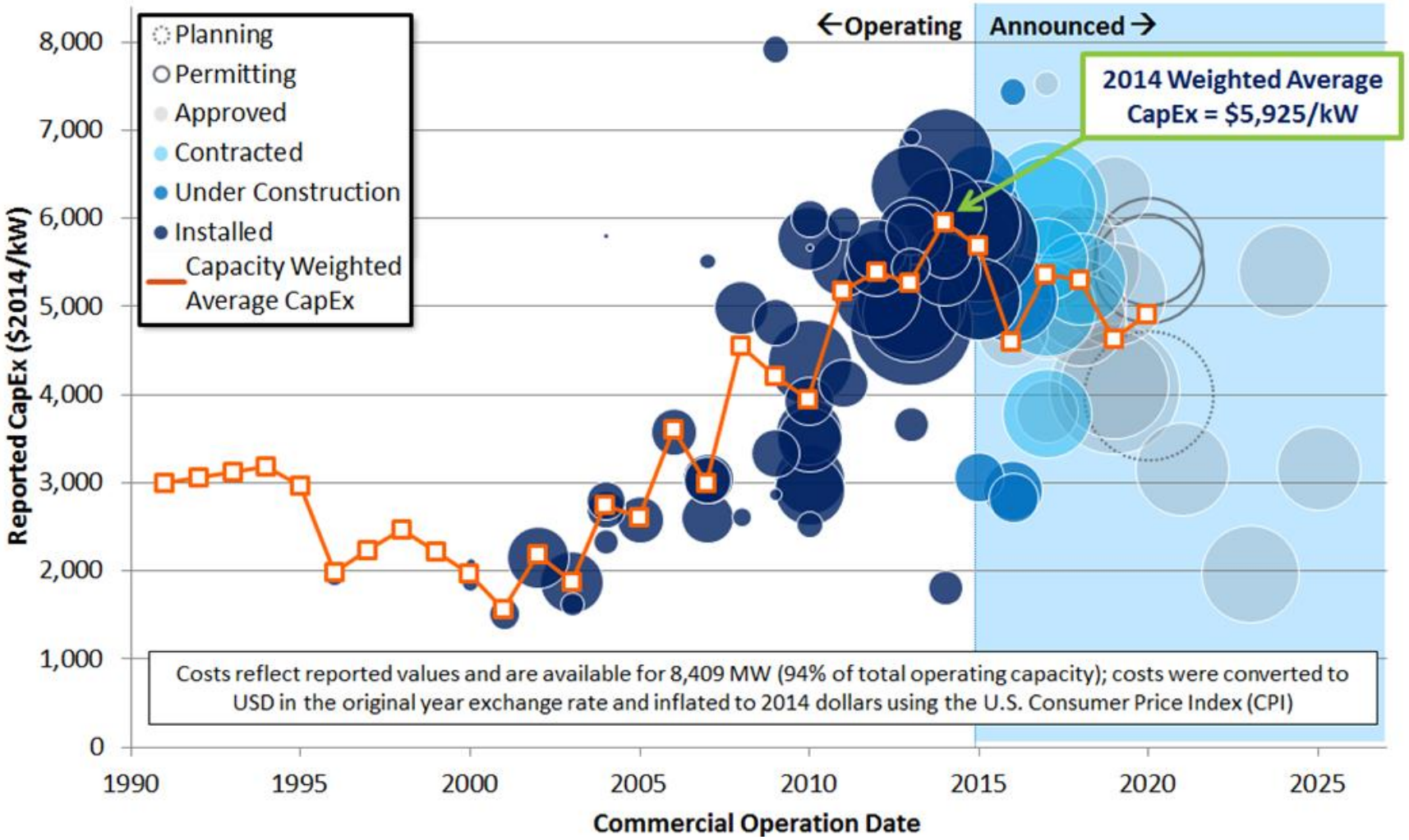
Global Offshore Wind Development Pipeline Totals 248 GW



Global Offshore Wind Projects:
Water Depth and Distance to Shore
(Fixed Bottom Projects)

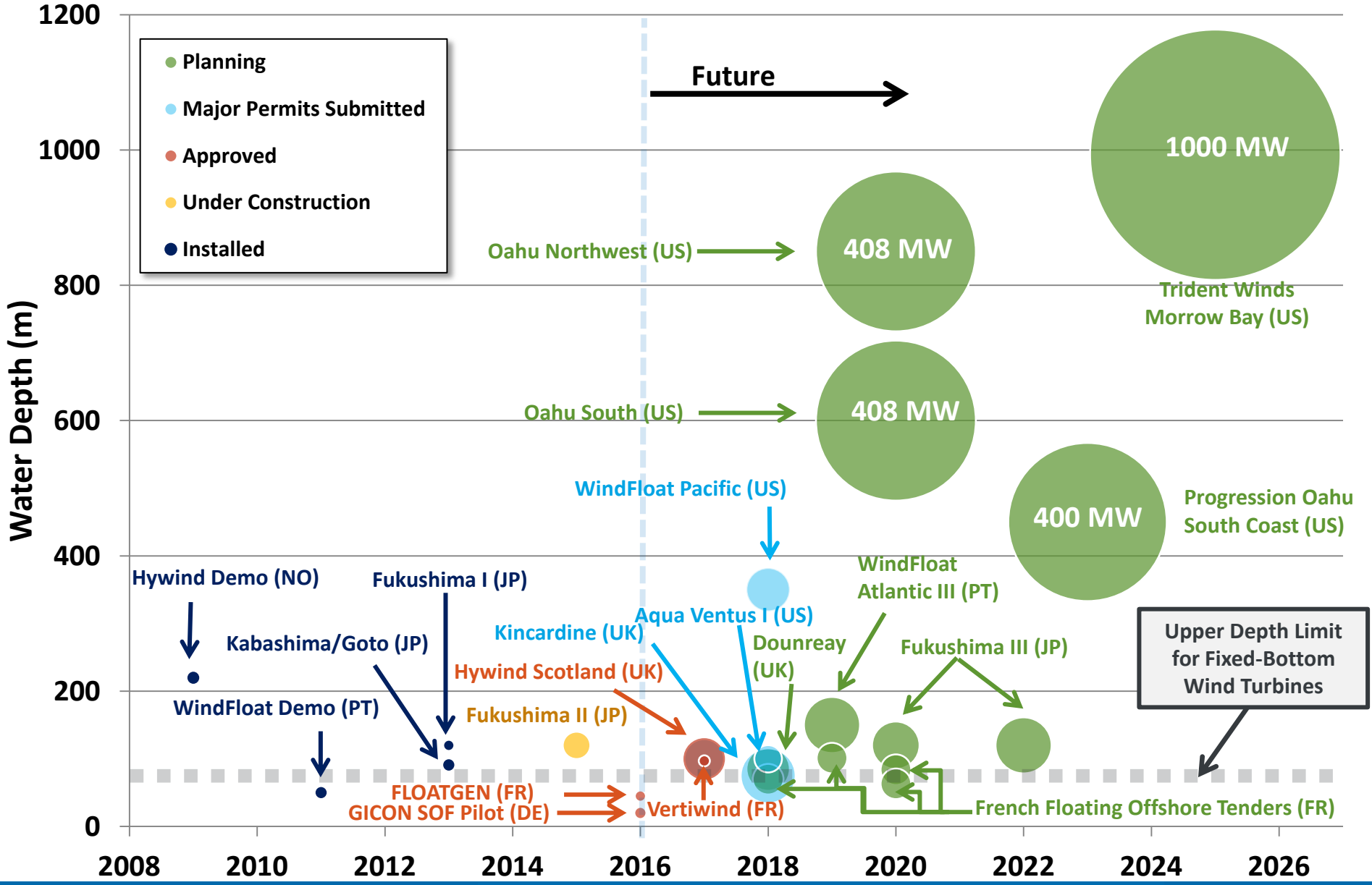


Global Offshore Wind Capital Expenditures At Commercial Operation Date



New 6-8 MW Offshore Purpose Designed Machines are Beginning to Drive Down Cost

Floating Wind Energy Global Market Timeline



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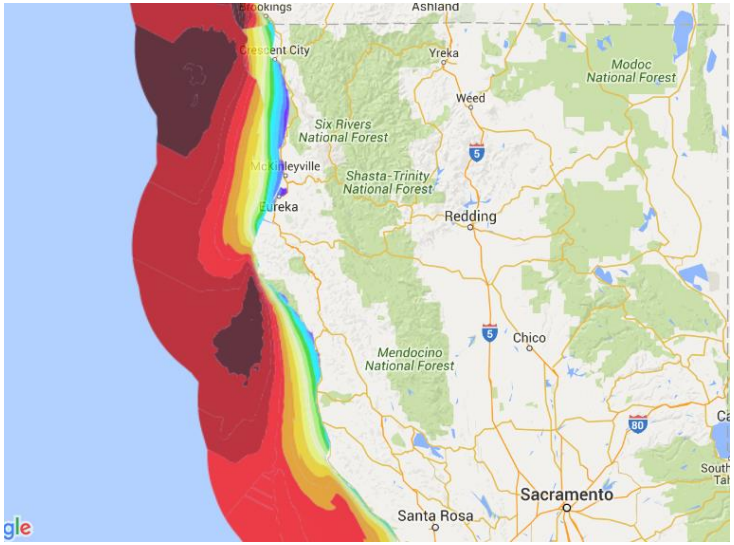
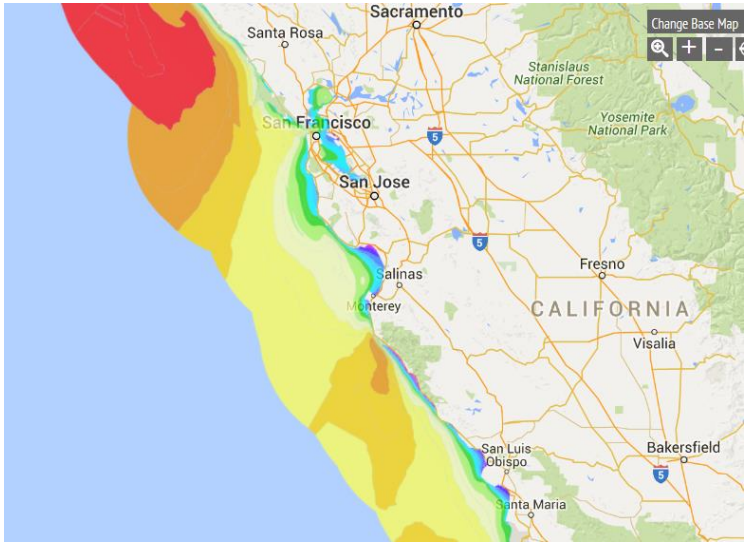
California Offshore Wind Resource Characteristics

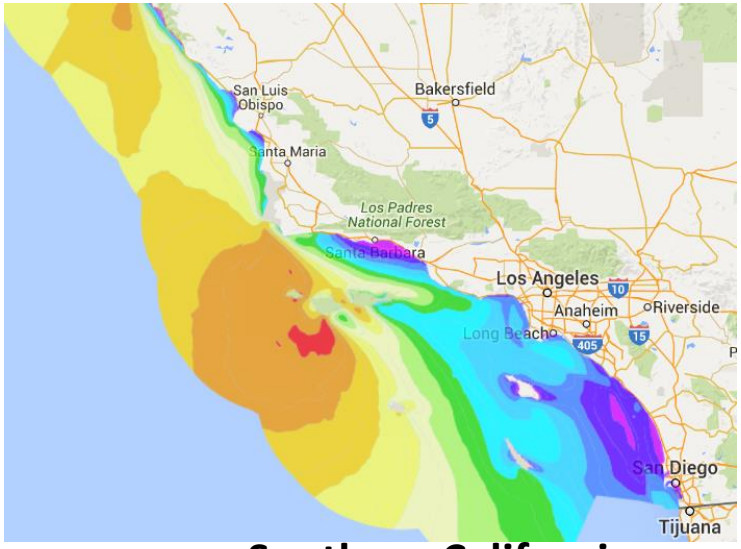
Wind Resource Maps for California



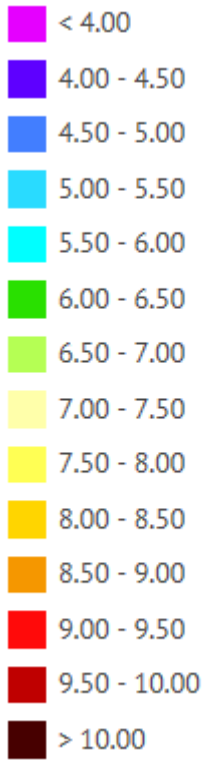
Northern California



Central California



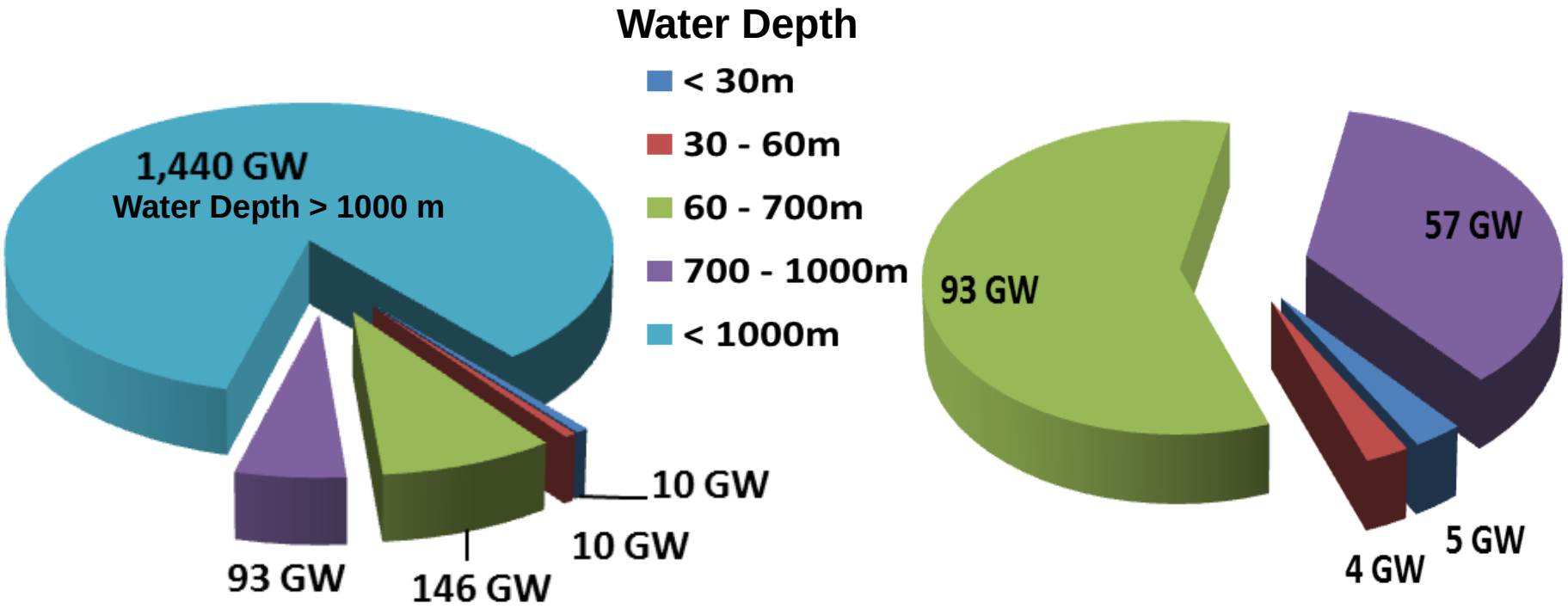
Southern California



- **Average wind characteristics**
- **Validated long term statistical data**

Source: NREL Wind Prospector
90-m Wind Speed Interactive Map
https://maps.nrel.gov/wind-prospector/

Water Depth Comparison of California Gross Offshore Resource to Technical Resource Potential

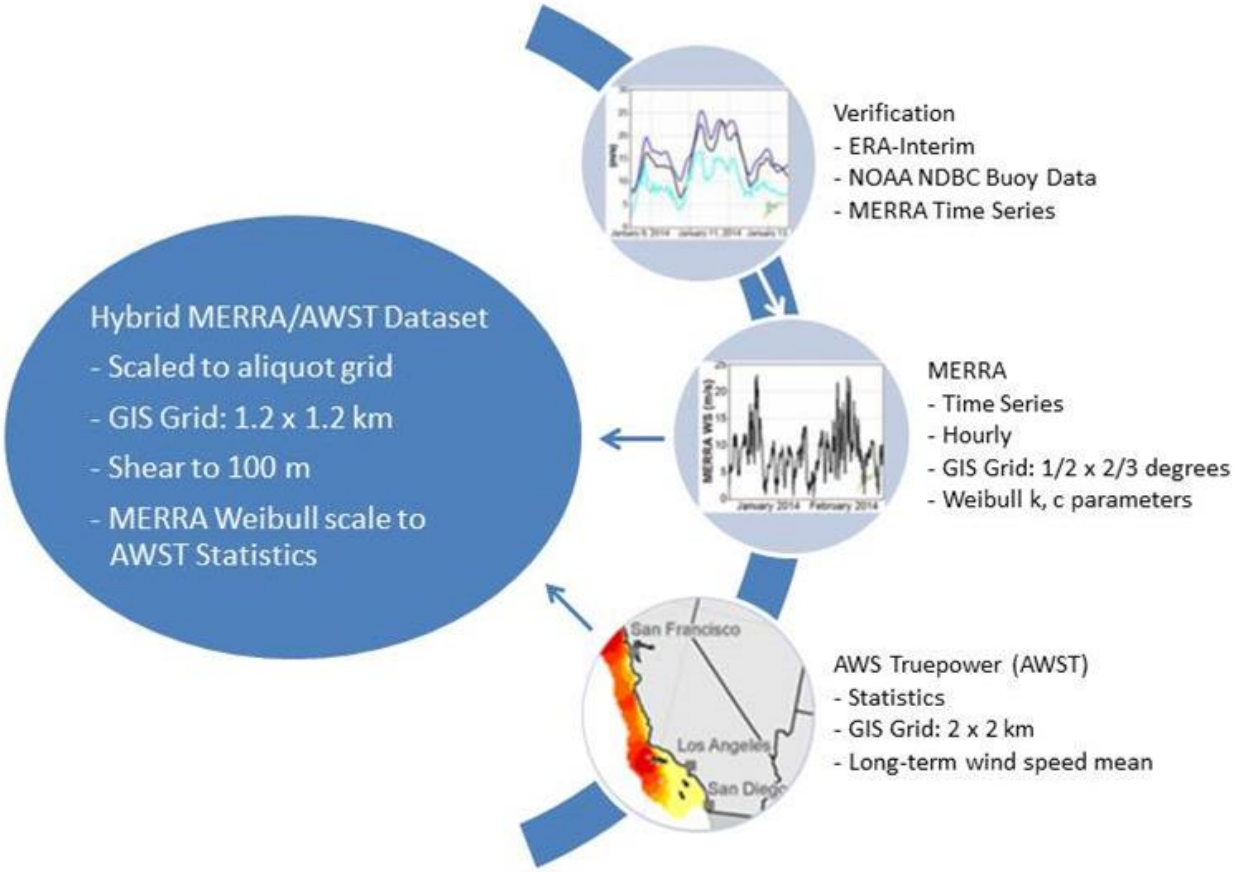


California Gross Resource Capacity
1,698 GW
All resource area 0 to 200nm (EEZ)
3 MW/km^2
All depth
All wind speeds

California Technical Resource Capacity
159 GW
Water Depths < 1000 m
Wind Speeds > 7 m/s

No Use Exclusions

Hourly Wind Speed Data



- Hourly data was created from two data sources
- AWST 17-year statistical data extrapolated to 100 m
- NASA's MERRA hourly time series data fit to AWST Weibull
- Resulting data set is merged with Wind Prospector data base
- Verification with NOAA NDBC buoys
- Sponsored by BOEM

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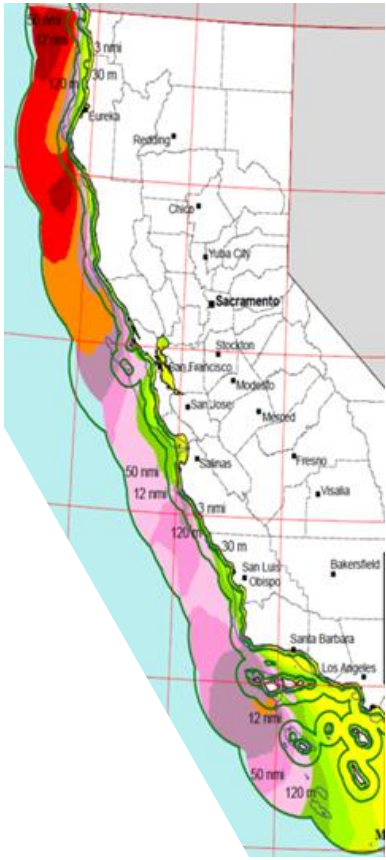
Future Cost and Performance Potential through 2030

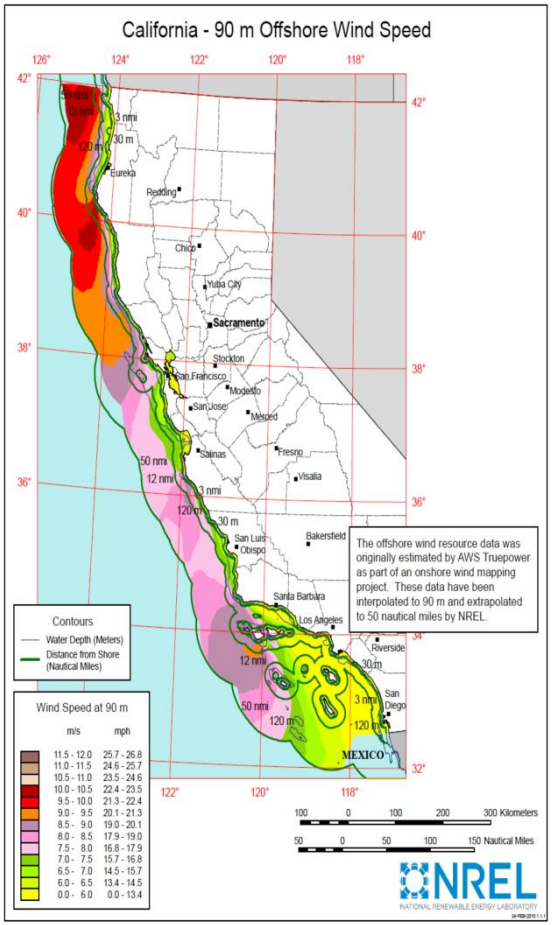
Offshore Wind Future Cost and Performance

- Identified 6 hypothetical sites that could support offshore wind development
- Cost and performance were assessed for 2015, 2020, and 2025
  - Reference technologies established (e.g. generic turbines for 6 MW, 8 MW, and 10 MW capacity)
  - Windographer software to calculate Capacity Factor (CF) and 8760 annual energy production profiles at each site
  - Technology innovation impact assumptions based on DELPHOS, an online tool provided by KICInnoEnergy, that combines technology innovation impact potential with commercial readiness assumptions
  - NREL spacio-economic model to generate CAPEX and OPEX
  - Work was sponsored by BOEM

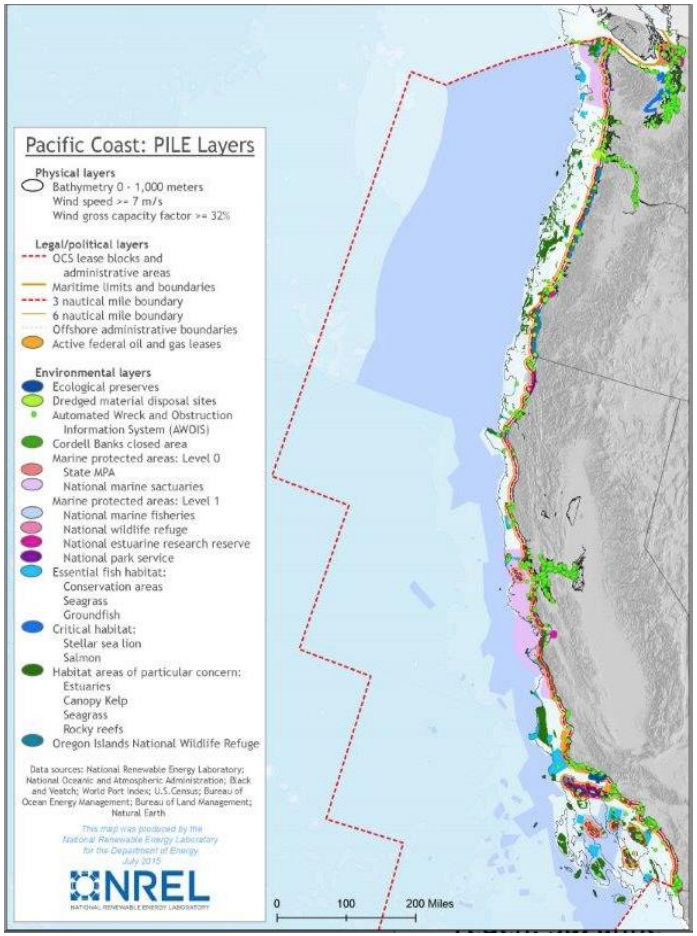


DELPHOS Reference: http://www.kic-innoenergy.com/wp-content/uploads/2014/09/KIC_IE_OffshoreWind_anticipated_innovations_impact1.pdf

Identification of Hypothetical Sites



California Offshore Wind Speed Map

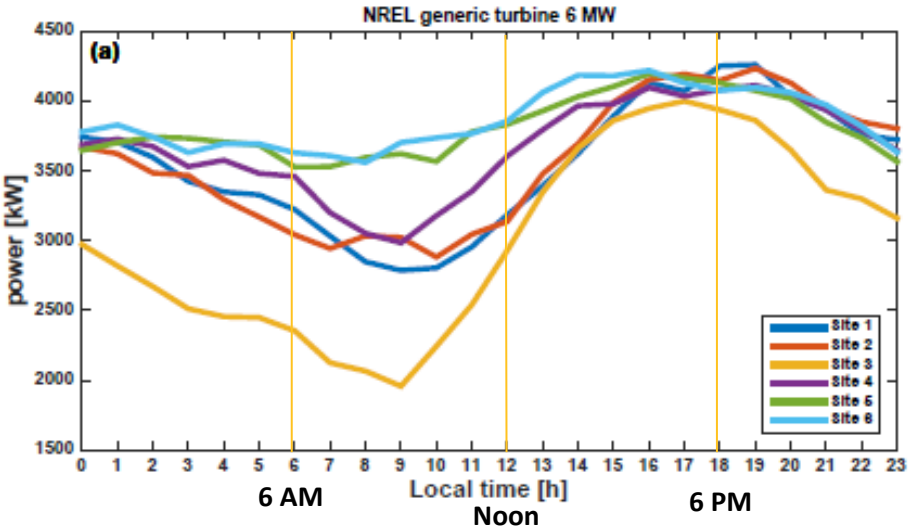


Preliminary California Offshore PILE Layers – Competing Use Zones

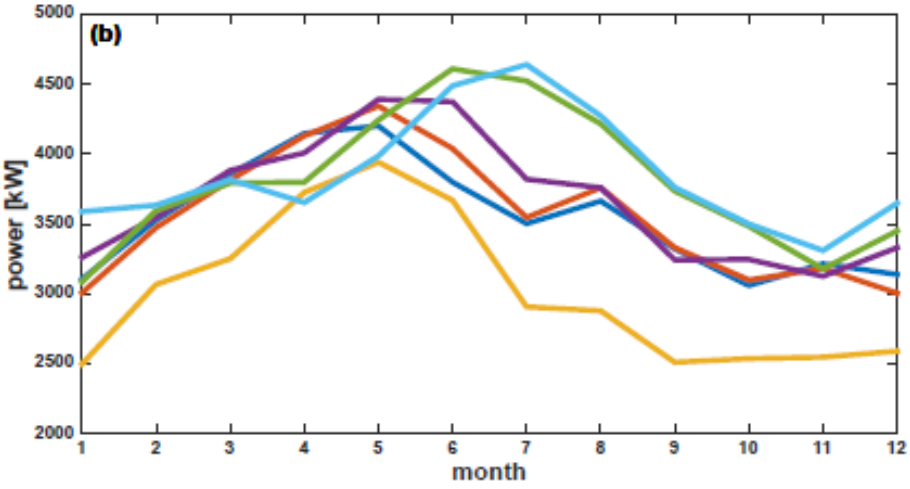
Criteria for Identification of Sites to be analyzed

- Greater than 7 m/s annual average wind speed
- Shallower than 1000-m
- Lowest use conflicts
- Potential for grid connections
- Potential proximity to operations ports

Power Production Observations



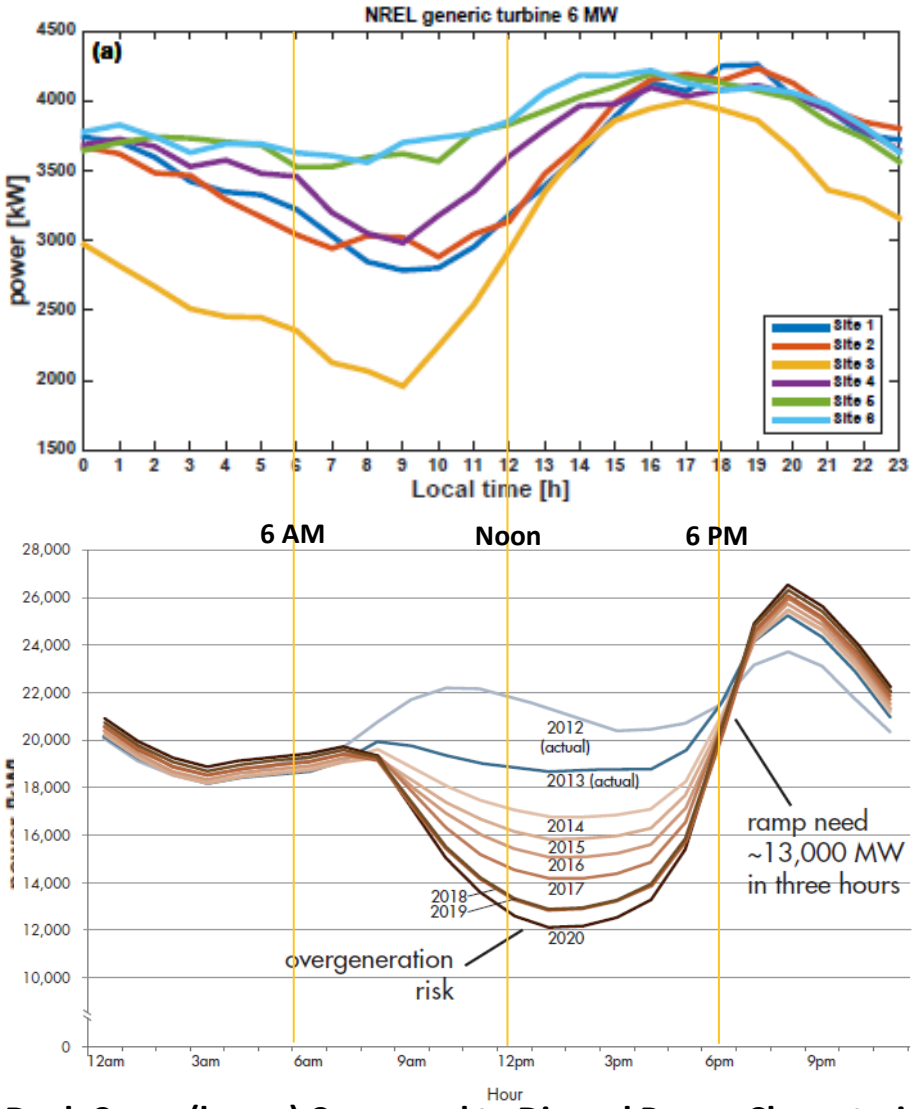
Diurnal Power Characteristics of 6 OSW Sites (March)



Average Monthly Power for 6 OSW Sites

Hypothetical California Offshore Site Identification

Duck Curve Preliminary Observations



Duck Curve (lower) Compared to Diurnal Power Characteristics of 6 Preliminary OSW Sites Identified (Upper)

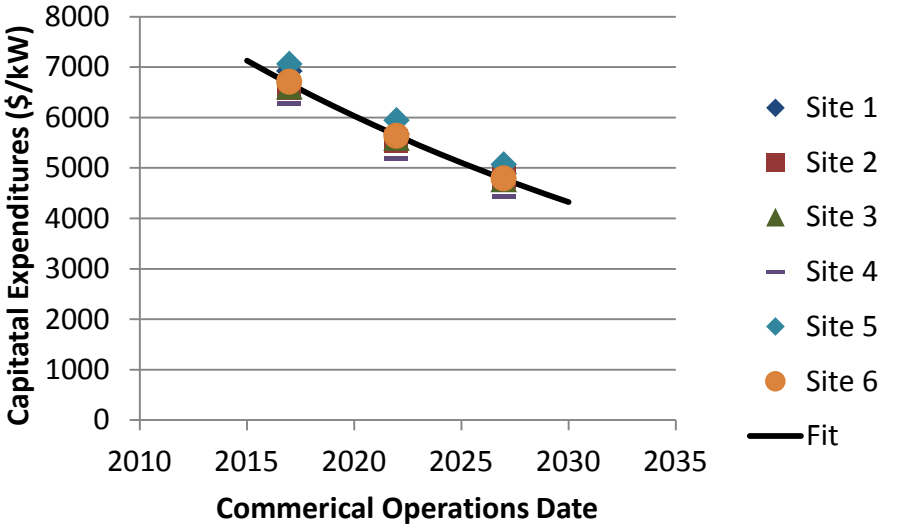
- All 6 sites follow similar diurnal patterns for offshore wind from Channel Islands to OR border
- Offshore wind peak may correlate with hourly and seasonal demand
- Offshore wind characteristics may compliment solar to offset curtailment risk

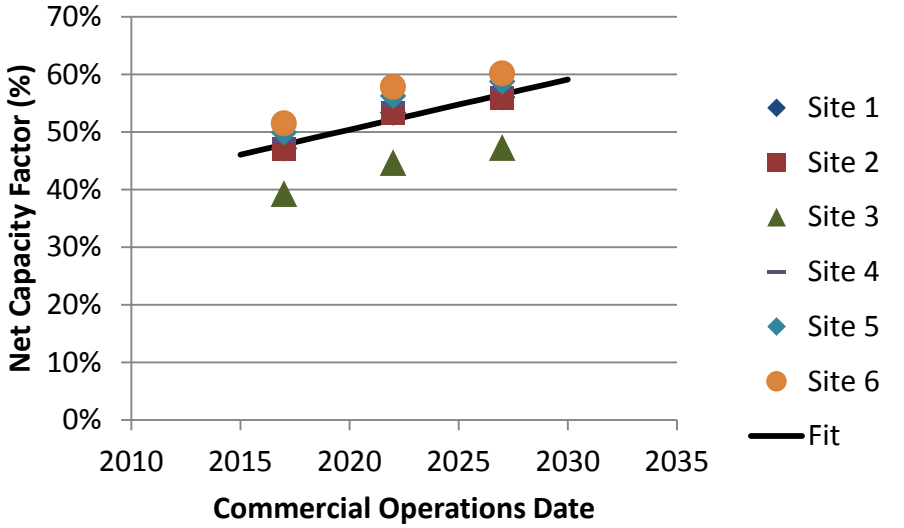
Technology Assumptions for Present and Future Offshore Wind Turbines

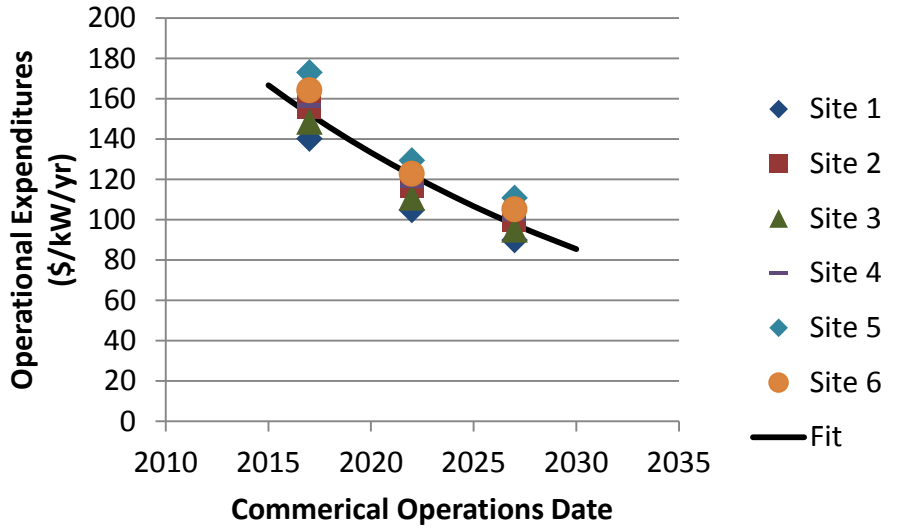
	2015 Technology	2020 Technology	2025 Technology
Turbine Rated Power (MW)	6	8	10
Turbine Rotor Diameter (m)	155	180	205
Turbine Hub Height (m)	100	112	125
Turbine Specific Power (W/m^2)	318	314	303
Substructure Technology	Floating	Floating	Floating

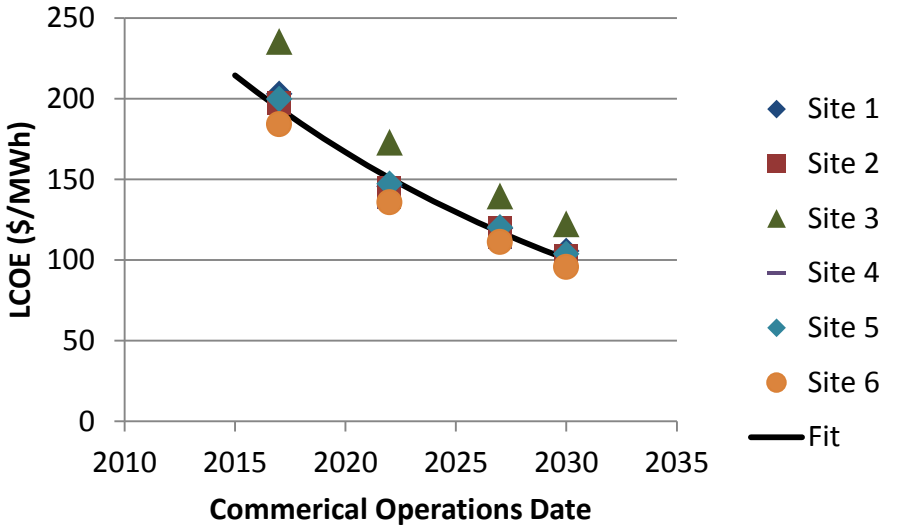
- Impact of technology innovation based on DELPHOS tool assumptions for fixed bottom systems out to 2025
- Modified by NREL to include floating innovations out to 2030.
- Full documentation will be released in an NREL report , July 2016

Future Cost and Performance : CAPEX, OPEX, CF, LCOE









California Offshore Wind Summary

- Global fixed bottom markets show about 250 GW in pipeline with cost beginning to trend downward
- Floating offshore wind technology is at a nascent stage globally but market is growing
- Floating offshore wind costs are higher than current fixed LCOE, but floating cost reduction potential is high
- Floating wind has beneficial characteristics that may offset challenges of water depth (lower vessel dependence, siting)
- Preliminary analysis shows offshore wind hourly characteristics may be complementary to solar in CA.

Key References

1. Schwartz, M.; Heimiller, D.; Haymes, S.; Musial, W. (April 2010). Assessment of Offshore Wind Energy Resources for the United States. NREL/TP-500-45889. Golden, CO: NREL.
2. Dvorak M. J; Archer, C. L.; and Jacobson M. Z.; "California offshore wind energy potential", Renewable Energy 35 (2010) 1244–1254, December 2009.
3. Rhodri James and Marc Costa Ros, "Floating Offshore Wind: Market and Technology Review" Prepared for the Scottish Government by the Carbon Trust, June 2015 https://www.carbontrust.com/media/670664/floating-offshore-wind-market-technology-review.pdf
4. Valpy, B. ;English, P.; Martínez, A.; Simonot, E.;"Future renewable energy costs: offshore wind" © KIC InnoEnergy, 2014, ISBN 978-94-92056-00-9 : http://www.kic-innoenergy.com/wp-content/uploads/2014/09/KIC_IE_OffshoreWind_anticipated_innovations_impact1.pdf
5. Smith, Aaron, Tyler Stehly, Walter Musial. 2015. 2014-2015 Offshore Wind Technologies Market Report (Technical Report). NREL/TP-5000-64283. National Renewable Energy Laboratory (NREL), Golden, CO (US). http://www.nrel.gov/docs/fy15osti/64283.pdf.
6. MERRA: MODERN-ERA RETROSPECTIVE ANALYSIS FOR RESEARCH AND APPLICATIONS, http://gmao.gsfc.nasa.gov/research/merra/

DELPHOS Reference: http://www.kic-innoenergy.com/wp-content/uploads/2014/09/KIC_IE_OffshoreWind_anticipated_innovations_impact1.pdf

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For more than 35 years, NREL has delivered innovation impact enabling the emergence of the U.S. clean energy industry.

Thank You For Your Attention!

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