2016
Life-Cycle Costs for Offshore Wind Workshop

October 5, 2016

The Hotel Viking
1 Bellevue Ave.
Newport, RI 02840

Hosts:

- Ross Tyler, Business Network for Offshore Wind
- Peter Sandborn, University of Maryland

Workshop Speakers:

- Camilla Thomson, Institute for Energy Systems at the School of Engineering, The University of Edinburgh
- Erin Baker, Wind Energy IGERT, Department of Mechanical and Industrial Engineering, UMass Amherst
- Dennise Gayme, Networked and Spatially Distributed Systems Research Group, Department of Mechanical Engineering, John Hopkins University
- Xin Lei, CALCE Center for Advanced Life Cycle Engineering, Department of Mechanical Engineering, University of Maryland
- Deniz Ozkan, Research and Systems Engineering, Atlantic Wind Connection
- Philipp Beiter, NREL
- Tyler Stehly, NREL

University of Maryland 1856

National Offshore Wind Innovation Center

Business Network for Offshore Wind

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Center for Advanced Life Cycle Engineering

Agenda

Time	Title	Presenter(s)	Organization(s)
1:00	Welcome and Introductions	Ross Tyler Peter Sandborn	Business Network for Offshore Wind University of Maryland
1:15	Costs of Offshore Wind	Camilla Thomson	Institute for Energy Systems (IES) at the School of Engineering, The University of Edinburgh
1:45	Expert Elicitation Survey on Future Wind Energy Costs	Erin Baker	Wind Energy IGERT, Department of Mechanical and Industrial Engineering, UMass Amherst
2:15	Siting and Resource Management Challenges for Wind Integrated Power Systems	Dennise Gayme	Networked and Spatially Distributed Systems Research Group, Department of Mechanical Engineering, John Hopkins University
2:45	PHM-Based Predictive Maintenance Optimization for Offshore Wind Farms	Xin Lei	CALCE Center for Advanced Life Cycle Engineering, Department of Mechanical Engineering, University of Maryland
3:15	Break		
3:30	Impact of Port Infrastructure Investment on the Life Cycle Costs and Rate Impacts of Offshore Wind	Deniz Ozkan	Research and Systems Engineering, Atlantic Wind Connection
4:00	A Spatial-Economic Cost Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030	Philipp Beiter & Tyler Stehly	National Renewable Energy Laboratory (NREL)
4:45	A Levelized Cost of Energy (LCOE) Model for Wind Farms that Includes Power Purchase Agreement (PPA) Energy Delivery Limits	Peter Sandborn	CALCE Center for Advanced Life Cycle Engineering, Department of Mechanical Engineering, University of Maryland
5:15	Wrap-up and Looking Forward	Ross Tyler Peter Sandborn	Business Network for Offshore Wind University of Maryland

Costs of Offshore Wind

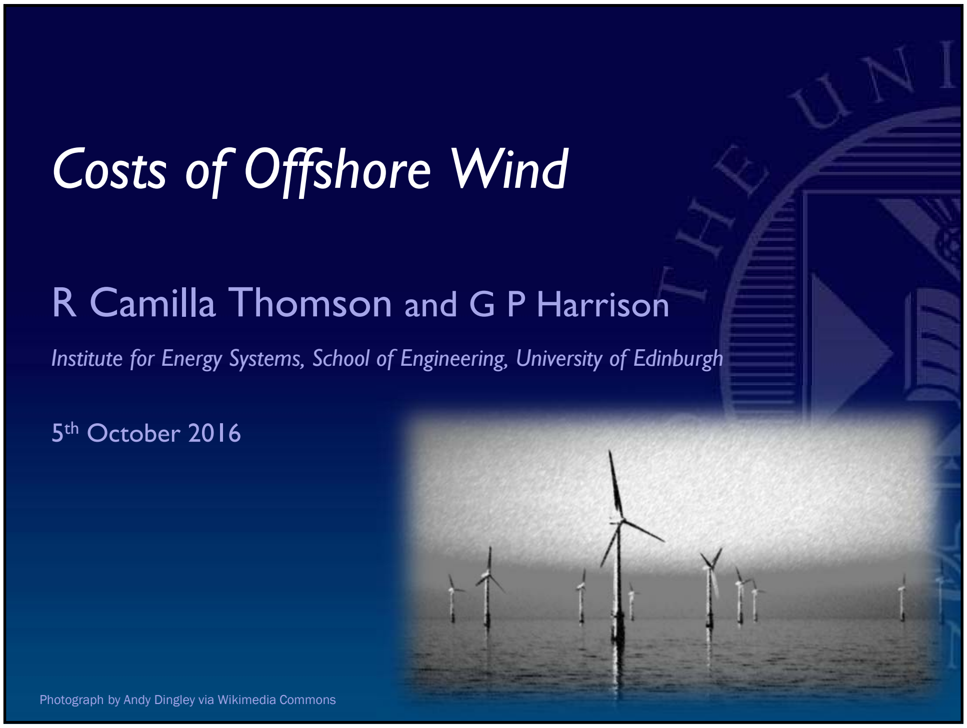
R. Camilla Thomson and Gareth P. Harrison
Institute for Energy Systems (IES) at the School of Engineering
University of Edinburgh, Scotland UK
C.Thomson@ed.ac.uk

Understanding the economics of offshore wind energy is essential for rational discussions about its role within the energy mix; however, there is a significant diversity of views on the costs. This paper critically examines published estimates of the levelised cost of offshore wind and associated system costs, the differing uncertainties and underpinning assumptions, and identifies the most critical factors. It is found that realistic estimates for the costs of offshore wind are currently substantially higher than more mature low-carbon technologies, like nuclear and onshore wind, but significant cost reduction opportunities exist.

Biographies:

R. Camilla Thomson
Camilla Thomson is a post-doctoral researcher interested in the GHG emissions and offsets of power generation, the flow of carbon through electricity networks, and the impacts of renewable generation on network operation. Her PhD research included a detailed life cycle assessment of the Pelamis Wave Energy converter, with a comprehensive examination of carbon and energy footprinting methodology and impact of practitioner assumptions on results, as well as a detailed analysis of the marginal displacement of wind power on the National Grid. Prior to commencing her PhD research, she gained experience as an electrical building services engineer, with projects including regional developments in the UK, USA, Russia, China and the Middle East in a variety of building sectors including education, commercial, hotels, residential, transportation and tall towers. Her particular interests include sustainable and energy efficient design. Her specialties include: Life Cycle Assessment (LCA) and carbon footprinting of products, in particular renewable generators. Marginal analysis of Elexon grid data. She has extensive experience in designing schools and developing lighting schemes, also including daylighting analysis for building physics studies.

Gareth P. Harrison
Professor Gareth Harrison is Bert Whittington Chair of Electrical Power Engineering and Deputy Head of the Institute for Energy Systems at the University of Edinburgh. He holds a Bachelor’s degree and a Doctorate from the same institution and was appointed to staff in 2000. He leads research activity across a wide area including grid integration of renewable energy, renewable resource assessment, climate change impacts on electricity systems; and carbon footprints of energy systems. Professor Harrison is a Chartered Engineer, a member of the Institution of Engineering and Technology, a Senior Member of the Institute of Electrical and Electronics Engineers and is an Affiliate of the Association of Chartered Certified Accountants. He is a member of the RSE Young Academy of Scotland.



Costs of Offshore Wind

R Camilla Thomson and G P Harrison

Institute for Energy Systems, School of Engineering, University of Edinburgh

5th October 2016

Photograph by Andy Dingley via Wikimedia Commons

Introduction

- Understanding the economics of offshore wind is essential, but there is a diversity of views.
- Types of cost:
  - CAPEX – typically high for renewables;
  - OPEX – typically high for fossil/nuclear;
  - Decommissioning – typically high for nuclear.
- Levelised cost of energy (LCOE) avoids limitations of looking at only one of the above.
- System costs are usually excluded from LCOE, but include:
  - Costs of balancing the system to cope with variable output
  - Costs of providing 'backup';
  - Cost of additional transmission and associated losses.

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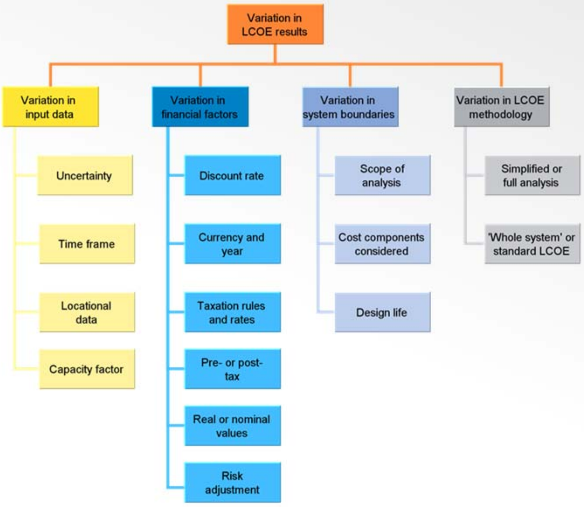
LCOE – IEA method

$$\text{LCOE} = \frac{\sum_{t}^{T} \frac{C_t + O_t + F_t + D_t}{(1+r)^t}}{\sum_{t}^{T} \frac{E_t}{(1+r)^t}}$$

Where:

- *C* is the capital cost (£);
- *O* is operations and maintenance (O&M) cost (£);
- *F* is fuel cost (£);
- *D* is the decommissioning cost (£);
- *E* is the electricity produced (MWh);
- *r* is the discount rate (%);
- *t* is the year in which a cost occurs during the project lifetime *T*.

Sources of variation



- Variation in LCOE results
  - Variation in input data
    - Uncertainty
    - Time frame
    - Locational data
    - Capacity factor
  - Variation in financial factors
    - Discount rate
    - Currency and year
    - Taxation rules and rates
    - Pre- or post-tax
    - Real or nominal values
    - Risk adjustment
  - Variation in system boundaries
    - Scope of analysis
    - Cost components considered
    - Design life
  - Variation in LCOE methodology
    - Simplified or full analysis
    - 'Whole system' or standard LCOE

LCOE – Full cash flow method

$$\text{LCOE} = \frac{e \times C + \displaystyle\sum_{t=1}^{T} \frac{(1-Tax)\times(O_t + F_t + D_t) - Tax \times (Int_t + Dep_t)}{(1+r_e)^t}}{\displaystyle\sum_{t=1}^{T} \frac{E_t(1-Tax)}{(1+r_e)^t}}$$

Where:

- *e* is the proportion of the project funded by equity;
- r_e is the return on equity;
- *Tax* is the tax rate;
- *Int* is the interest paid on the loan;
- *Dep* is depreciation.

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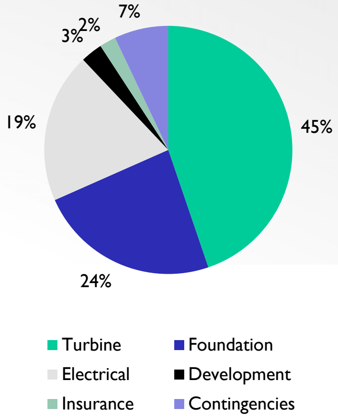
Capital Cost

- 60 to 80% of total life cycle costs
- Largest proportion due to labour costs
  - Particularly manufacture of carbon and glass-fibre rotors
- Significant fluctuations due to commodity prices, year, site conditions, etc.

Typical breakdown of costs

(Source: MottMacdonald, 2011)



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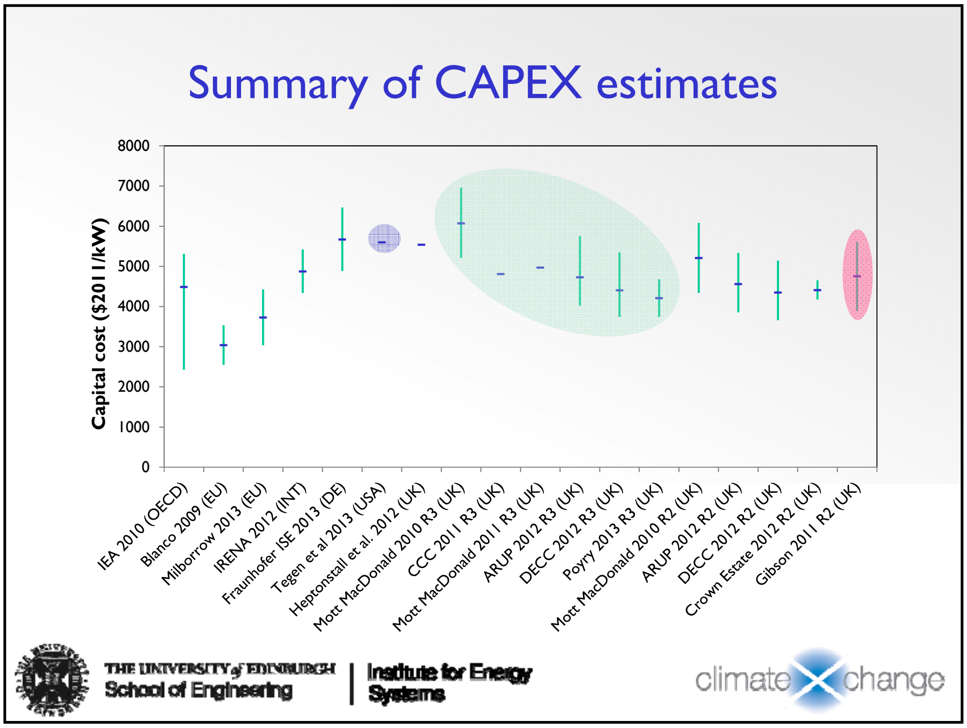

Summary of CAPEX estimates

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OPEX & Decommissioning

- Operating cost is less significant than capital cost
- Typically expressed as fixed and/or variable components:
  - Fixed annual cost as proportion of capital cost (%)
  - Fixed annual cost per unit of capacity (£/kW/yr)
  - Variable/levelised cost per unit production (£/MWh)
- 16 to 35% of LCOE
- Higher more recently
  - Greater experience and recognition of challenge
  - Further offshore and deeper
- Decommissioning costs are largely neglected:
  - Discounted value low
  - Costs assumed equivalent to salvage value

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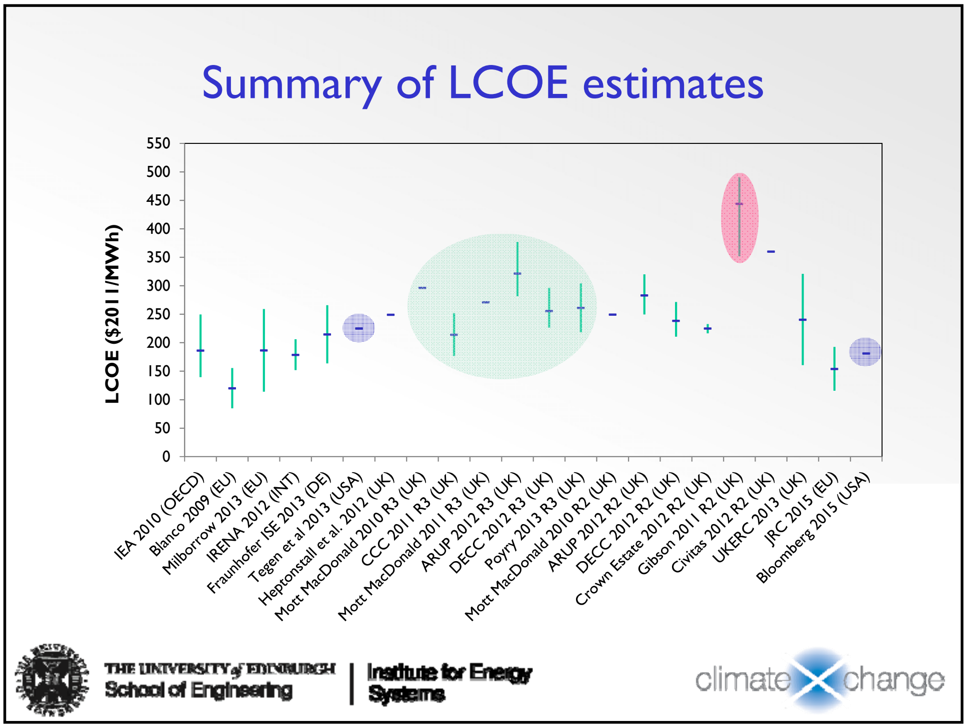

Summary of LCOE estimates

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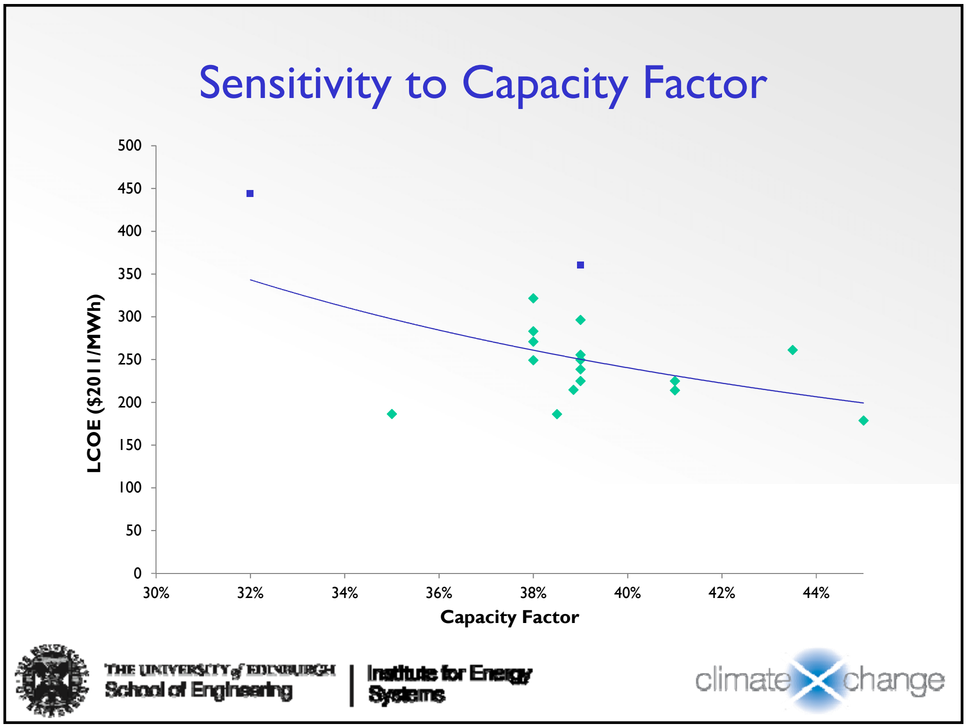

Sensitivity to Capacity Factor

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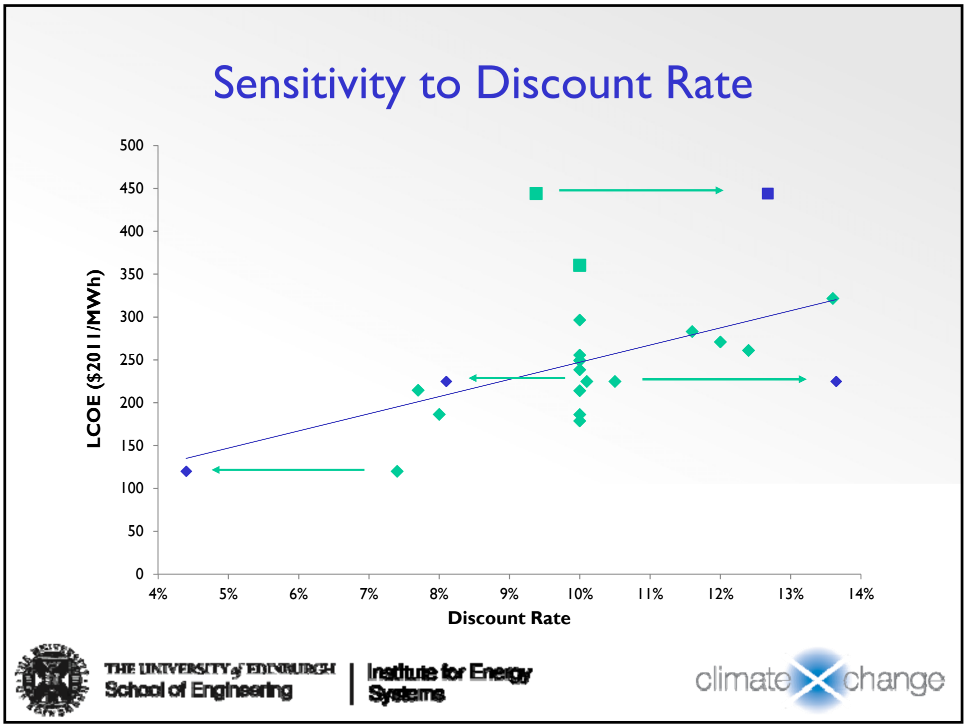

Sensitivity to Discount Rate

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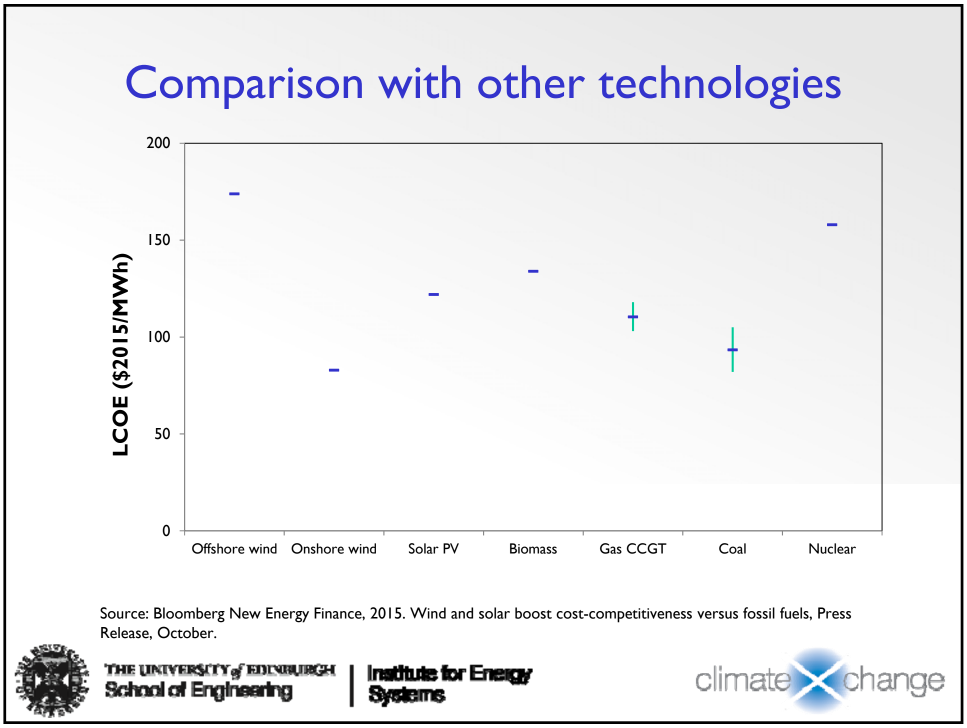

Comparison with other technologies

Source: Bloomberg New Energy Finance, 2015. Wind and solar boost cost-competitiveness versus fossil fuels, Press Release, October.

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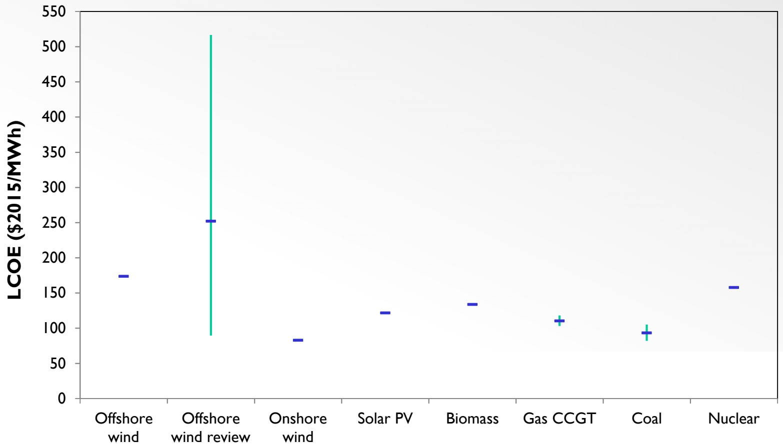
Comparison with other technologies



Source: Bloomberg New Energy Finance, 2015. Wind and solar boost cost-competitiveness versus fossil fuels, Press Release, October.

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Outlook

- Bloomberg's findings support the established expectation that costs will come down and performance will increase with time.
- Two approaches for forecasting costs:
  - Technical engineering assessment
  - Extrapolation using experience curves
- Available literature suggests a generally downward cost trend for most technologies, despite move to more challenging sites, due to:
  - Erosion of 'market congestion' premiums
  - Larger turbines allowing new low-mass generator designs, fewer foundations for a given capacity and higher capacity factor
  - Larger farms allow sharing of infrastructure
  - Move to HVDC reducing number of subsea cables
  - Improvement in foundation design and manufacture
  - Improvements in installation and maintenance requirements and supplier capabilities

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System Costs

Cost component	Range ($2011/MWh)
Balancing costs	3 – 11
Backup costs	0.3 – 0.8
Transmission costs	8 – 16
Total 'system' costs	**11 - 28**

- The impact of wind on other generators and the system is generally excluded from LCOE calculations
- There are suggestions that system costs of offshore wind increases the apparent cost by 30 to 45%
- System costs include:
  - Costs of balancing the system to cope with variable output
  - Costs of providing 'backup'; ensuring generation can meet demand
  - Cost of additional transmission and associated losses

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System Costs

Cost component	Range ($2011/MWh)
Balancing costs	3 – 11
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Total 'system' costs	**11 - 28**

- There is no disagreement that such costs exist, but little agreement as to their value (IEA, 2010)
- Literature suggests that balancing costs are likely to be lower in larger markets
- Backup costs are overstated due to a partial understanding of the system
- Transmission costs are more challenging to estimate.

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Conclusions

- There is scope for large variations in LCOE estimates for offshore wind power, most significantly from:
  - Capital cost of turbines
  - Capacity factor
  - Discount rate
- System costs are normally not considered, but where they're included they're often overestimated.
- System costs arising from accommodating wind do exist, but at relatively modest levels.
- Levelised costs for offshore wind are currently higher than other forms of low carbon generation; however, there are very substantial potential cost reduction opportunities.

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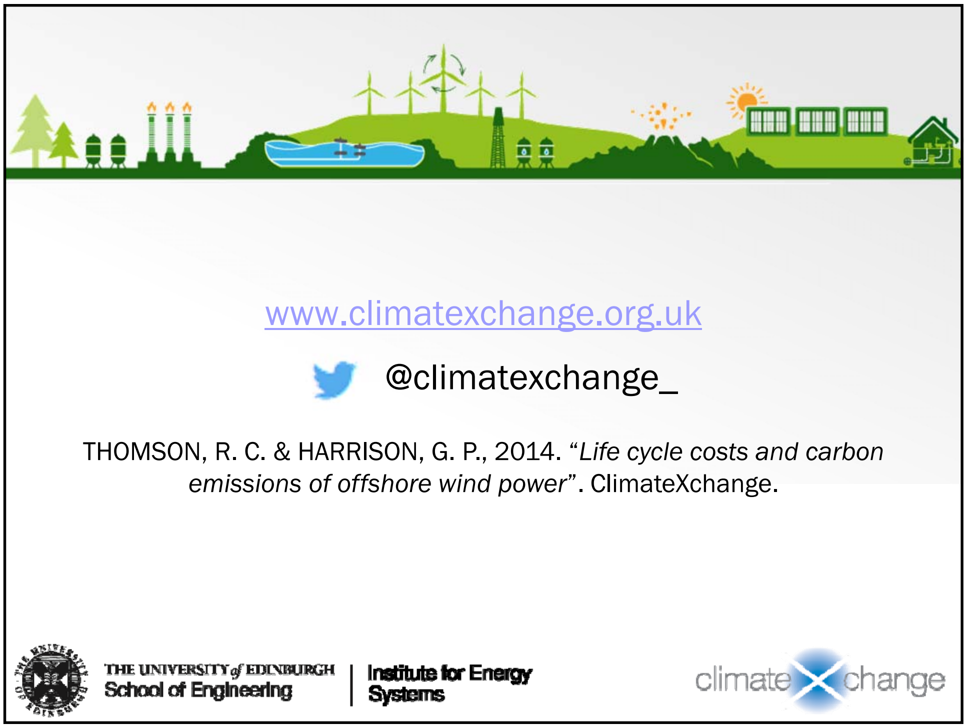

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THOMSON, R. C. & HARRISON, G. P., 2014. "*Life cycle costs and carbon emissions of offshore wind power*". ClimateXchange.

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Expert Elicitation Survey on Future Wind Energy Costs

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While wind energy supply has grown rapidly over the last decade, the long-term contribution of wind to future energy supply depends-in part-on the future costs of both onshore and offshore wind. In this study we summarize the results of an expert survey of 163 of the world's foremost wind experts, aimed at better understanding future costs and technology advancement possibilities. Three wind applications were covered: onshore (land-based) wind, fixed-bottom offshore wind, and floating offshore wind. We find expected declines of 24%-30% by 2030 and 35%-41% by 2050. Overall, results suggest significant opportunities for cost reductions, but also underlying uncertainties.

Biography

Erin Baker is a Professor of Industrial Engineering and Operations Research at University of Massachusetts, Amherst. She has a Ph.D. in Engineering-Economic Systems & Operations Research from the department of Management Science and Engineering at Stanford University, and a B.A. in Mathematics from U.C. Berkeley. She is the director of the NSF-funded *IGERT: Offshore wind energy engineering, environmental impacts, and policy* and of a related REU. She teaches courses in probability, decision making, and economics. Her research is in decision making under uncertainty applied to the field of energy and the environment, with a focus on publically-funded energy technology Research and Development portfolios in the face of climate change. She has received grants from the National Science Foundation, the U.S. E.P.A., NOAA, the U.S. Department of Energy, the Sloan Foundation and others. She is the Past President of the Energy, Natural Resources, and the Environment section of INFORMS, and an active member of the Decision Analysis Society and the Association of Environmental and Resource Economists. She is on the editorial boards of *Energy Economics* and *Decision Analysis*.

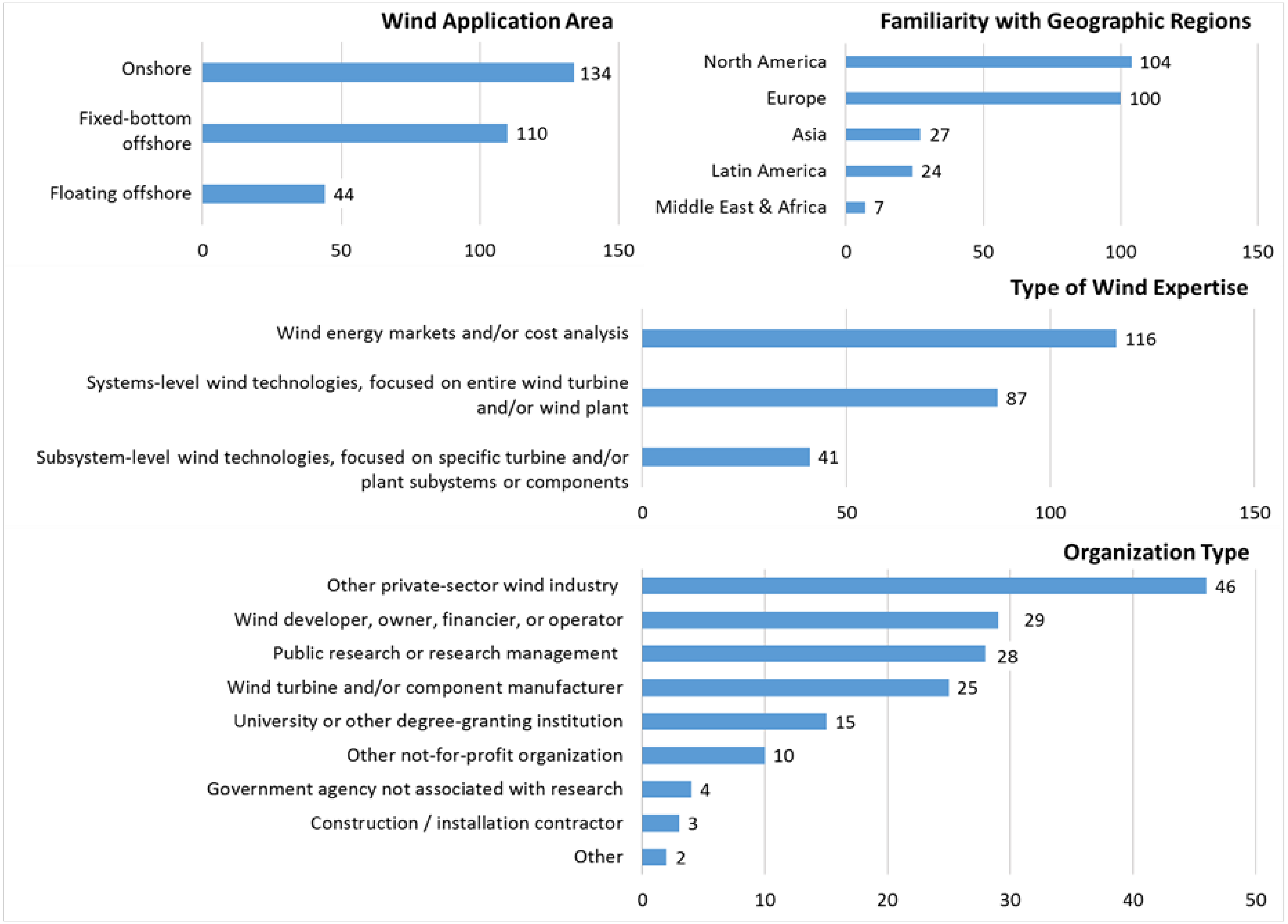
EXPERT ELICITATION SURVEY ON FUTURE WIND ENERGY COSTS

Presented by Erin Baker
Professor, *Industrial Engineering and Operations Research*
Director, *NSF IGERT: Offshore Wind Energy, Environmental Impacts, and Policy*
University of Massachusetts Amherst

Based on: *Wiser, Jenni, Seel, Baker, Hand, Lantz, & Smith* (2016) ***Nature Energy*** *Vol 1 : 16135*

Expert Elicitation

A structured method for eliciting subjective probabilities from experts.



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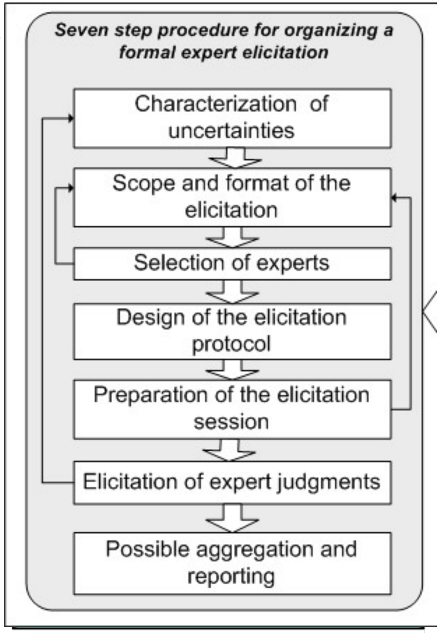
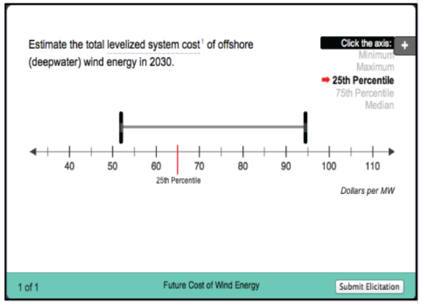


Seven step procedure for organizing a formal expert elicitation

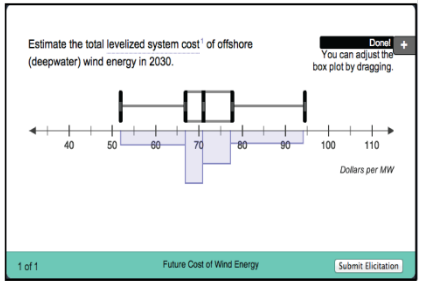
- Characterization of uncertainties
- Scope and format of the elicitation
- Selection of experts
- Design of the elicitation protocol
- Preparation of the elicitation session
- Elicitation of expert judgments
- Possible aggregation and reporting

C



Estimate the total levelized system cost[1] of offshore (deepwater) wind energy in 2030.

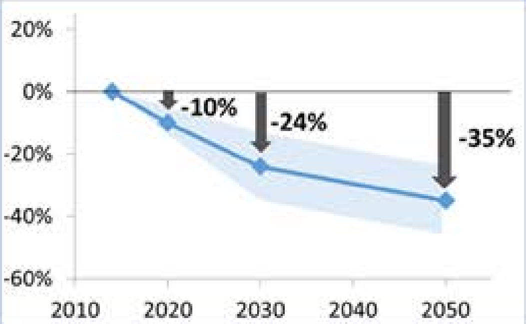
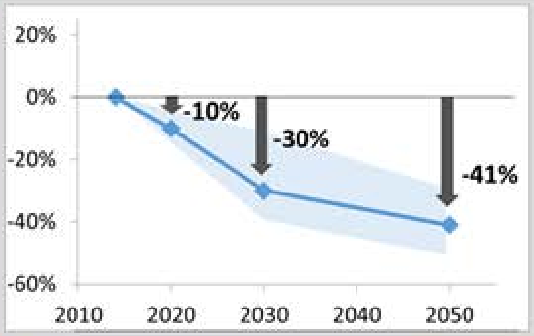
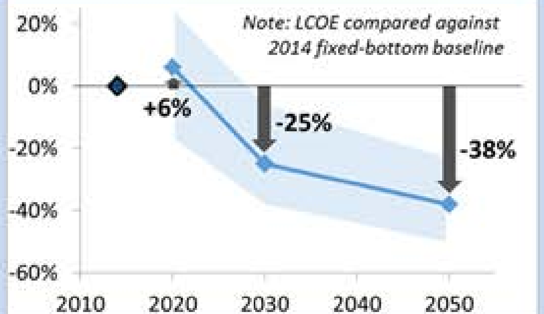
D



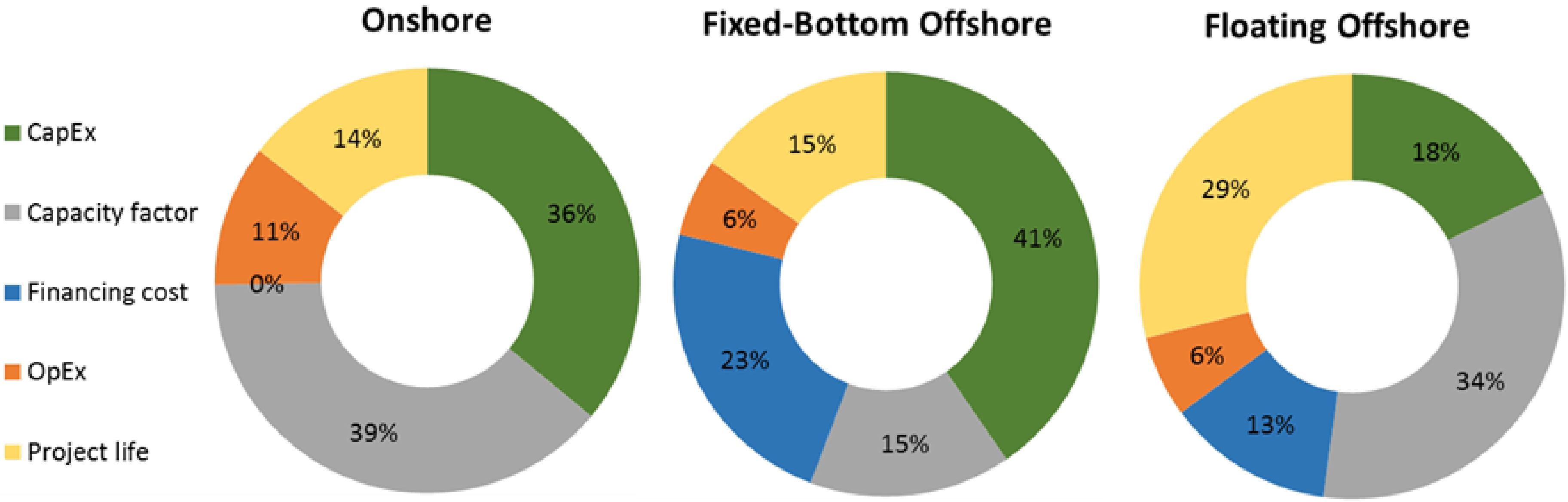
Estimate the total levelized system cost[1] of offshore (deepwater) wind energy in 2030.

You can adjust the box plot by dragging.

Summary of key results

	ONSHORE (LAND-BASED)	FIXED-BOTTOM OFFSHORE	FLOATING OFFSHORE
a) LEVELIZED COST OF ENERGY			 *Note: LCOE compared against 2014 fixed-bottom baseline*
b) DRIVERS FOR COST REDUCTION IN 2030	Capacity factor: +10% Project life: +10% CapEx: -12% OpEx: -9% WACC: no Δ	Capacity factor: +4% Project life: +15% CapEx: -14% OpEx: -9% WACC: -10%	Capacity factor: +9% Project life: +25% CapEx: -5% OpEx: -8% WACC: -5%
c) TURBINE SIZE IN 2030	3.25 MW 115 m hub height 135 m rotor diameter	11 MW 125 m hub height 190 m rotor diameter	9 MW 125 m hub height 190 m rotor diameter
d) TOP-FIVE IMPACT CATEGORIES	• Larger rotors, reduced specific power • Rotor design advancements • Taller towers • Reduced financing costs • Component durability / reliability	• Larger turbine capacity • Foundation / support structure design • Reduced financing costs • Economies of scale via project size • Component durability / reliability	• Foundation / support structure design • Installation process efficiencies • Foundation / support manufacturing • Economies of scale via project size • Installation / transport equipment

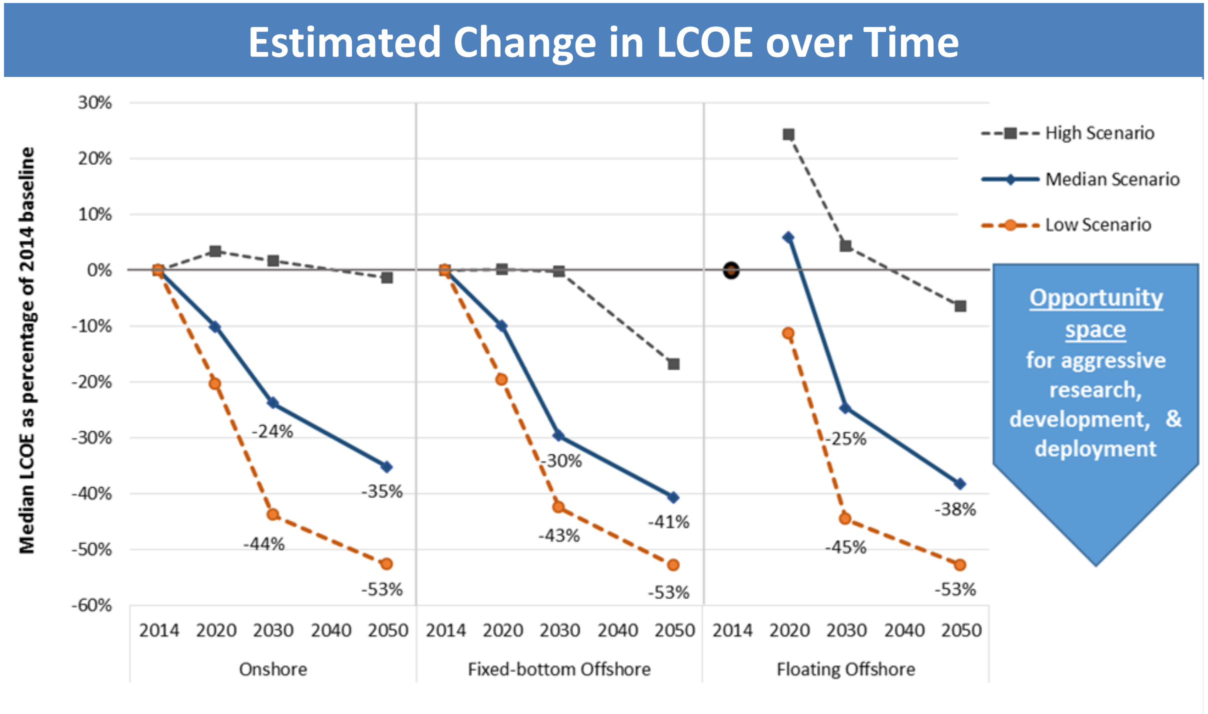
Relative impact of drivers for median-scenario LCOE reduction in 2030.



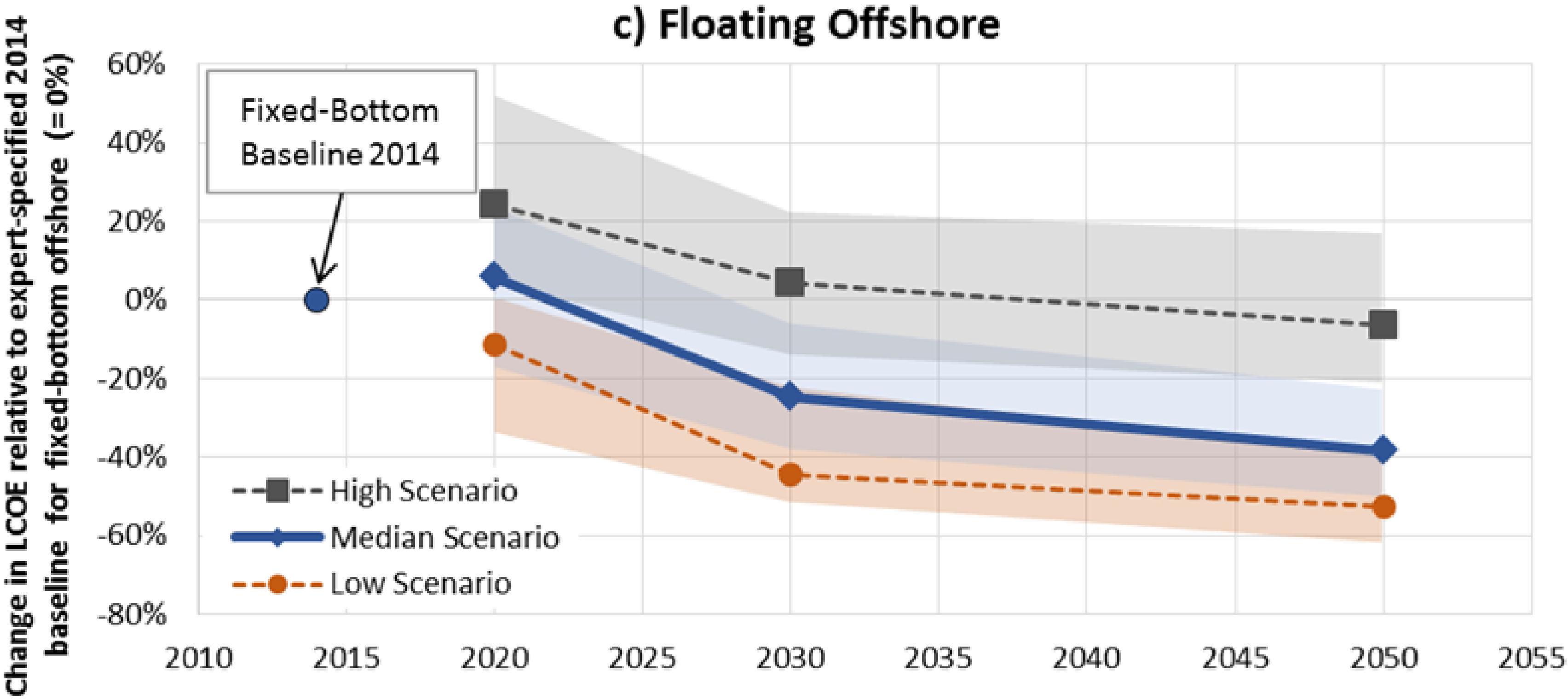
Note: Floating offshore wind is compared with 2014 baselines for fixed-bottom offshore wind.

Opportunity Space for Greater Cost Reductions Is Sizable

- Sought insight not only on the most-likely median-LCOE scenario, but also on less-likely scenarios for high and low future LCOEs
- Sizable resulting range in expert-specified LCOEs suggests significant uncertainty in degree and timing of future advancements
- Managing this uncertainty is—at least partially—within the control of decision makers; low scenario represents what might be possible with aggressive RD&D
- Survey results further show that “learning with market growth” and “research and development” are the two most-significant enablers for the low LCOE scenario



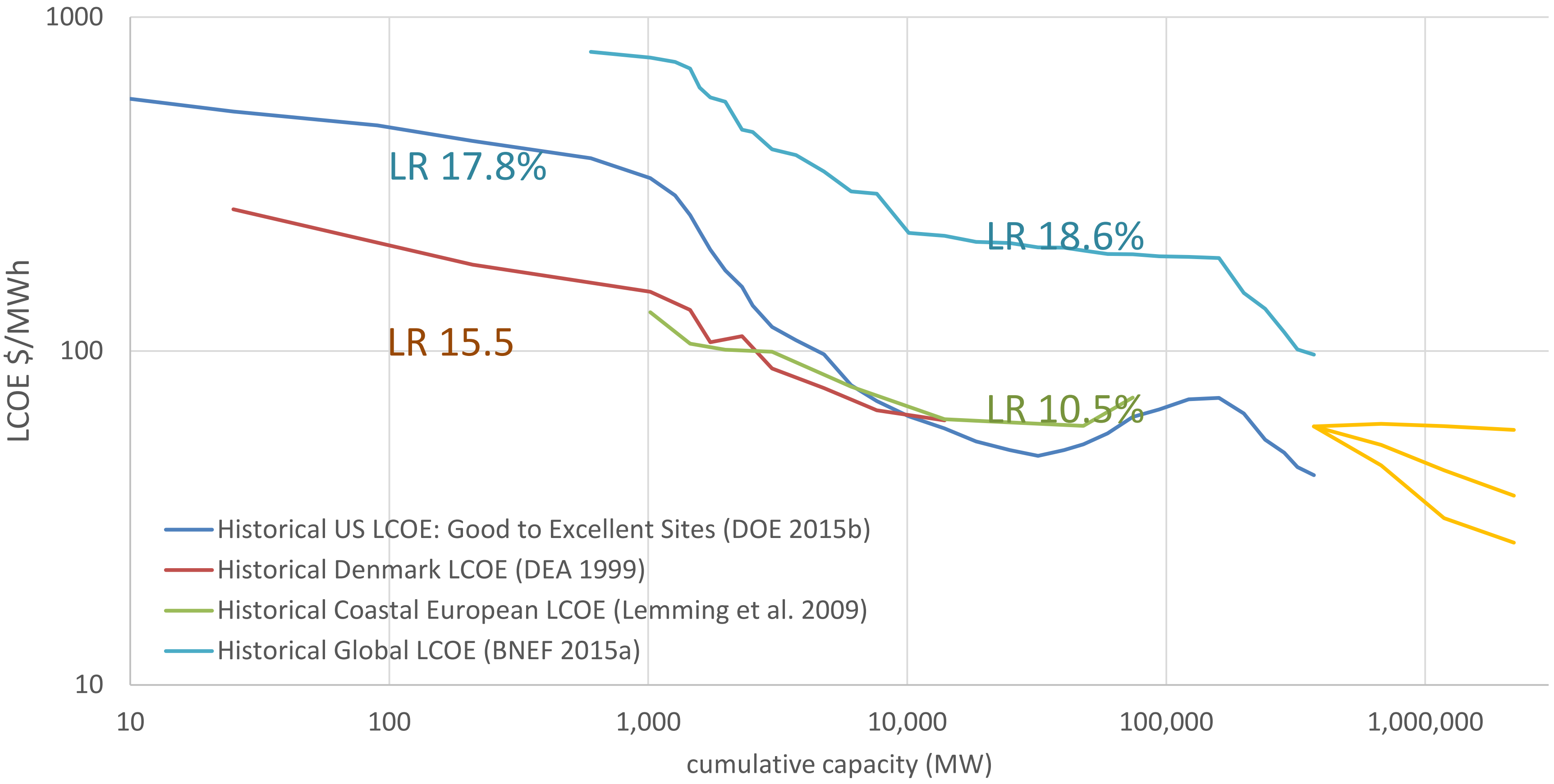
Significant uncertainty around cost reductions for floating offshore



Lines/markers indicate the **median** expert response
Shaded areas show the 1st-3rd quartile range of expert responses

Note: Change is shown relative to baseline for fixed-bottom offshore as no 2014 baseline was established for floating offshore

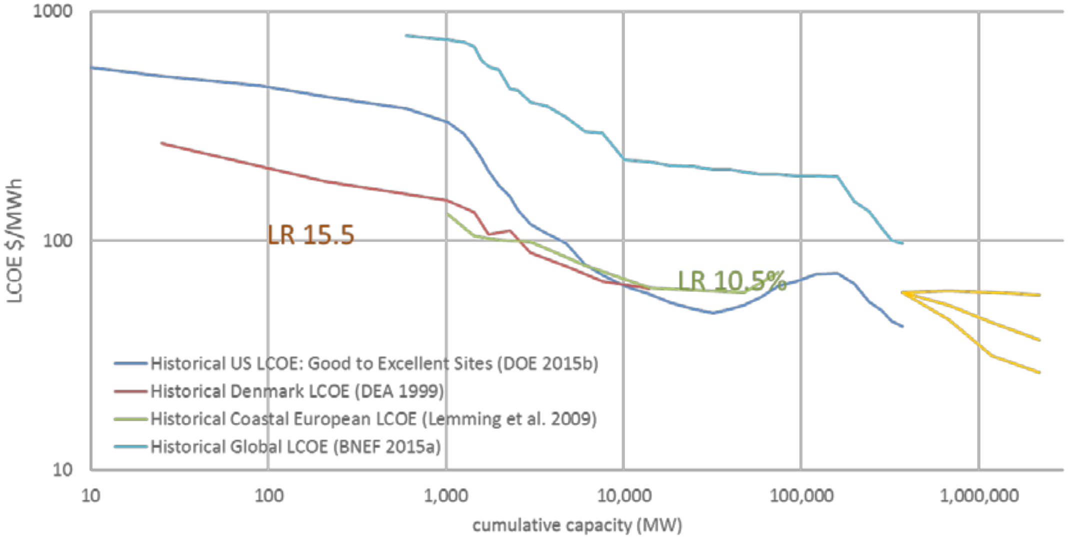
Historical and forecast experience curves for onshore wind



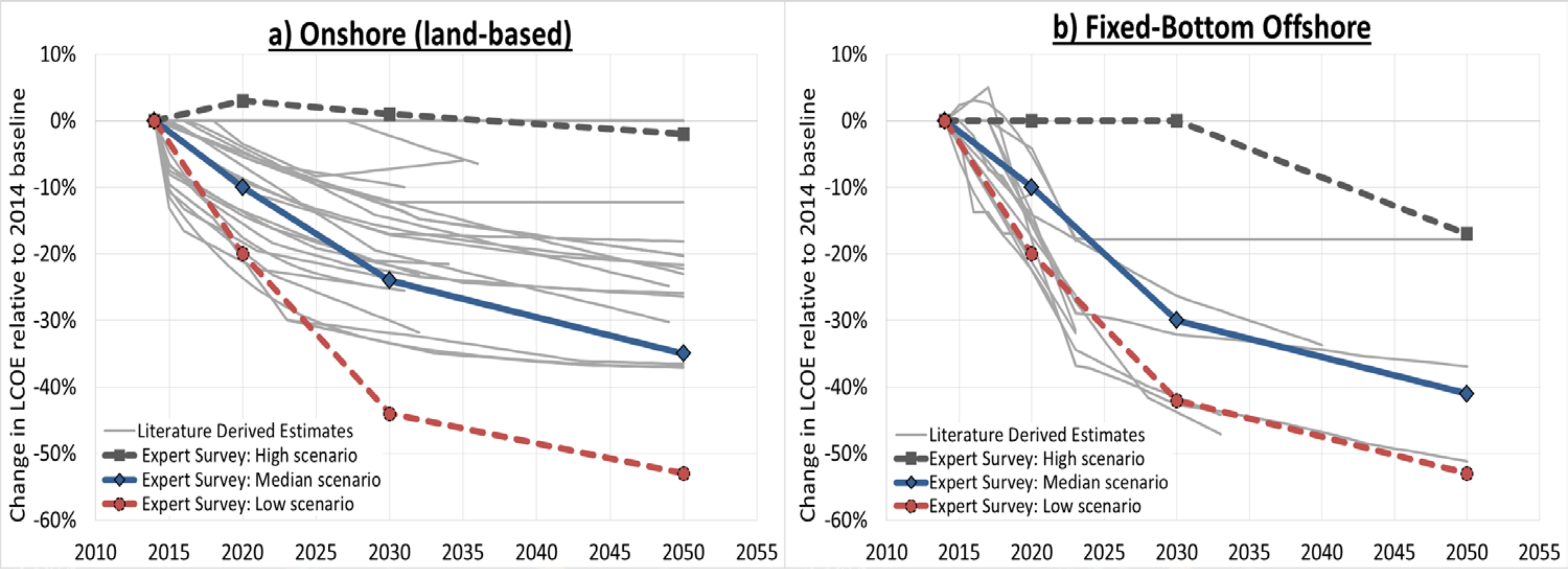
Historical LCOE estimates come from four sources (Global: BNEF 2015a; US: DOE 2015b; Denmark: DEA 1999; European Coastal: Lemming et al. 2009). Historical single-factor learning rates (LRs) are calculated based on cumulative global wind capacity. To estimate the implicit learning rate from the expert elicitation, we use median-scenario LCOE estimates and a range of projections for cumulative global wind capacity from IEA “New Policies” (IEA 2015), Bloomberg “Base Scenario” (BNEFb 2015), and GWEC “Moderate Scenario” (GWEC 2014).

Survey Results Broadly Consistent with Other Literature

- Though expert elicitation as a method is subject to possible bias and over-confidence, and notwithstanding the sizable range in LCOEs, survey results are broadly consistent with historical LCOE trends and other wind cost forecasts
- Figure here depicts four distinct estimates of historical onshore wind LCOE and associated learning rates (LRs = 10.5%–18.5%, meaning that LCOE declines by this amount for each doubling of global cumulative wind capacity)
- Implicit learning rate embedded in the median-scenario LCOE forecast from our experts to 2030 (about 14%–18%) is squarely within the range of these past, long-term learning trends for onshore LCOE



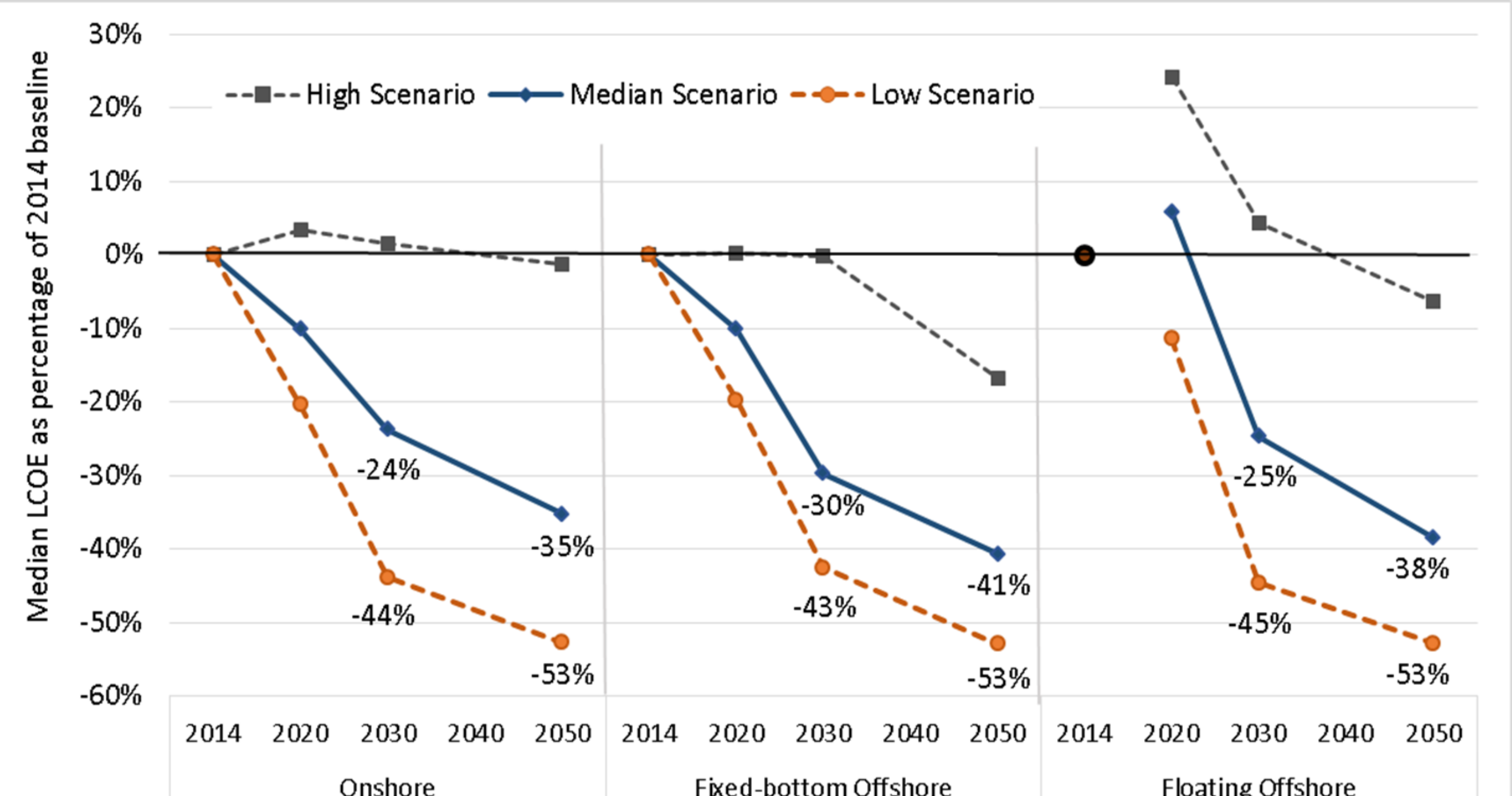
- Expert elicitation results also generally within the range of other forecasts of future wind energy LCOE, for both onshore and offshore wind



Estimated change in LCOE for (a) onshore and (b) fixed-bottom offshore: expert survey results vs. other forecasts. Depicts the median of expert responses for expected LCOE reductions in the median (50th percentile) scenario as well as the low scenario (10th percentile) and high scenario (90th percentile) in percentage terms relative to 2014 baseline values. Other forecasts are included for comparison, originally compiled and presented in a U.S. Department of Energy report (DOE 2015).

Conclusions

- Significant opportunity for cost reductions
- Option value in policies that increase future flexibility



Siting and Resource Management Challenges for Wind Integrated Power Systems

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Offshore wind energy has the potential to play a key role in transforming our power grid into a more sustainable system. The opportunities presented by this transformation come with significant grid integration challenges, in particular how to efficiently maintain grid reliability. This talk focuses on how the siting or grid interconnection location of a wind farm can affect grid stability and performance. We also discuss the complementary problem of storage siting and dispatch strategies to improve the efficiency of wind integrated power systems.

Biography

Dennice F. Gayme received a B.Eng & Society from McMaster University in 1997 and an MS from the University of California at Berkeley in 1998, both in Mechanical Engineering. She was a Senior Research Scientist in the Systems and Control Technology and Vehicle Health Monitoring Groups at Honeywell Laboratories in Minneapolis, MN from 1999-2003. She received her PhD in Control and Dynamical Systems in 2010 from the California Institute of Technology, where she was later a postdoctoral fellow in the Computing and Mathematical Sciences Department. In January 2012, she joined the Department of Mechanical Engineering at the Johns Hopkins University, where she is currently an Assistant Professor with secondary appointments in the Departments of Electrical and Computer Engineering and Geography and Environmental Engineering. Professor Gayme's research interests are in modeling, analysis and control of large-scale networked and spatially distributed systems in applications such as power networks, wind farms and wall-turbulence.

Predictive Maintenance Scheduling for Offshore Wind Farms Managed Using Power Purchase Agreements

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College Park, MD USA
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Prognostics and Health Management (PHM) technologies have been introduced into wind turbines to forecast the Remaining Useful Life (RUL). An RUL for a wind turbine represents the time or other applicable lifetime usage measure (e.g., cycles) that the turbine has left before it fails. PHM with RUL predictions enables predictive maintenance for wind turbines prior to failure, thus avoiding corrective maintenance that may be expensive and cause long downtimes. In this paper, for a wind farm managed using an outcome-based contracts known as power purchase agreement (PPA) with multiple wind turbines indicating RUL predictions, a simulation-based European real options analysis (ROA) approach is applied to schedule the predictive maintenance for the farm by maximizing the predictive maintenance option value. When a remaining useful life (RUL) is predicted for a single turbine managed under an “as-delivered” contract in isolation, a predictive maintenance option is triggered. If predictive maintenance is implemented before the turbine fails, the option is exercised; if the predictive maintenance is not implemented and the turbine runs to failure, the option expires and the option value is zero. The time-history cumulative revenue loss and avoided corrective maintenance cost paths are simulated considering the uncertainties in wind and the RUL predictions. By valuating a series of European real options based on all possible predictive maintenance opportunities, the maintenance opportunity with the maximum value can be obtained. For multiple wind turbines in a wind farm managed using a PPA indicating RULs concurrently, the cumulative revenue loss and avoided corrective maintenance cost for each turbine not only depend on the uncertainties in wind and the RUL predictions, but also on the operational state of all the other turbines in the farm, the amount of energy delivered, and the energy delivery target, prices and penalization mechanism for under-delivery defined in the PPA. A case study is presented, in which the optimum predictive maintenance opportunity is scheduled determined for a wind farm managed using a PPA. It is found that the optimum predictive maintenance opportunity for the farm under managed using a PPA an “as-delivered” contract changes from when the farm is managed using an “as-delivered” contract.

Biographies:

Xin Lei

Xin Lei received a B.S. degree in Reliability System Engineering and an M.S. degree in Systems Engineering from the Beihang University, Beijing. He is a Ph.D. student in the CALCE Electronic Products and Systems Center (EPSC), in the Department of Mechanical Engineering at the University of Maryland, College Park, where his interests include system life-cycle economics and prognostics and health management. Prior to attending the University of Maryland, he was an Integration & Verification Engineer of Ericsson (China) Communications Co. Ltd., Beijing.

Peter A. Sandborn

Dr. Sandborn received a B.S. degree in engineering physics from the University of Colorado, Boulder, and an M.S. degree in electrical science and Ph.D. degree in electrical engineering, both from the University of Michigan, Ann Arbor. He is a Professor in the CALCE Electronic Products and Systems Center (EPSC), in the Department of Mechanical Engineering at the University of Maryland, College Park, where his interests include system life-cycle economics, electronic part obsolescence and prognostics and health management. Prior to joining the University of Maryland, he was a founder and Chief Technical Officer of Savantage, Austin, TX, and a Senior Member of Technical Staff at the Microelectronics and Computer Technology Corporation, Austin. He is the author of over 200 technical publications and books on multichip module design and part obsolescence forecasting. Dr. Sandborn is an Associate Editor of the IEEE Transactions on Components Packaging and Manufacturing Technology, a member of the board of directors of the International PHM Society and the International Institute of Obsolescence Management. Dr. Sandborn is a Fellow of the IEEE and ASME.

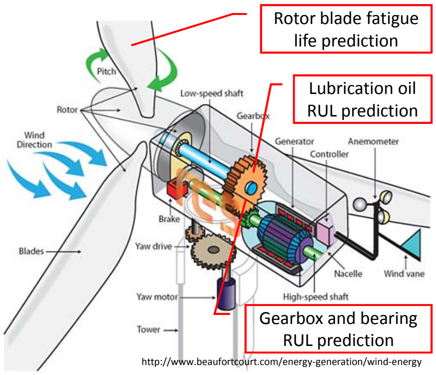
Predictive Maintenance Scheduling for Offshore Wind Farms Managed Using Power Purchase Agreements

Xin Lei and Peter Sandborn
CALCE, University of Maryland

Oct 5, 2016

Wind Turbines & Offshore Wind Farms

- Condition Monitoring (CM) and Prognostics and Health Management (PHM) technologies have been introduced into wind turbines
- Remaining useful lives (RULs) can be predicted by PHM for turbine subsystems or the system



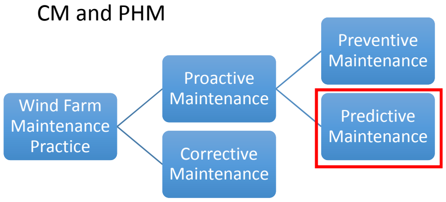
Rotor blade fatigue life prediction

Lubrication oil RUL prediction

Gearbox and bearing RUL prediction

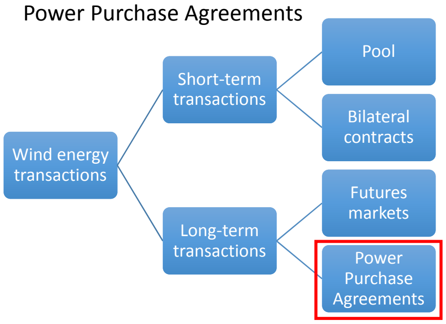
http://www.beaufortcourt.com/energy-generation/wind-energy

- Predictive maintenance is enabled by CM and PHM



Wind Farm Maintenance Practice
- Proactive Maintenance
  - Preventive Maintenance
  - Predictive Maintenance
- Corrective Maintenance

- Many offshore farms are under Power Purchase Agreements



Wind energy transactions
- Short-term transactions
  - Pool
  - Bilateral contracts
- Long-term transactions
  - Futures markets
  - Power Purchase Agreements

Motivation

RUL is predicted by PHM

Predictive
Maintenance
Opportunity

JANUARY

Mo	Tu	We	Th	Fr	Sa	Su
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

Options:
- Switch to a redundant subsystem (if any)
- Slow down
- Shut down
- Do nothing

Options:
- Maintain at the earliest opportunity
- Wait until closer to the end of the RUL to maintain
- Do nothing and run to failure for corrective maintenance

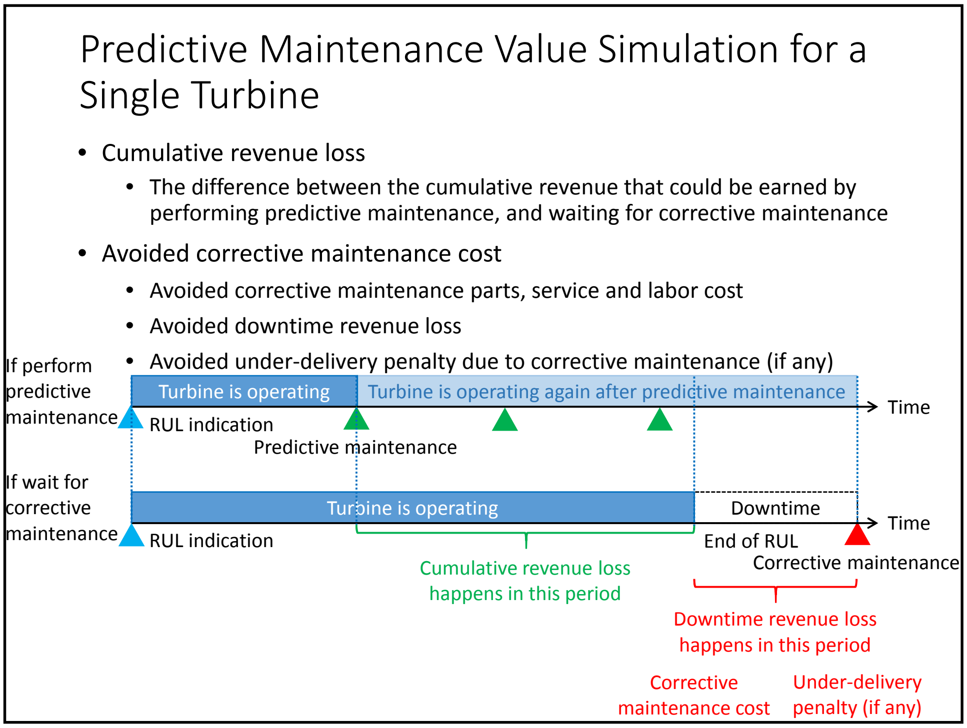
DECEMBER

Mo	Tu	We	Th	Fr	Sa	Su
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

If I could determine the ***value*** *of each of the options, I would have a basis upon which to make a decision about what action to take in response to the RUL prediction*

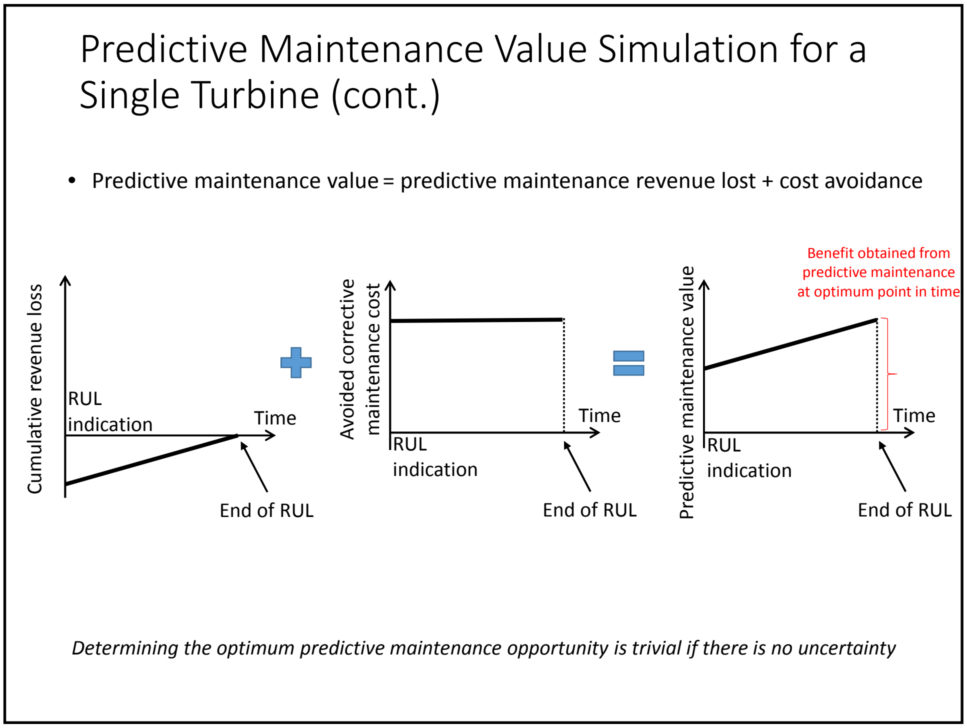
A Real Options View of Predictive Maintenance

- Real Options
  - The right, but not the obligation to invest, defer, abandon, expand, or stage a project at the future date
  - Assume the value-maximizing decisions will always be made at each decision point with the managerial flexibility
  - Enable the flexibility to alter the course of an action in a real assets decision depending on future developments
- Predictive maintenance opportunities triggered by RUL predictions can be treated as Real Options:
  - Buying the option = paying to add PHM into wind turbine subsystems
  - Exercising the option = performing predictive maintenance prior to failure
  - Exercise price = predictive maintenance cost
  - Letting the option expire = doing nothing and running the turbine to failure for corrective maintenance
- Value returned by exercising the option = cumulative revenue loss + avoided corrective maintenance cost
  - Representing the additional value obtained by implementing the predictive maintenance instead of waiting for the corrective maintenance



Predictive Maintenance Value Simulation for a Single Turbine

- Cumulative revenue loss
  - The difference between the cumulative revenue that could be earned by performing predictive maintenance, and waiting for corrective maintenance
- Avoided corrective maintenance cost
  - Avoided corrective maintenance parts, service and labor cost
  - Avoided downtime revenue loss
  - Avoided under-delivery penalty due to corrective maintenance (if any)



Predictive Maintenance Value Simulation for a Single Turbine (cont.)

- Predictive maintenance value = predictive maintenance revenue lost + cost avoidance

Determining the optimum predictive maintenance opportunity is trivial if there is no uncertainty

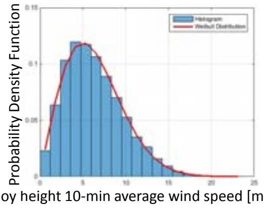
Path Simulation with Uncertainties

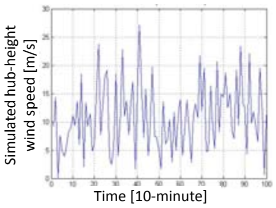
- Path = starting at the RUL indication, one possible way the future could occur considering the uncertain PHM prediction and future wind speed
- Paths modeled:
    - Future wind speed paths, based on which cumulative revenue loss and a avoided corrective maintenance cost paths are simulated
    - Cumulative revenue loss paths, each step represents how much revenue loss could happen if implementing the predictive maintenance at that time
    - Avoided corrective maintenance cost path, each step represents how much corrective maintenance and related costs can be avoided if implementing the predictive maintenance at that time
    - Each path is a single member of a population of paths

Wind Speed and TTF Simulation

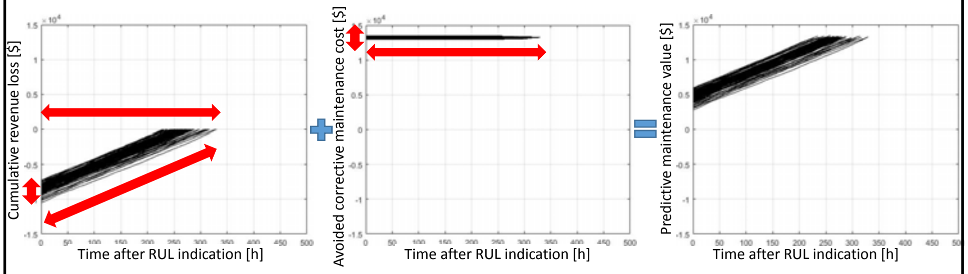

http://www.4coffshore.com/windfarms/turbine-mhi-vestas-offshore-wind-v112-3.0-mw-offshore-tid55.html

- Wind turbine: Vestas V112-3.0 MW Offshore
- Wind speed simulation
    - 2003 to 2012 wind data of NOAA Buoy 44009 (in the Maryland Offshore Wind lease area) fit with a Weibull distribution
    - Monte Carlo simulation used to get buoy height wind speed paths
    - Power Law used to transfer buoy height wind speed to hub height
- Time to Failure (*TTF*) simulation
    - A TTF represents a possible calendar time (e.g., in hours) for the turbine to fail considering the uncertain PHM predictions and future wind speeds
    - A Normal distribution is assumed for the RUL prediction (e.g., in cycles) to represent the uncertainties in the PHM forecasting ability
    - For each wind speed path, Monte Carlo simulation is used to get an RUL sample
    - Wind speed → rotational speed → RUL consumption → *TTF* (e.g. in hours)





Case Study for a Single Turbine under an "As-delivered" Contract



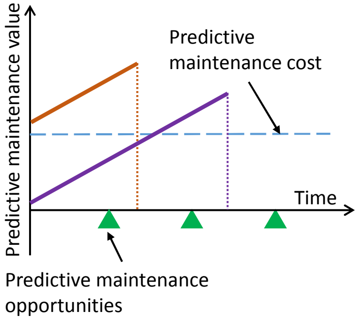
- Due to the uncertainties in RUL prediction and wind speed, each path starts at a different point
  - Generally the shorter the *TTF*, the higher the cumulative revenue loss path starts, because the fewer the cumulative revenue will be lost by predictive maintenance before *TTF*
  - The avoided corrective maintenance cost paths start at different but close points, because the length of corrective maintenance downtime is assumed to be fixed, while the wind speed is uncertain
- Due to the uncertainties in RUL prediction and wind speed, each path terminates at a different point
  - The point is the last predictive maintenance opportunity before the *TTF*
- The fluctuations of the cumulative revenue loss paths represent the uncertainties in wind speed

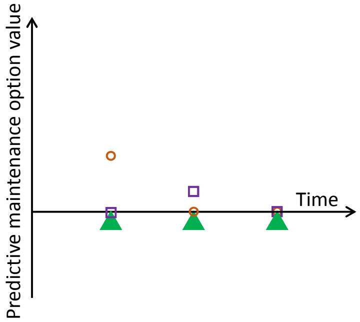
So how do we schedule the predictive maintenance based on this set of paths?

Predictive Maintenance Scheduling for a Single Turbine under an "As-delivered" Contract

- Predictive maintenance can only be performed on specific opportunities
- Assume at each opportunity, the decision-maker has flexibility to determine whether to implement the predictive maintenance (exercise the option) or not (let the option expire)
- This makes the option a sequence of "European" style options that can only be exercised at specific points in time in the future
- European Real Option Analysis (ROA) is performed for the option valuation, where *OV(t)* is the option value, C_{PM} is the predictive maintenance cost at *t* assumed to be constant:

$$OV(t) = max(V(t) - C_{PM}, 0)$$

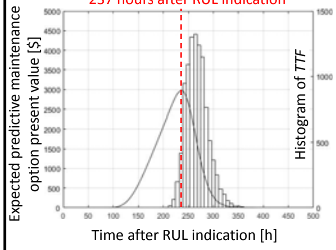




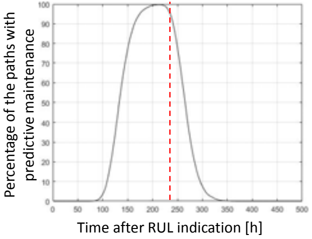
Case Study for a Single Turbine under an “As-delivered” Contract

- On each predictive maintenance opportunity, the European ROA approach is implemented on all predictive maintenance value paths
- The results are averaged to get the expected predictive maintenance option value
- This process is repeated for all maintenance opportunity opportunities
- The optimum predictive maintenance opportunity is determined as the one with the maximum expected predictive maintenance option value

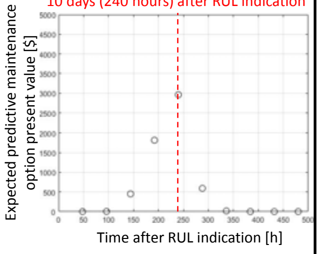
If predictive maintenance opportunity is once every hour, the optimum predictive maintenance opportunity is 237 hours after RUL indication



At the optimum predictive maintenance opportunity, 93.9% of the paths choose to implement the predictive maintenance



If predictive maintenance opportunity is once every two days, the optimum predictive maintenance opportunity is 10 days (240 hours) after RUL indication



The ROA approach is not aiming at totally avoiding corrective maintenance, but maximizing the predictive maintenance option value

Power Purchase Agreement (PPA) Modeling

- PPA is an outcome-based contract between wind energy seller and buyer
- PPA example:
  - Seller: PPM Energy, Inc. (now Iberdrola Renewables)
  - Buyer: City of Anaheim, CA
  - 20-year agreement signed in 2003
  - Constant amount of energy required to be delivered for every hour
  - Contract energy price: $53.50/MWh of delivered energy
  - From the contract: **3.1.2 <u>Sources of Electric Energy and Environmental Attributes</u>**
    - “Seller may obtain electric energy for delivery at the Delivery Point from market purchases or from any other source or sources or combination thereof as determined by Seller in its sole discretion”

Nothing in the contract says “only when the wind blows” or “only if the turbines are operational”

http://iberdrolarenewables.us/

Power Purchase Agreement (PPA) Modeling

- PPA Modeling:
  - An annual energy delivery target is agreed by the seller and the buyer at the beginning of the year to reflect the buyer's annual wind energy demand, which will not change through the year
  - Constant contract energy price applies for each MWh generated before the annual target is met
  - Seller still buys the energy over-delivered at an constant over-delivery energy price lower than the contract energy price
  - If under-delivery happens, the difference between the annual target and the amount actually delivered by wind is calculated. The seller has to buy energy to make up the difference from other sources (e.g., burning coal/oil) at a price higher than the contract energy price

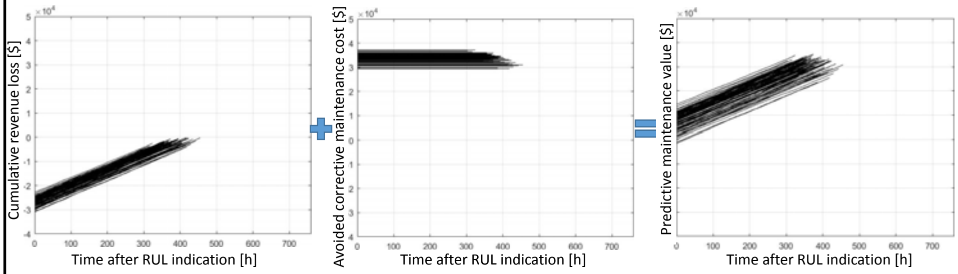
Extension the Predictive Maintenance Value Simulation Method to Wind Farms

- Assume maintenance will be performed on multiple turbines (and multiple turbine subsystems) on each maintenance visit because:
  - Expensive resources are required (e.g., vessels, cranes, helicopters)
  - Maintenance windows are limited due to the harsh marine environment
- Predictive maintenance value paths of all turbines with RULs need to be combined together then to do the European ROA
  - An alternative is to do ROA on each turbine with RUL and then sum the results, which implies that the maintenance can be scheduled for each turbine independently (which is not considered in the proposed work)

Therefore, we must be able to determine the optimum maintenance opportunity for multiple turbines by adding the predictive maintenance values

Case Study for a Wind Farm under a PPA

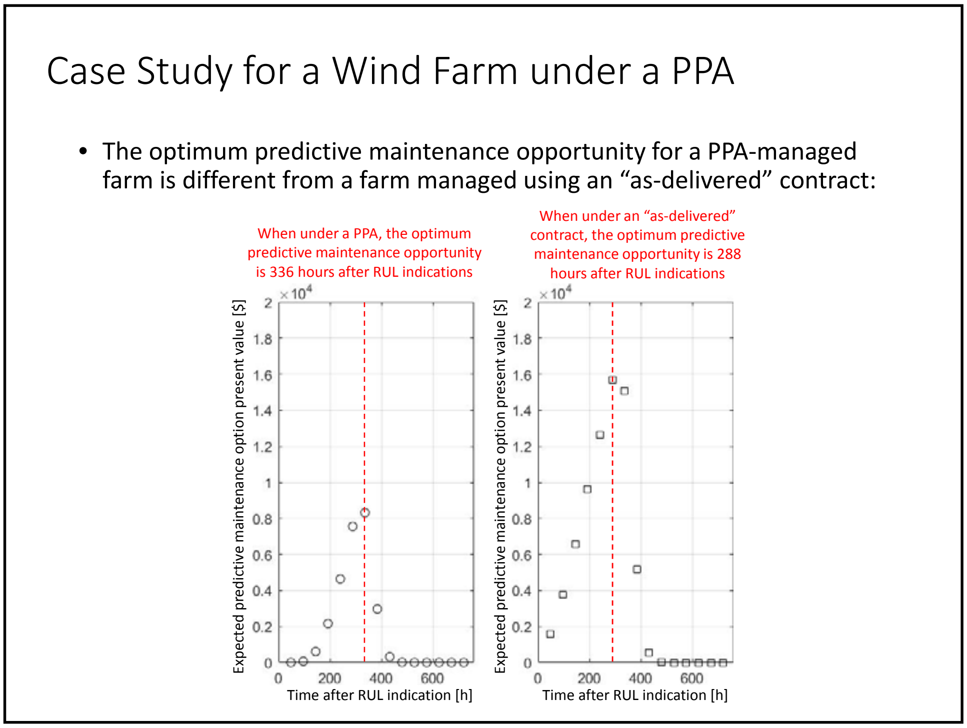
- Assume a 5-turbine-farm managed via a PPA, Turbines *1* & *2* indicate RULs on Day 0, all the other 3 turbines operate normally
- Cumulative revenue loss, avoided corrective maintenance cost and predictive maintenance value paths for Turbines *1* & *2*:



Predictive Maintenance Scheduling for a Wind Farm under a PPA

- European Real Option Analysis (ROA) is performed for the option valuation, where $C_{PM,K}$ is the total predictive maintenance cost for all K turbines with RULs
- It is assumed that all K turbines will be maintained together, so once the first turbine failure happens, the predictive maintenance option expires

$$OV(t) = max\left(V(t) - \sum_{k=1}^{K} C_{PM,K}\,, 0\right)$$

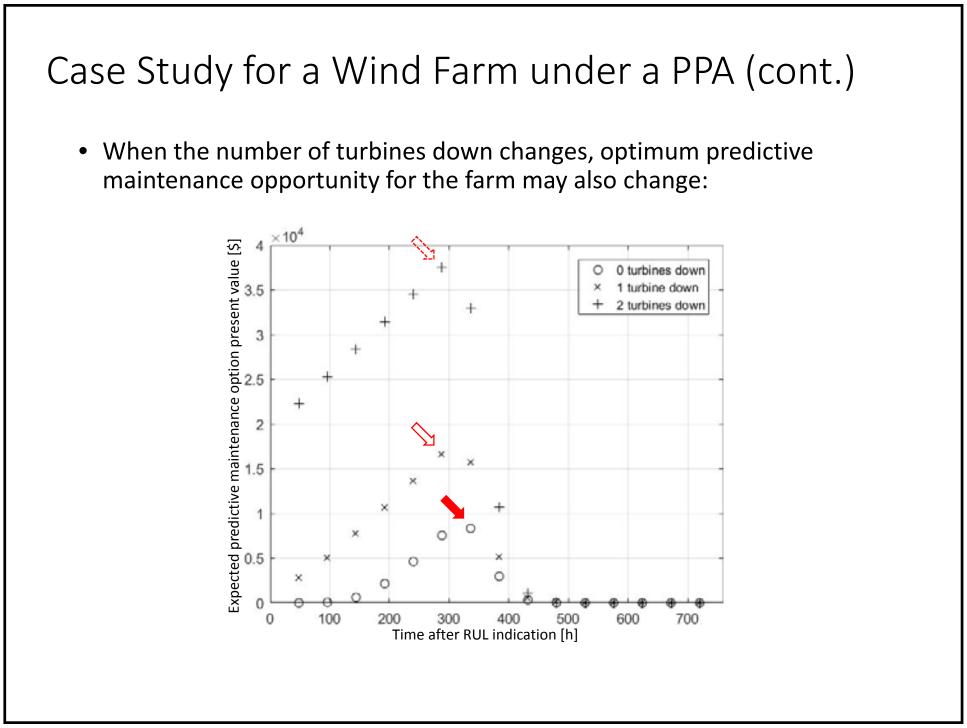


Case Study for a Wind Farm under a PPA

- The optimum predictive maintenance opportunity for a PPA-managed farm is different from a farm managed using an “as-delivered” contract:

When under a PPA, the optimum predictive maintenance opportunity is 336 hours after RUL indications

When under an “as-delivered” contract, the optimum predictive maintenance opportunity is 288 hours after RUL indications



Case Study for a Wind Farm under a PPA (cont.)

- When the number of turbines down changes, optimum predictive maintenance opportunity for the farm may also change:

Conclusions

- The optimum predictive maintenance opportunity by European ROA approach is a tradeoff between minimizing the risk of corrective maintenance and minimizing the value of the part of the RUL thrown away
- For a wind farm under a PPA with multiple wind turbines indication RULs, the predictive maintenance value for each turbine depends on the operational state of the other turbines, the amount of energy delivered and to be delivered by the whole wind farm
- When the predictive maintenance calendar changes, the optimum predictive maintenance opportunity may also change
- The optimum predictive maintenance opportunity for a PPA-managed farm is different from a farm managed using an “as-delivered” contract
- The optimum predictive maintenance date for the turbines with RULs in a farm under a PPA may change when the number of the turbines down changes

Generalization of Maintenance Options for Non-Production Systems

- Contactor = owner and maintainer of the system
- Customer = recipient of (pays for) the outcome of the system
- Production vs. Non-production Systems
    - Production Systems = contractor’s revenue depends on the quantity of outcome
    - Non-production Systems = contractor’s revenue is determined by the availability
    - Production vs. non-production can modify the contractor’s analysis

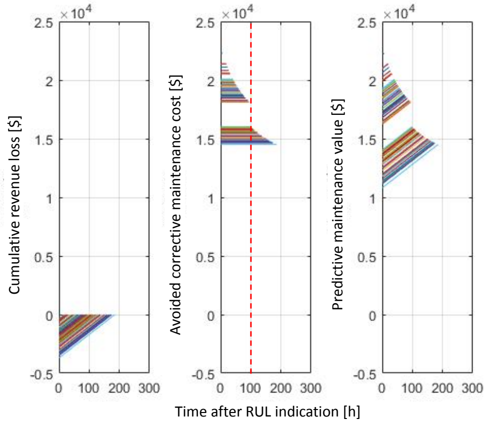
Example System	Contractor	Customer	Outcome for the Customer	Customer Value	Contractor View
Wind Farm	Farm Owner	Utility	Power	Power they can sell to their customers	Production
Parking Management	Towing Company	Municipal Government	Illegally Parked Cars Removed	Managed Parking	Production
Commercial Aircraft Engine	Engine Manufacturer	Airline	Engine Availability	Passengers they can fly or retain	Non-production
Military Aircraft Engine	Engine Manufacturer	Military	Engine Availability	Successful mission completion	Non-production

Generalization of Maintenance Options for Non-Production Systems (cont.)

- Modeling for a single non-production system managed under an availability-based contract
  - Customer pays a fixed contract price to contractor for each unit time the system is operating
  - Contractor compensates customer the same price for each unit time the system is down
  - Customer requires a minimum availability target
    - Availability is measured from time of RUL indication to the end of either a predictive or corrective maintenance event
    - Actual availability failing to meet the target will lead to a penalty
  - Number of spares in inventory is considered
    - Inventory will be replenished at a known future time if empty when RUL indication is given
    - Predictive or corrective maintenance without a spare in inventory will lead to a penalty (e.g., by an urgent buy)

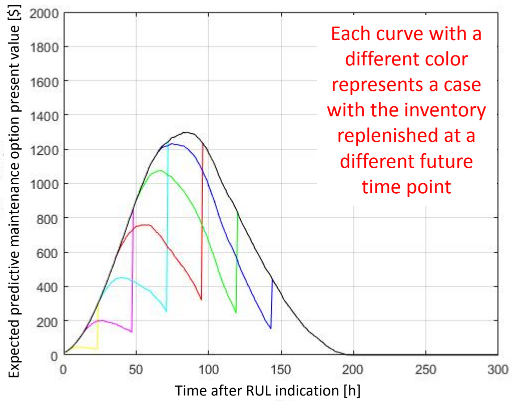
Generalization of Maintenance Options for Non-Production Systems (cont.)

Inventory is empty when RUL indication is given, and will be replenished at 96 hours after the RUL indication



Generalization of Maintenance Options for Non-Production Systems (cont.)

Time for the inventory to be replenished can affect the optimum predictive maintenance opportunity (the peak of the curve)



Each curve with a different color represents a case with the inventory replenished at a different future time point

Publications from this Work to Date

- X. Lei, and P. Sandborn, “Maintenance Scheduling Based on Remaining Useful Life Predictions for Wind Farms Managed Using Power Purchase Agreements,” submitted to Renewable Energy Special Issue: Real-time monitoring, prognosis and resilient control for wind energy systems, June 2017.
- A. Kashani-Pour, N. Goudarzi, X. Lei, and P. Sandborn, “Book Chapter: Product-Service Systems Under Availability-Based Contracts: Maintenance Optimization and Concurrent System and Contract Design,” to be published Through-Life Engineering Services: Perspectives and Developments, Springer, January 2017.
- P. Sandborn, A. Kashani-Pour, N. Goudarzi, and X. Lei, “Outcome-based contracts – concurrently designing products and contracts,” to be published Proceedings of the 5th International Conference on Through-life Engineering Services, Cranfield University, UK, November 2016.
- X. Lei, and P. Sandborn, “PHM-Based Wind Turbine Maintenance Optimization Using Real Options,” International Journal of Prognostics and Health Management, 2016.
- X. Lei, P. Sandborn, and N. Goudarzi, “PHM Based Predictive Maintenance Option Model for Offshore Wind Farm O&M Optimization,” Proceedings of the Annual Conference of the PHM Society, San Diego, CA, October 2015.
- X. Lei, and P. Sandborn, “Offshore Wind Farm O&M Optimization Based on Real Options Analysis,” AWEA Offshore 2015, Baltimore, MD, September 2015.
- X. Lei, P. Sandborn, R. Bakhshi, A. Kashani-Pour, and N. Goudarzi, “PHM Based Predictive Maintenance Optimization for Offshore Wind Farms,” Proceedings of the IEEE Prognostics and Health Management, Austin, TX, June 2015.
- X. Lei, P. Sandborn, R. Bakhshi, A. Kashani-Pour, and N. Goudarzi, “Using Maintenance Options to Optimize Wind Farm O&M,” Presented at NAWEA, Blacksburg, VA, June 2015.
- X. Lei, P. Sandborn, R. Bakhshi, and A. Kashani-Pour, “Development of a Maintenance Option Model to Optimize Offshore Wind Farm O&M,” Proceedings of EWEA Offshore, Copenhagen, Denmark, March 2015.
- R. Bakhshi, P. Sandborn, X. Lei, and A. Kashani-Pour, “Return on Investment Modeling to Support Cost Avoidance Business Cases for Wind Farm O&M,” Proceedings of EWEA Offshore, Copenhagen, Denmark, March 2015.
- P. Sandborn, G. Haddad, A. Kashani-Pour, and X. Lei, “Development of a Maintenance Option Model to Optimize Offshore Wind Farm Sustainment,” Proceedings of SciTech, AIAA, January 2014.

Q&A

Impact of Port Infrastructure Investment on the Life Cycle Costs and Rate Impacts of Offshore Wind

Deniz Ozkan
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Atlantic Wind Connection, LLC
Silver Spring, MD USA
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This presentation will discuss the port investment strategies and requirements for different staging, assembly and manufacturing activities, to support offshore wind installations on the East Coast. Preliminary cost and impact figures will be shared for representative activities and the impact of future innovative designs and applications will be introduced.

Biography

Dr. Deniz Ozkan is an engineer working in the area of analysis, project design and permitting for Atlantic Grid Development (AGD). Dr. Ozkan has conducted extensive research in the field of optimizing the siting of offshore wind energy facilities from both an engineering and economic perspective. Dr. Ozkan understands the constraints that affect wind farm siting and is instrumental in ensuring that offshore wind plant and transmission design is focused on the efficient and economical development of the offshore wind industry. Dr. Ozkan has a Ph.D. in Engineering Management / Economics, Finance and Cost Engineering from The George Washington University, and an MBA in Management and Organization and a B.Sc. in Industrial Engineering from Marmara University in Istanbul, Turkey. Dr. Ozkan has conducted more than eight years of research in the fields of renewable energy, sustainability, and integrated system analysis.

Atlantic Grid Development

Impact of Port Infrastructure Investment on the Life Cycle Costs and Rate Impacts of Offshore Wind

IPF 2016, Life Cycle Costs for Offshore Wind – New Port, RI

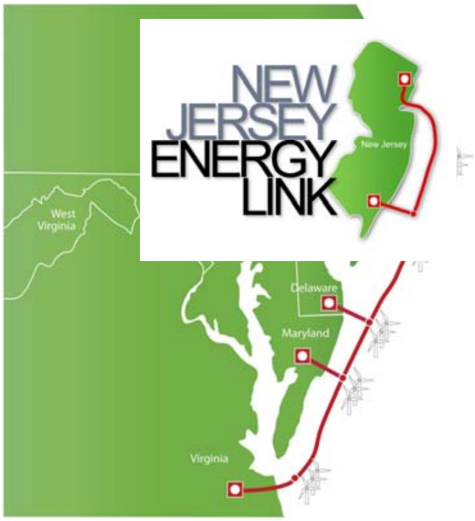
October 5th, 2016

Deniz Ozkan, Ph.D.
Director of Analysis, Research and Systems Engineering
dozkan@atlanticwindconnection.com

Former Research and Studies

- Cost Studies
    - Massachusetts Offshore Wind Cost Study, November 2015 – January 2016
    - New York Offshore Wind Cost Reduction Study, June 2014 - February 2015
        - University of Delaware, Special Initiative on Offshore Wind
- DOE funded research projects
    - Mid-Atlantic Offshore Wind Interconnection and Transmission (MAOWIT), 2011 - 2014
        - University of Delaware, Princeton University, PJM Interconnection, Stanford University and AGD
    - A System Design Study for Wilmington Canyon Offshore Wind Farm, 2011 - 2014
        - University of Delaware, Moffat & Nichol, Saipem, CG Power Systems, Signal International, Stanford University and AGD
- Ph.D. in Engineering Management – Economics, Finance and Cost Engineering- The George Washington University, 2011
    - Dissertation: Financial Analysis and Cost Optimization of Offshore Wind Energy under Uncertainty and in Deregulated Power Markets

Atlantic Grid Development
Atlantic Wind Connection Project



- Multi-year plan to build subsea high voltage transmission system off mid-Atlantic states in phases
- Enables up to 6,000 MW of offshore wind to be developed 12 or more miles off the coast
- Helps reduce offshore wind transmission costs
- Makes onshore grid more robust

Google elia Powering a world in progress BregalEnergy Marubeni Corporation

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Offshore Wind Farm

Complex System

Relatively New Technology

Various, Interrelated Uncertain Parameters

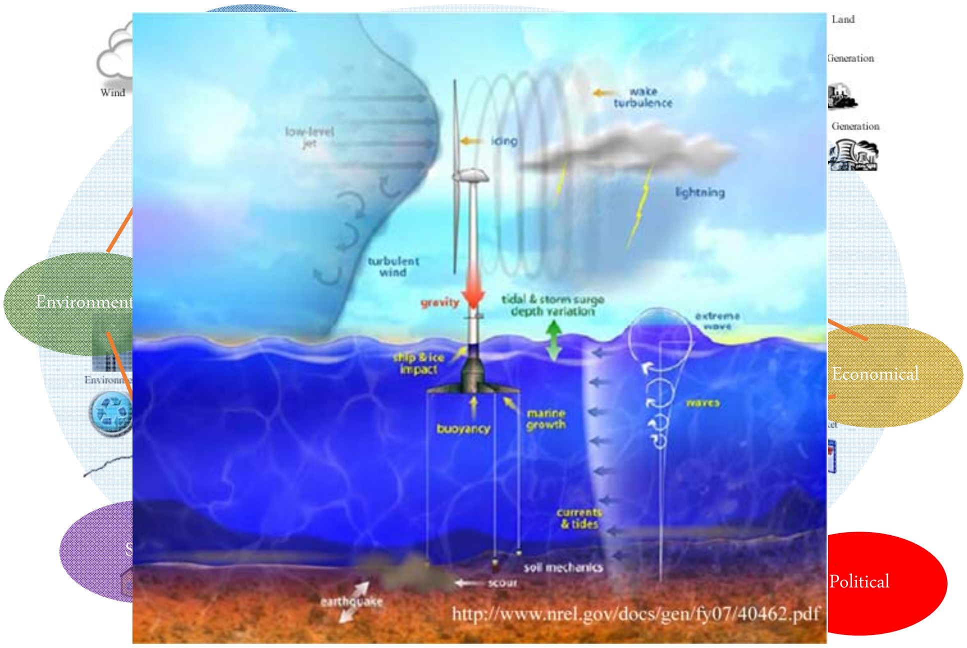
High COE

Inadequate, Traditional LCC

London Array Wind Farm
July 2013

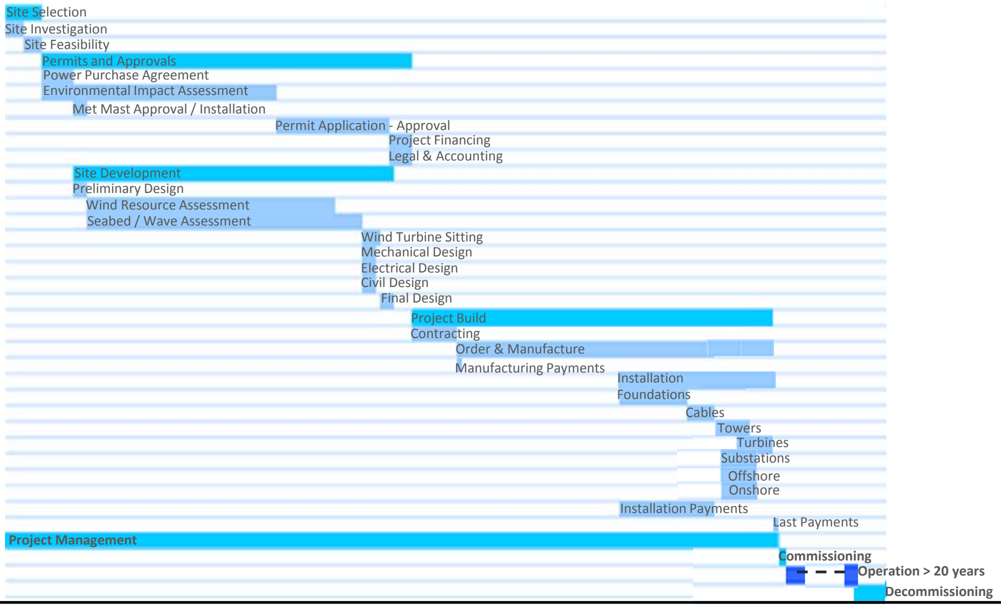
Wind turbines:	175 Siemens SWT - 3.6 MW
Capacity:	630 MW
Water depth:	0 - 25 meters
Distance from shore:	20 kilometers
Surface area:	100 km²
Hub height:	87 meters
Blade Length:	58.5 meters
Annual power production:	2,500 GWh
Enough to power:	450,000 households
CO_2 emission reduction:	925,000 tons/yr

Picture taken from http://www.londonarray.com/offshore-2/



http://www.nrel.gov/docs/gen/fy07/40462.pdf

Life Cycle of an Offshore Wind Project



Site Selection
Site Investigation
Site Feasibility
Permits and Approvals
Power Purchase Agreement
Environmental Impact Assessment
Met Mast Approval / Installation
Permit Application - Approval
Project Financing
Legal & Accounting
Site Development
Preliminary Design
Wind Resource Assessment
Seabed / Wave Assessment
Wind Turbine Sitting
Mechanical Design
Electrical Design
Civil Design
Final Design
Project Build
Contracting
Order & Manufacture
Manufacturing Payments
Installation
Foundations
Cables
Towers
Turbines
Substations
Offshore
Onshore
Installation Payments
Last Payments
Project Management
Commissioning
Operation > 20 years
Decommissioning

Levelized Cost Of Offshore Wind Energy

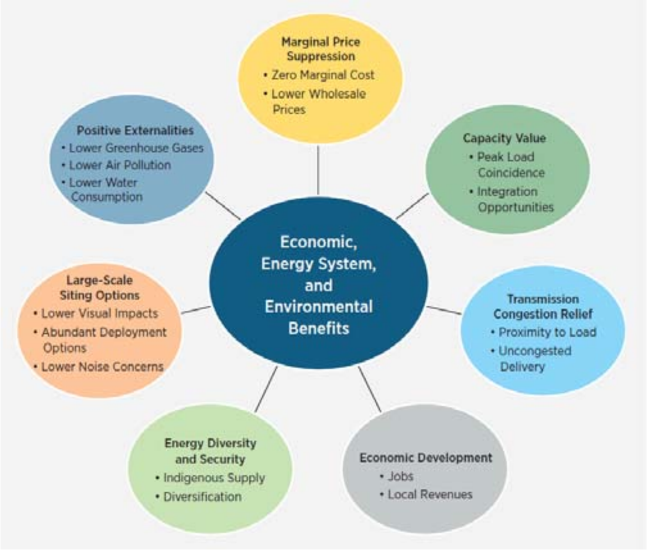
Calculated from project characteristics, including among others:

- Capital Costs (equipment, transport, etc.) - CAPEX
- Construction cost, including contingency fee
- Operations & Maintenance - OPEX
- Construction Financing
- Permanent Financing
- Development cost
- Capacity and capacity factor
- Taxes

LCOE is analytical, PPA is commercial

- Tax credits can lower (PTC/ITC)
- Strategy by bidder may raise or lower
- PPC can have an escalator to match increasing fossil fuel prices

System Benefits of Offshore Wind Energy



Economic, Energy System, and Environmental Benefits

Marginal Price Suppression
- Zero Marginal Cost
- Lower Wholesale Prices

Capacity Value
- Peak Load Coincidence
- Integration Opportunities

Transmission Congestion Relief
- Proximity to Load
- Uncongested Delivery

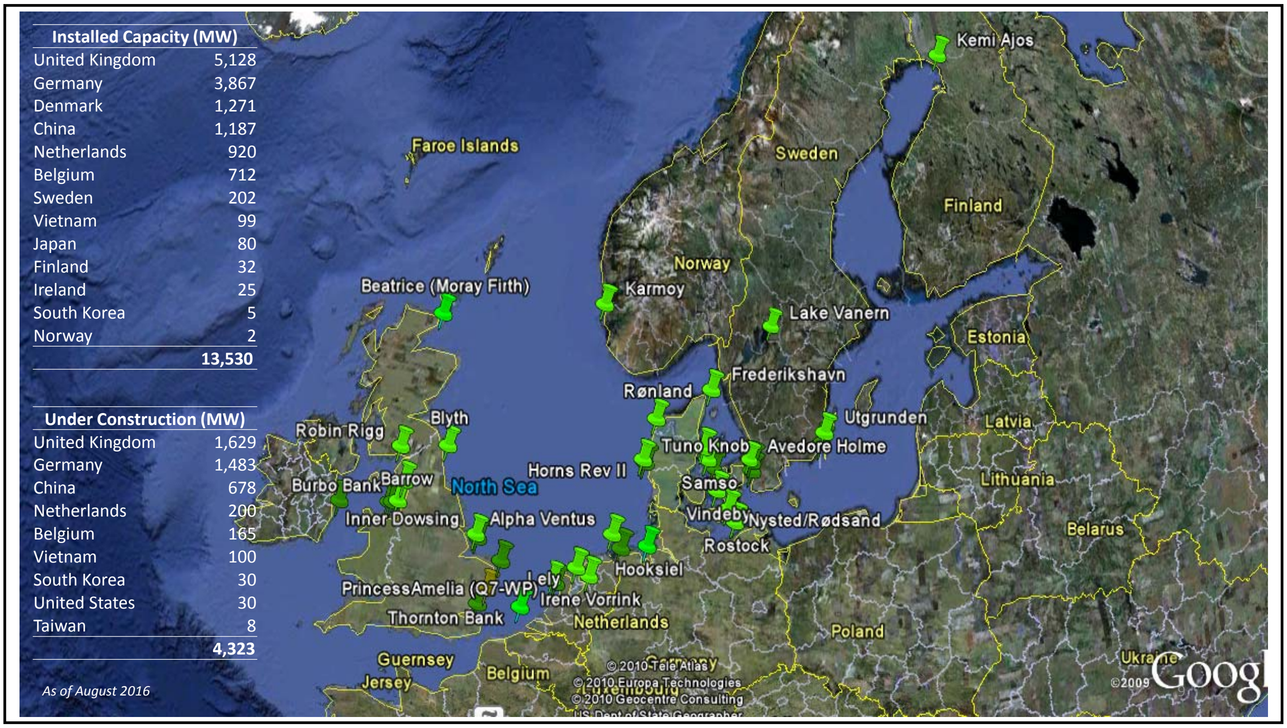
Economic Development
- Jobs
- Local Revenues

Energy Diversity and Security
- Indigenous Supply
- Diversification

Large-Scale Siting Options
- Lower Visual Impacts
- Abundant Deployment Options
- Lower Noise Concerns

Positive Externalities
- Lower Greenhouse Gases
- Lower Air Pollution
- Lower Water Consumption

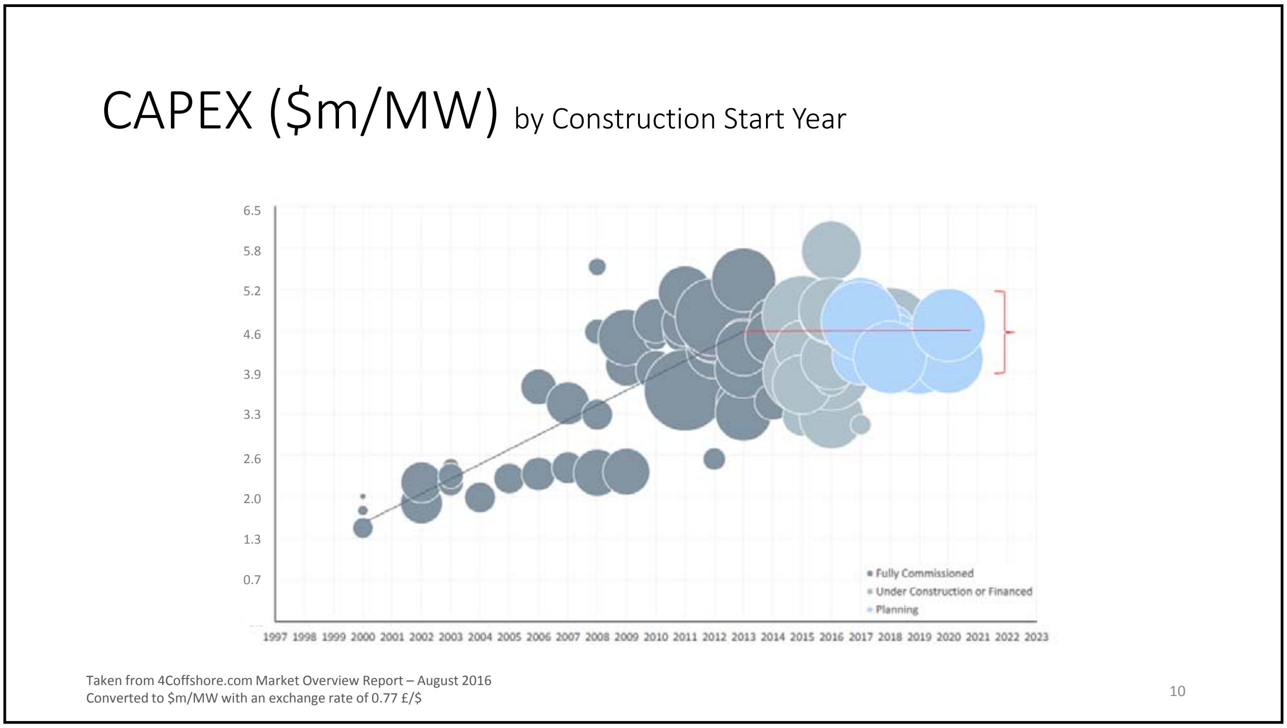
Taken from *National Offshore Wind Strategy* - http://energy.gov/sites/prod/files/2016/09/f33/National-Offshore-Wind-Strategy-report-09082016.pdf



Installed Capacity (MW)	
United Kingdom	5,128
Germany	3,867
Denmark	1,271
China	1,187
Netherlands	920
Belgium	712
Sweden	202
Vietnam	99
Japan	80
Finland	32
Ireland	25
South Korea	5
Norway	2
	13,530

Under Construction (MW)	
United Kingdom	1,629
Germany	1,483
China	678
Netherlands	200
Belgium	165
Vietnam	100
South Korea	30
United States	30
Taiwan	8
	4,323

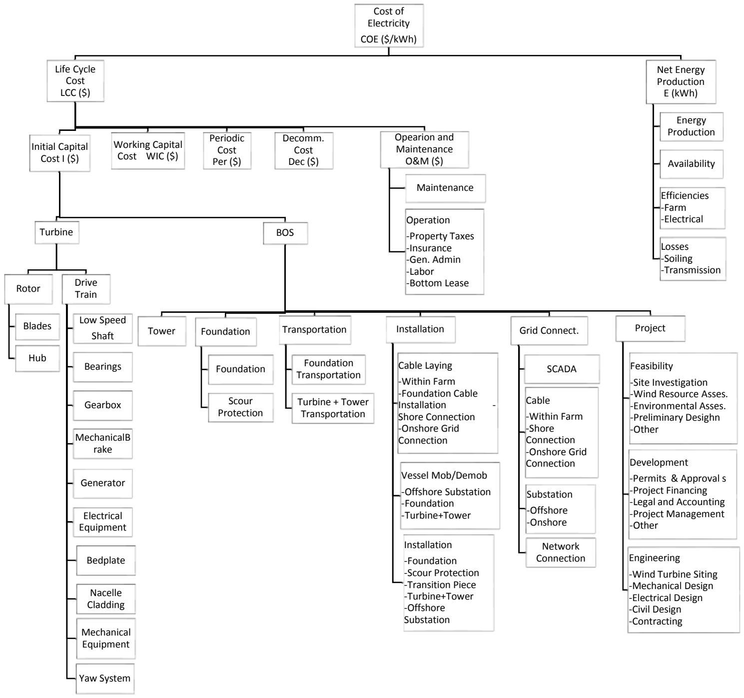
As of August 2016



CAPEX ($m/MW) by Construction Start Year

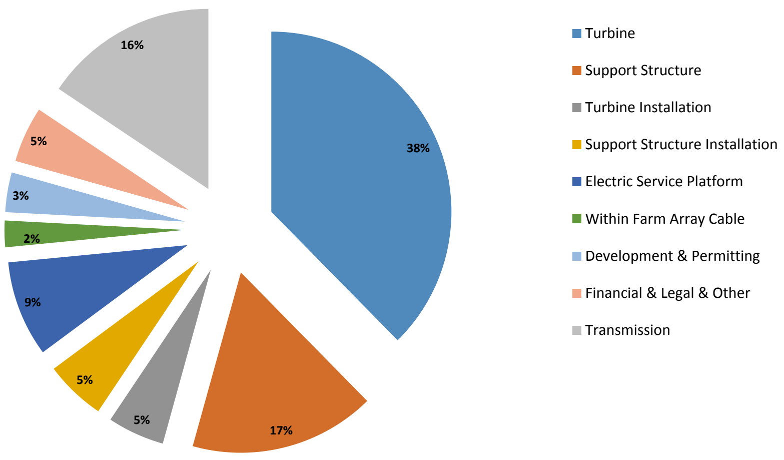
Taken from 4Coffshore.com Market Overview Report – August 2016
Converted to $m/MW with an exchange rate of 0.77 £/$

COE



- Cost of Electricity COE ($/kWh)
  - Life Cycle Cost LCC ($)
    - Initial Capital Cost I ($)
      - Turbine
        - Rotor
          - Blades
          - Hub
        - Drive Train
          - Low Speed Shaft
          - Bearings
          - Gearbox
          - MechanicalB rake
          - Generator
          - Electrical Equipment
          - Bedplate
          - Nacelle Cladding
          - Mechanical Equipment
          - Yaw System
      - BOS
        - Tower
        - Foundation
          - Foundation
          - Scour Protection
        - Transportation
          - Foundation Transportation
          - Turbine + Tower Transportation
        - Installation
          - Cable Laying -Within Farm -Foundation Cable Installation - Shore Connection -Onshore Grid Connection
          - Vessel Mob/Demob -Offshore Substation -Foundation -Turbine+Tower
          - Installation -Foundation -Scour Protection -Transition Piece -Turbine+Tower -Offshore Substation
        - Grid Connect.
          - SCADA
          - Cable -Within Farm -Shore Connection -Onshore Grid Connection
          - Substation -Offshore -Onshore
          - Network Connection
        - Project
          - Feasibility -Site Investigation -Wind Resource Asses. -Environmental Asses. -Preliminary Desighn -Other
          - Development -Permits & Approval s -Project Financing -Legal and Accounting -Project Management -Other
          - Engineering -Wind Turbine Siting -Mechanical Design -Electrical Design -Civil Design -Contracting
    - Working Capital Cost WIC ($)
    - Periodic Cost Per ($)
    - Decomm. Cost Dec ($)
    - Opearion and Maintenance O&M ($)
      - Maintenance
      - Operation -Property Taxes -Insurance -Gen. Admin -Labor -Bottom Lease
  - Net Energy Production E (kWh)
    - Energy Production
    - Availability
    - Efficiencies -Farm -Electrical
    - Losses -Soiling -Transmission

Capital Cost Breakdown



Port and Supply Chain Development Studies

- Virginia Offshore Wind Port Readiness Evaluation, BVG Associates, April 2015
- Assessment of Ports for Offshore Wind Development in the United States, GL Garrad Hassan, March 2014
- U.S. Offshore Wind Manufacturing and Supply Chain Development, Navigant Consulting, February 2013
- Port and Infrastructure Analysis for Offshore Wind Energy Development, Massachusetts Clean Energy Center, February 2010

Port Activities – Vessels – Components

- **Port Activities**
  - Construction Staging
  - Assembly
  - Manufacturing

- **Vessels**
  - General Cargo Vessels
  - Heavy-lift vessels
    - Jack up leg-stabilized ships
    - Jack up barges / ships
    - Derrick barge
  - Cable Vessels

✓Length
✓Beam
✓Navigation Draft
✓Air Draft

- **Components**
  - Blades
  - Nacelle
    - Gearboxes
    - Generators
    - Bearings
    - Transformers
    - Pitch and Yaw Systems
    - Castings and Forgings
  - Towers
  - Support Structures
    - Foundations
    - Transition Pieces
  - Substations
    - Transformers / Electrical Equipment
    - Platforms
  - Cables
    - Array cables
    - Export Cables

✓Dimensions
✓Weight
✓Storage area
✓Bearing area
✓Bearing pressure

Ultimate Port Evaluation Criteria

erminal operating parameters

inancial condition of the port

ecurity

afety record

ariff assessment on tonnage or project cargo rates

erminal free time and storage charges

- Alternate uses
- Compliance with US federal security regulations
- Berth size including depth of water and length of pier face
- Width of apron / Distance from apron to storage
- Road and rail access
- Crane availability and capacity
- Labor costs / Stevedoring

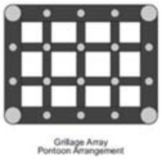
Costs and Impacts

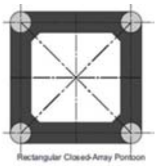
	Port Investment (million dollar)	Duration (years)	Construction Jobs (FTE)	CAPEX impact (%)	LCOE impact (%)
Construction Staging	10 to 30	2	15-25	2-4%	1-2%
Assembly					
ESP	10 to 50	2 to 3	15-20	5-7%	2-3%
Nacelle	5 to 30	2 to 3	15-25	5-7%	2-3%
Manufacturing					
Blades	5 to 30	2 to 4	10-15	10-20%	3-7%
Generator	3 to 30	2 to 4	10-15	10-20%	3-7%
Tower	5 to 50	2 to 4	15-25	10-20%	3-7%
Foundation	5 to 40	2 to 4	15-25	10-20%	3-7%

Preliminary numbers. Cite with caution.

Innovative Designs

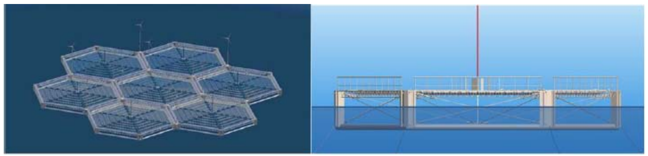
- Offshore Assembly Harbor*





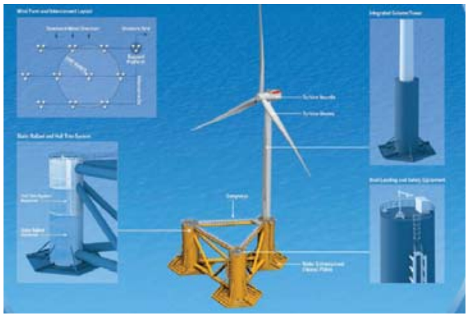
Huisman Shuttle Vessel*

- Floating BreakWaters*



Hexifloat*

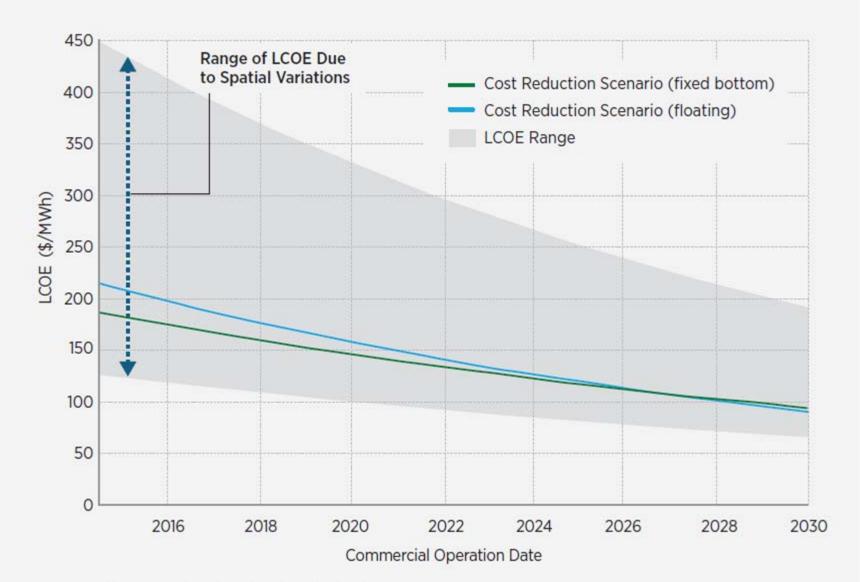
- Cluster Assembly*



Principle Power Wind Float Technology*

* Taken from report "Commercial Proof of Innovative Offshore Wind Installation Concepts using ECN Install Tools"

LCOE for potential offshore wind projects from2015 to 2030



Taken from *National Offshore Wind Strategy* - http://energy.gov/sites/prod/files/2016/09/f33/National-Offshore-Wind-Strategy-report-09082016.pdf

Future Work

- Innovative Designs
- Modeling and tool building
- Methodology
- Standardization vs. Optimization
- Uncertainties and Data Gaps
- Validation and Verification

Questions?

Block Island Wind Farm

Photo taken from https://cleantechnica.com/2016/08/24/turbines-block-island-first-us-offshore-wind-farm/

A Spatial-Economic Cost Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030

Philipp Beiter and Tyler Stehly
National Renewable Energy Laboratory (NREL)
Golden, CO USA
Philipp.Beiter@nrel.gov, Tyler.Stehly@nrel.gov

The potential for cost reduction and economic viability for offshore wind varies considerably within the United States. This analysis models the cost impact of a range of offshore wind locational cost variables across more than 7,000 potential coastal sites in the United States' offshore wind resource area. It also assesses the impact of over 50 technology innovations on potential future costs between 2015 – 2027 (Commercial Operation Date) for both fixed bottom and floating wind systems. Comparing these costs to an initial assessment of local avoided generating costs, this analysis provides a framework for estimating the economic potential for offshore wind. Analyzing economic potential within this framework can help establish a refined understanding across industries of the technology and site-specific risks and opportunities associated with future offshore wind development. The findings from this report indicate that under the modeled scenario, offshore wind can be expected to achieve significant cost reductions and may approach economic viability in some parts of the United States within the next 15 years.

Operational expenditures (OpEx) are expected to vary considerably between offshore wind farm locations. From previous experience (Maples et al. 2013; Jacquemin 2011; Pieterman 2011) the two largest locational drivers of operations and maintenance (O&M) cost differences between offshore wind projects are the distance between the project and maintenance facilities (e.g., O&M port and/or inshore assembly area) and the prevailing metocean conditions at the project site. This O&M analysis models the cost impact for a range of metocean conditions and O&M strategies for both fixed-bottom and floating wind systems across potential coastal sites in the United States. It also assesses future O&M technologies (e.g., service operation vessels) that have potential to lower OpEx. The findings of this work help refine understanding of optimal O&M strategies for a range of site-specific metocean conditions and identify ways to make offshore wind more economical in the United States.

Biographies

Philipp Beiter

Philipp Beiter is a member of the Market and Policy Impact Group in the Strategic Energy Analysis Center and NREL. His areas of expertise include: energy policy analysis, regulatory policy, data analysis and statistical modeling, Electricity markets, Utility business models for distributed generation, Regulatory analysis, and Grid integration of renewable energy. He has an M.P.A. in energy management and policy from Columbia University and the London School of Economics (LSE), and a B.A. in political science and economics, University of Mannheim, Baden-Württemberg, Germany. Prior to joining NREL he was a Junior Policy Analyst, Organization for Economic Co-operation and Development (OECD), Paris.

Tyler Stehly

Tyler is currently a member of the Technology Systems and Sustainability Analysis group in the Strategic Energy Analysis Center. His current research focuses on support and development of U.S. offshore wind turbine cost models. While part of NREL's Research Participant Program, he supported the NWTC with research on utility-scale wind turbine supply chain and manufacturing issues in addition to wind turbine transportation and logistics studies to develop investment recommendations for DOE. Tyler's experience includes heavy civil construction cost estimating, wind industry root-cause-analysis, and renewable energy systems analysis and design.

A Spatial-Economic Cost-Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030

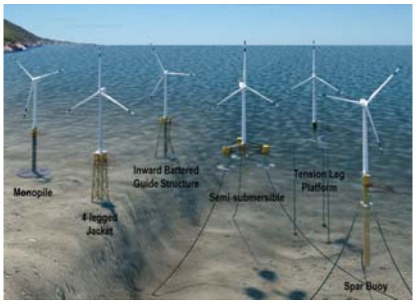
Philipp Beiter and Tyler Stehly

Life-Cycle Cost for Offshore Wind Workshop
Newport, Rhode Island

October 5, 2016

Objectives

- Quantify the impact from a variety of spatial characteristics on the levelized cost of energy (LCOE) in the United States at specific points in time
  - Fixed-bottom foundations (e.g., monopile, jacket)
  - Floating foundations (e.g., spar, semisubmersible)
- Model the impact from technology innovation and market maturity during the time frame from 2015–2027 (commercial operation date [COD])* on LCOE
- Provide a framework to quantify economic viability for offshore wind in the United States
- Determine the cost-optimal choice between fixed-bottom and floating offshore wind technologies under various site conditions.



Offshore wind substructure types for varying water depths.
Illustration by Josh Bauer, National Renewable Energy Laboratory

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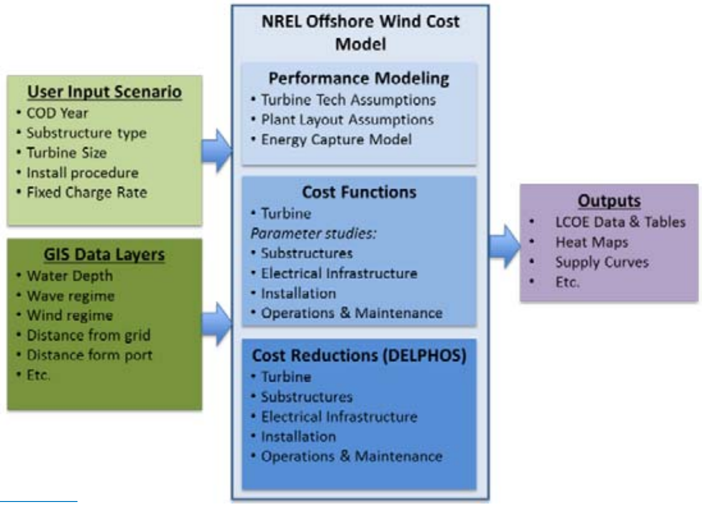
* The modeled LCOE from 2015–2027 (COD) was extrapolated until 2030 (COD).

General Methodology

- The general methodology consists of a combination of geographic information system (GIS) data layers, performance modeling, and cost modeling.



User Input Scenario
- COD Year
- Substructure type
- Turbine Size
- Install procedure
- Fixed Charge Rate

GIS Data Layers
- Water Depth
- Wave regime
- Wind regime
- Distance from grid
- Distance form port
- Etc.

NREL Offshore Wind Cost Model

Performance Modeling
- Turbine Tech Assumptions
- Plant Layout Assumptions
- Energy Capture Model

Cost Functions
- Turbine

Parameter studies:
- Substructures
- Electrical Infrastructure
- Installation
- Operations & Maintenance

Cost Reductions (DELPHOS)
- Turbine
- Substructures
- Electrical Infrastructure
- Installation
- Operations & Maintenance

Outputs
- LCOE Data & Tables
- Heat Maps
- Supply Curves
- Etc.

DELPHOS: "a series of cost models and basic data sets to improve the analysis of the impact of innovations on (future offshore wind) costs" developed in the United Kingdom by BVG Consulting and KIC InnoEnergy (KIC InnoEnergy 2016)

General Assumptions

- **Domestic deployment and supply chain maturity**
- **Technology assumptions**

Key Assumptions	***Financial Close (FC)***	**2013**	**2020**	**2025**
	Commercial Operations Date (COD)	**2015**	**2022**	**2027**
Turbine Rated Power (megawatts [MW])		3.4	6	10
Plant Size (MW)		600	600	600
Turbine Hub Height (meters [m])		85	100	125
Turbine Rotor Diameter (m)		115	155	205
Turbine Specific Power (watts [W]/m^2)		327	318	303

- **Focus on fundamental differences between technologies**
- **Technology availability to meet industry needs**
- **All costs reported in real 2015 dollars.**

Several Methodological Simplifications

The following several spatial variables were not considered:

- **Extreme design conditions**
- **Surface ice exposure**
- **Hurricane exposure**
- **Soil conditions**

The following modeling generalizations were used:

- **Generic project layout**
- **Focus on 6-MW turbines.**

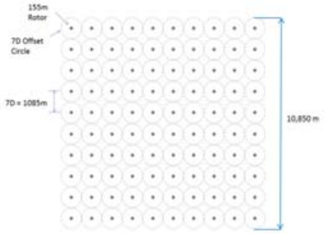
Wind Project Layout and Performance Modeling

Coverage includes:
- Major offshore areas except for Alaska
- Depths restricted up to 1,000 m to reflect limits of current technology

Wind project layout includes:
- One cell comprising 100 turbines
- Spacing based on 6-MW turbines in a 10-by-10 grid, spaced at 7 rotor diameters

Each project layout considered independently includes:
- 7,159 distinct wind power plant layouts*
- No gaps between adjacent layouts
- No wake interaction between layouts.

Using Openwind, 7,159-unit wind power plants were modeled throughout the resource area of the continental United States from 0 nautical miles (nm) to 50 nm



Conceptual project layout with 100 generic 6-MW turbines

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* A potential wind farm was considered to qualify if at least 50% of the turbines met the depth restriction criteria.

Cost Reduction Pathways – DELPHOS Tool

- The DELPHOS tool (BVG Consulting/KIC InnoEnergy) is a “series of cost models and basic data sets to improve the analysis of the impact of innovations on [offshore wind] costs”*
  - **Method:** Involves a comprehensive bottom-up assessment of the potential to reduce cost from elements in the cost breakdown structure and by improving system reliability and performance; aggregates 58 potential technology innovations and supply chain effects and estimates the resulting LCOE ~~at~~ for two future focus years: 2022 (COD) and 2027 (COD), projected from the base year set at 2015 (COD)
  - **Data:** Obtained from the Crown Estate’s 2012 study based on expert elicitations from 54 entities involved in the offshore wind industry and projected the Crown Estate Financial Close (FC) year 2020 cost targets out to FC 2025
  - **Findings:** Discovered that small but significant improvements in cost from each subassembly in the offshore wind system can lead to LCOE reductions of sufficient magnitude to achieve economic competitiveness
- The DELPHOS tool only considers fixed-bottom technology
- NREL complemented the DELPHOS tool with a preliminary assessment of floating technology cost reductions for focus years 2022 (COD) and 2027 (COD).

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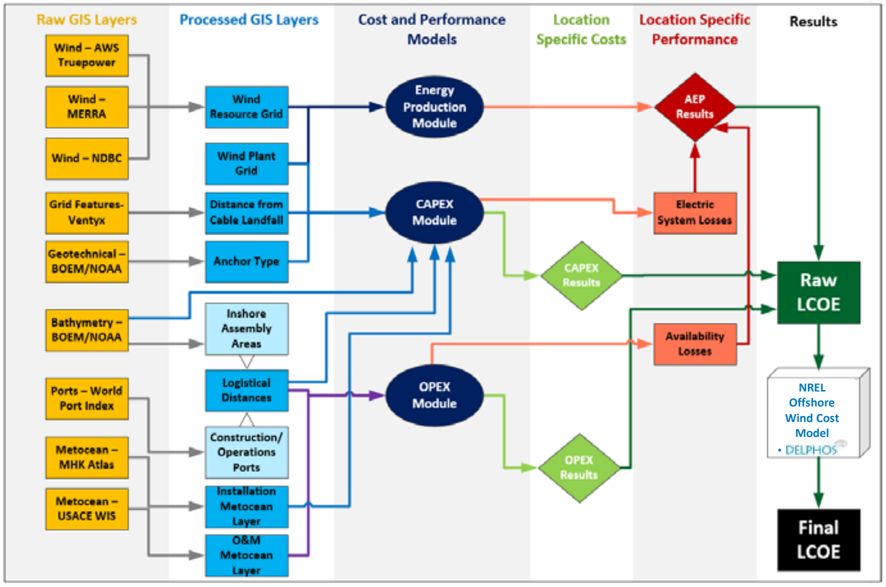
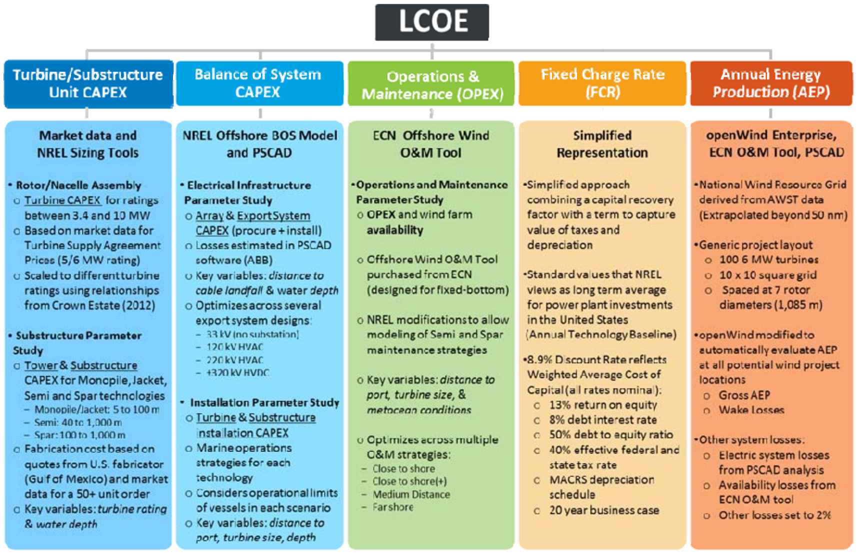
*DELPHOS (KIC Innoenergy 2016)

Spatio-Economic Analysis Combines a Number of Models and Data Sources to Estimate LCOE



Spatial-economic processing framework

The Spatio-Economic Analysis Combines a Number of Models and Data Sources to Estimate LCOE



LCOE

Turbine/Substructure Unit CAPEX

Market data and NREL Sizing Tools

- **Rotor/Nacelle Assembly**
  - Turbine CAPEX for ratings between 3.4 and 10 MW
  - Based on market data for Turbine Supply Agreement Prices (5/6 MW rating)
  - Scaled to different turbine ratings using relationships from Crown Estate (2012)
- **Substructure Parameter Study**
  - Tower & Substructure CAPEX for Monopile, Jacket, Semi and Spar technologies
    - Monopile/Jacket: 5 to 100 m
    - Semi: 40 to 1,000 m
    - Spar: 100 to 1,000 m
  - Fabrication cost based on quotes from U.S. fabricator (Gulf of Mexico) and market data for a 50+ unit order
  - Key variables: *turbine rating & water depth*

Balance of System CAPEX

NREL Offshore BOS Model and PSCAD

- **Electrical Infrastructure Parameter Study**
  - Array & Export System CAPEX (procure + install)
  - Losses estimated in PSCAD software (ABB)
  - Key variables: *distance to cable landfall* & water *depth*
  - Optimizes across several export system designs:
    - 33 kV (no substation)
    - 120 kV HVAC
    - 220 kV HVAC
    - ±320 kV HVDC
- **Installation Parameter Study**
  - Turbine & Substructure installation CAPEX
  - Marine operations strategies for each technology
  - Considers operational limits of vessels in each scenario
  - Key variables: *distance to port, turbine size, depth*

Operations & Maintenance (OPEX)

ECN Offshore Wind O&M Tool

- **Operations and Maintenance Parameter Study**
  - **OPEX and wind farm availability**
  - Offshore Wind O&M Tool purchased from ECN (designed for fixed-bottom)
  - NREL modifications to allow modeling of Semi and Spar maintenance strategies
  - Key variables: *distance to port, turbine size, & metocean conditions*
  - Optimizes across multiple O&M strategies:
    - Close to shore
    - Close to shore(+)
    - Medium Distance
    - Farshore

Fixed Charge Rate (FCR)

Simplified Representation

- Simplified approach combining a capital recovery factor with a term to capture value of taxes and depreciation
- Standard values that NREL views as long term average for power plant investments in the United States (Annual Technology Baseline)
- 8.9% Discount Rate reflects Weighted Average Cost of Capital (all rates nominal):
  - 13% return on equity
  - 8% debt interest rate
  - 50% debt to equity ratio
  - 40% effective federal and state tax rate
  - MACRS depreciation schedule
  - 20 year business case

Annual Energy Production (AEP)

openWind Enterprise, ECN O&M Tool, PSCAD

- National Wind Resource Grid derived from AWST data (Extrapolated beyond 50 nm)
- Generic project layout
  - 100 6 MW turbines
  - 10 x 10 square grid
  - Spaced at 7 rotor diameters (1,085 m)
- openWind modified to automatically evaluate AEP at all potential wind project locations
  - Gross AEP
  - Wake Losses
- Other system losses:
  - Electric system losses from PSCAD analysis
  - Availability losses from ECN O&M tool
  - Other losses set to 2%

LCOE calculation framework and modeling assumptions

Substructure Parameter Study

Substructure Unit CAPEX

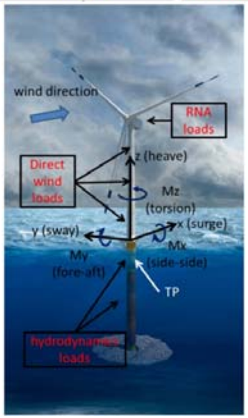
Case study: Monopile for 3-MW turbine

Cost Functions

- Turbine

Parameter studies:

- Substructures
- Electrical Infrastructure
- Installation
- Operations & Maintenance



Reference system, load locations, and definitions of subcomponents for a monopile substructure. *Image modified from an illustration by Josh Bauer, NREL*

Substructure Parameter Study

Substructure Unit CAPEX

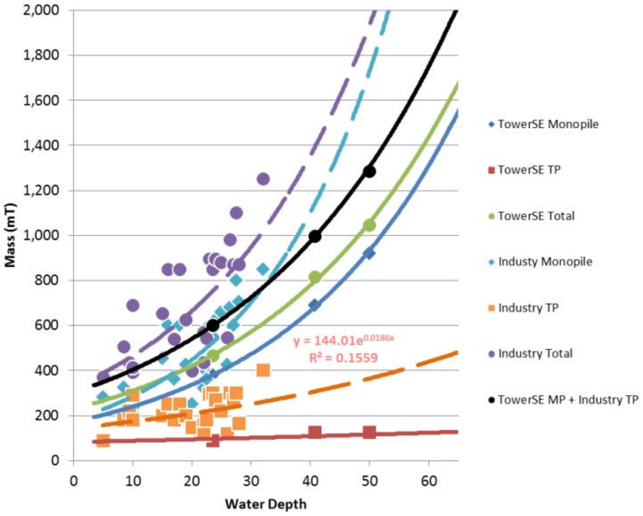
For each combination of turbine rating (3, 6, and 10 MW) and water depth we assessed:

- Fixed-bottom substructures, including:
  - A monopile (depths of 5 to 100 m) using the TowerSE model to optimize the pile, transition piece, and tower
  - A jacket (depths of 5 to 100 m) using the JacketSE model to optimize the pin-piles, trusses, transition piece, and tower
- Floating substructures, including:
  - A semisubmersible (depths of 40 to 1,000 m) using the Floating Sizing Tool to optimize the semisubmersible's platform and mooring system
  - A spar (depths of 100 to 1,000 m) using the Floating Sizing Tool to optimize the spar's platform and mooring system.

Key variables: Water depth and turbine rating

Substructure Parameter Study

Substructure Unit CAPEX



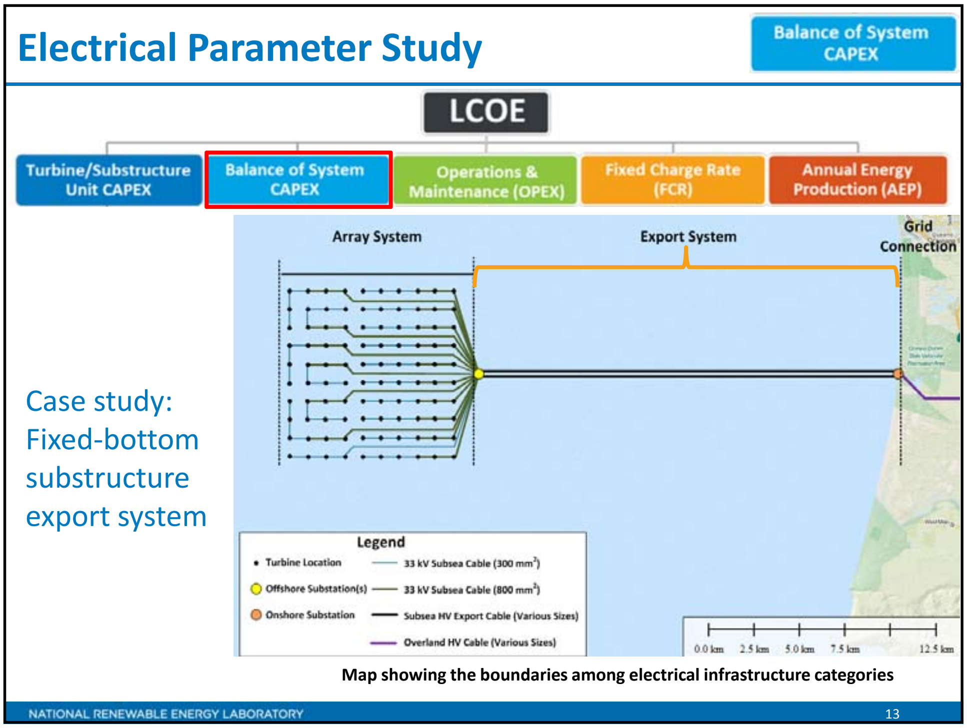
Mass results in metric tons for 3-MW monopile-based systems and comparison to industry data

Component	Cost/t (USD)
Pile	$2,250
Monopile Transition Piece	$3,230
Jacket Main Lattice Structure	$4,680
Jacket Transition Piece	$4,599

Component unit cost estimates

- Fabrication cost for fixed based on European market data and recent industry studies (e.g., cost reduction pathways, Great Lakes Wind Network subcontract, and so on)
- 100-unit order quantity

- Scaling equations are developed for each substructure type and application of fabrication and transportation costs are used to estimate the delivered cost at the staging port.



Electrical Parameter Study

Balance of System CAPEX

LCOE

Turbine/Substructure Unit CAPEX

Balance of System CAPEX

Operations & Maintenance (OPEX)

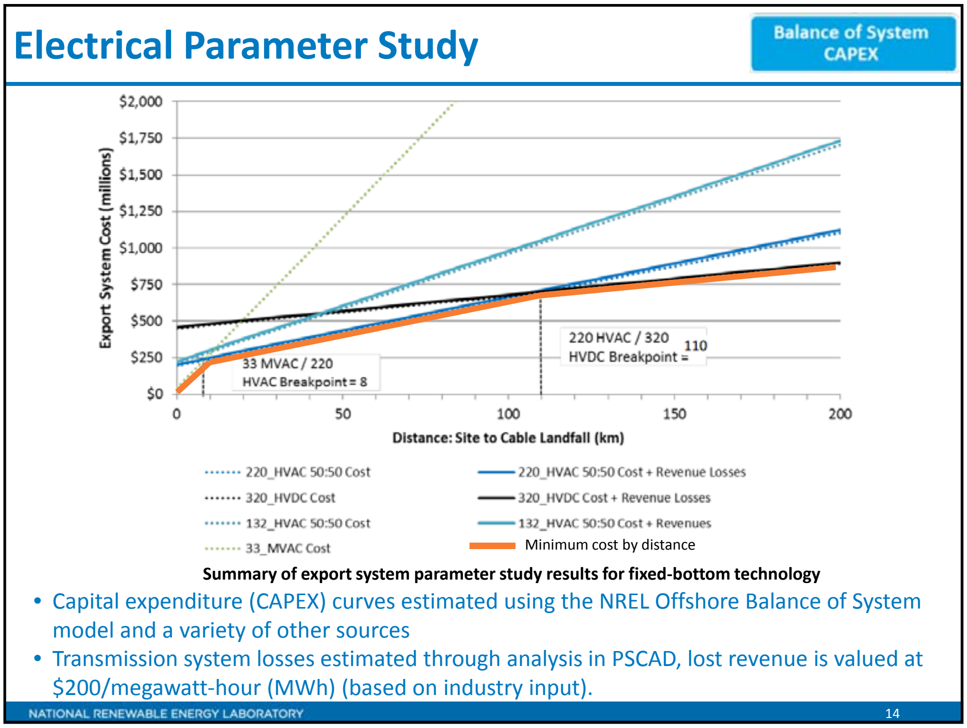
Fixed Charge Rate (FCR)

Annual Energy Production (AEP)

Case study: Fixed-bottom substructure export system

Map showing the boundaries among electrical infrastructure categories

NATIONAL RENEWABLE ENERGY LABORATORY 13



Electrical Parameter Study

Balance of System CAPEX

Summary of export system parameter study results for fixed-bottom technology

- Capital expenditure (CAPEX) curves estimated using the NREL Offshore Balance of System model and a variety of other sources
- Transmission system losses estimated through analysis in PSCAD, lost revenue is valued at $200/megawatt-hour (MWh) (based on industry input).

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Installation Parameter Study

Balance of System CAPEX

Case study: Installation of a 3-MW turbine on a monopile substructure

Pacific Orca installation vessel. ***Photo from Lars Blicher, Swire Blue Ocean***

Installation Parameter Study

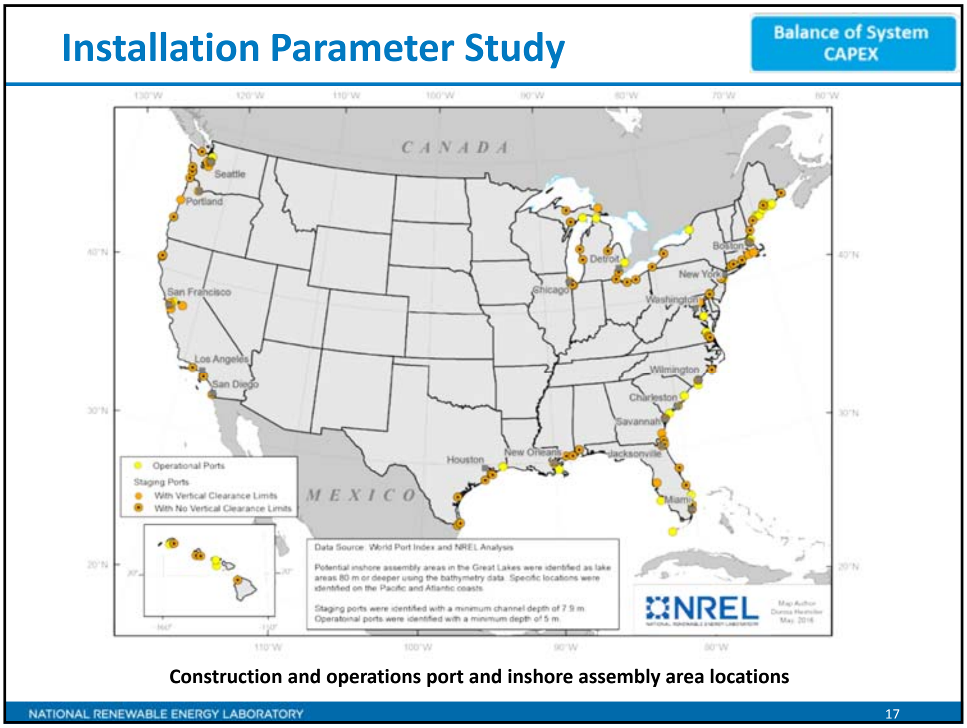
Balance of System CAPEX

The installation parameter study used the NREL Offshore Balance of System model to estimate the costs of installing each of the four substructure technologies (monopile, jacket, semisubmersible, and spar) over a range of location-specific conditions for three turbine sizes: 3, 6, and 10 MW.

Key variables: Distance from project site to staging port, turbine size, and water depth

Variable	Fixed Substructure	Floating Substructure
Water Depth	10 m–100 m, 10-m increments	66 m–1,000 m, varying increments
Distance from Port to Site	50 km–500 km, 50-km increments	50 km–500 km, 50-km increments
Distance from Port to Assembly Area	—	50 km–500 km, 50-km increments (spar only)
Distance from Assembly Area to Site	—	50 km–500 km, 50-km increments (spar only)

Key parameter ranges for installation



Installation Parameter Study

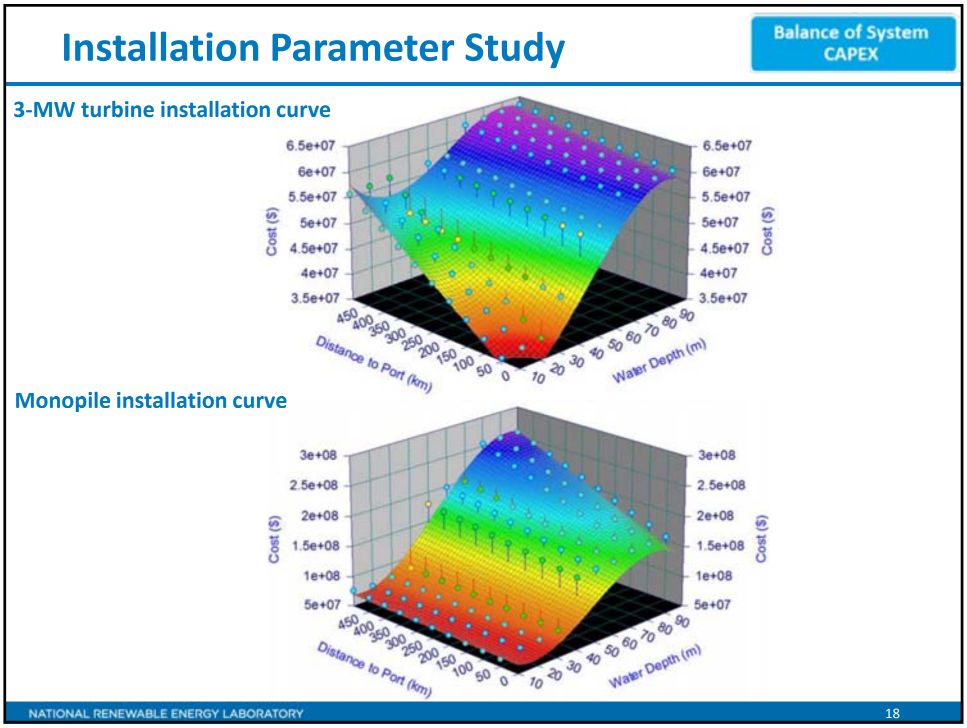
Balance of System CAPEX

Data Source: World Port Index and NREL Analysis

Potential inshore assembly areas in the Great Lakes were identified as lake areas 80 m or deeper using the bathymetry data. Specific locations were identified on the Pacific and Atlantic coasts.

Staging ports were identified with a minimum channel depth of 7.9 m. Operatoinal ports were identified with a minimum depth of 5 m.

Construction and operations port and inshore assembly area locations



Installation Parameter Study

Balance of System CAPEX

3-MW turbine installation curve

Monopile installation curve

Operation and Maintenance (O&M) Parameter Study

Operations & Maintenance (OPEX)

Case study: O&M for a fixed-bottom substructure

Illustration of the UMOE Mandel AS Wave Craft.
Image from Are Søreng, UMOE

The analysis considers three corrective maintenance strategies to represent the five substructure scenarios:

- **In-situ** (monopile, jacket), in which maintenance is performed at the project location by a jack-up crane vessel
- **Tow-to-Port** (semisubmersible, spar horizontal tow), in which the substructure-turbine unit is disconnected from moorings and towed to port for repair by a standard crawler crane
- **Tow-to-Assembly-Area** (spar vertical tow), in which the substructure-turbine unit is disconnected from the moorings and towed to the inshore assembly site. Requires mobilization of installation equipment spread (e.g., barges, cranes).

Key variables: Distance from project to operations port and meteorological ocean (metocean) conditions

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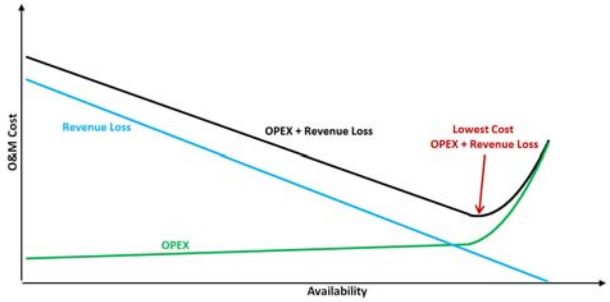
O&M Parameter Study

Operations & Maintenance (OPEX)

Model Outputs:

- The Energy Research Centre of the Netherlands (ECN) O&M Tool outputs are operational expenditures (OPEX), availability, and total O&M cost (OPEX + revenue loss)
- Parameterized curves fit to the ‘least cost O&M strategy’ at each distance (defined as O&M costs + lost revenue) for inclusion in the spatio-economic LCOE model.



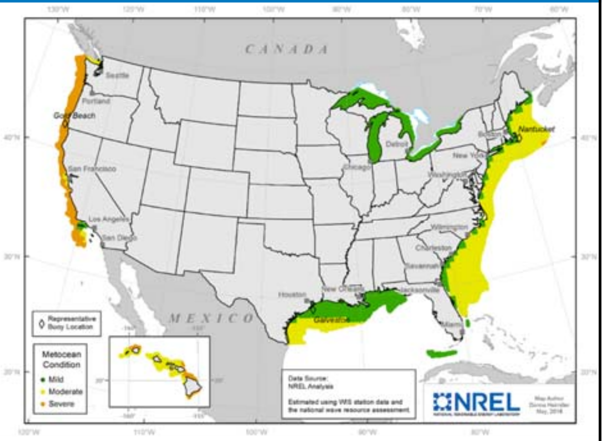
Depiction of O&M optimization criteria

O&M Parameter Study

Operations & Maintenance (OPEX)

Three sites were selected to represent the range of metocean conditions across the U.S. offshore wind resource (model requires 10 years of correlated wind and wave data)

- ECN O&M Tool set up for each site (i.e., mild, moderate, and severe)
- Results are applied across the Outer Continental Shelf by using average significant wave height as an indicator of severity of site-specific metocean conditions.

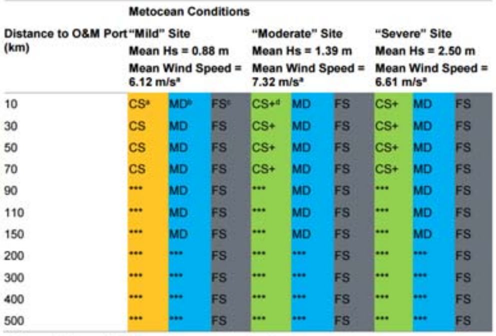


Representative wave information system stations for O&M analysis

O&M Parameter Study

Operations & Maintenance (OPEX)

- Access strategies (e.g., for getting personnel on to the wind turbine) will likely be similar for across technologies
- For each site and each corrective maintenance approach, the parameter study considers a range of different access strategies, ranging from basic to innovative.



	Metocean Conditions								
Distance to O&M Port (km)	"Mild" Site Mean Hs = 0.88 m Mean Wind Speed = 6.12 m/s[a]			"Moderate" Site Mean Hs = 1.39 m Mean Wind Speed = 7.32 m/s[a]			"Severe" Site Mean Hs = 2.50 m Mean Wind Speed = 6.61 m/s[a]		
10	CS[a]	MD[b]	FS[c]	CS+[d]	MD	FS	CS+	MD	FS
30	CS	MD	FS	CS+	MD	FS	CS+	MD	FS
50	CS	MD	FS	CS+	MD	FS	CS+	MD	FS
70	CS	MD	FS	CS+	MD	FS	CS+	MD	FS
90	***	MD	FS	***	MD	FS	***	MD	FS
110	***	MD	FS	***	MD	FS	***	MD	FS
150	***	MD	FS	***	MD	FS	***	MD	FS
200	***	***	FS	***	***	FS	***	***	FS
300	***	***	FS	***	***	FS	***	***	FS
400	***	***	FS	***	***	FS	***	***	FS
500	***	***	FS	***	***	FS	***	***	FS

[a] Mean wind speed at 10 m above mean sea level

[a] Close to shore

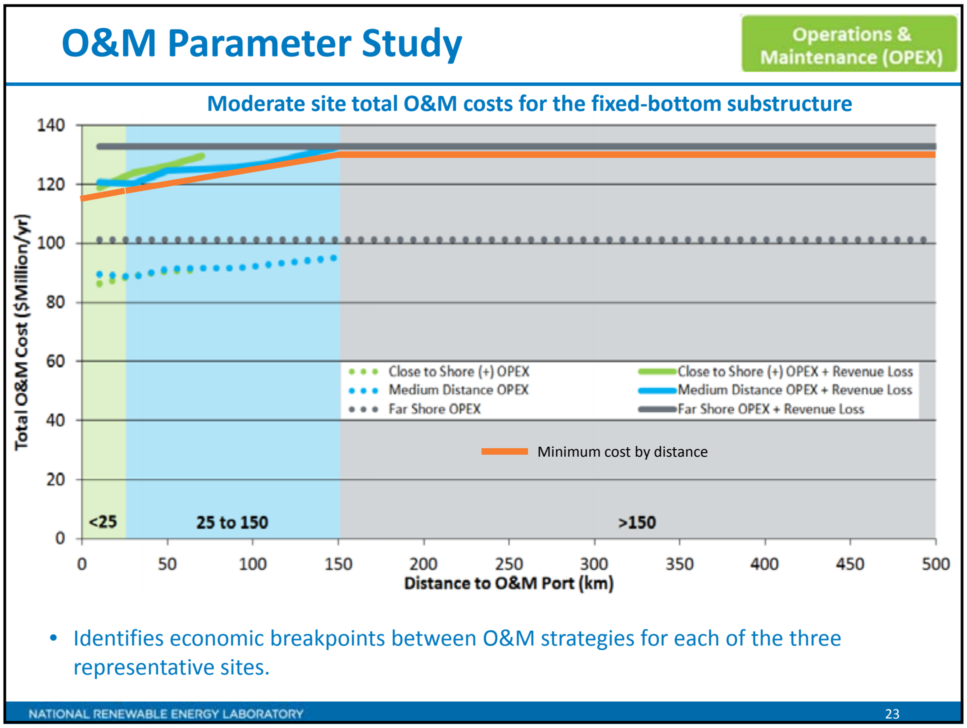
[b] Medium distance

[c] Far shore

[d] Advanced close to shore

*** Distance exceeds the 2-hour limit for transporting technicians between the O&M port and the project

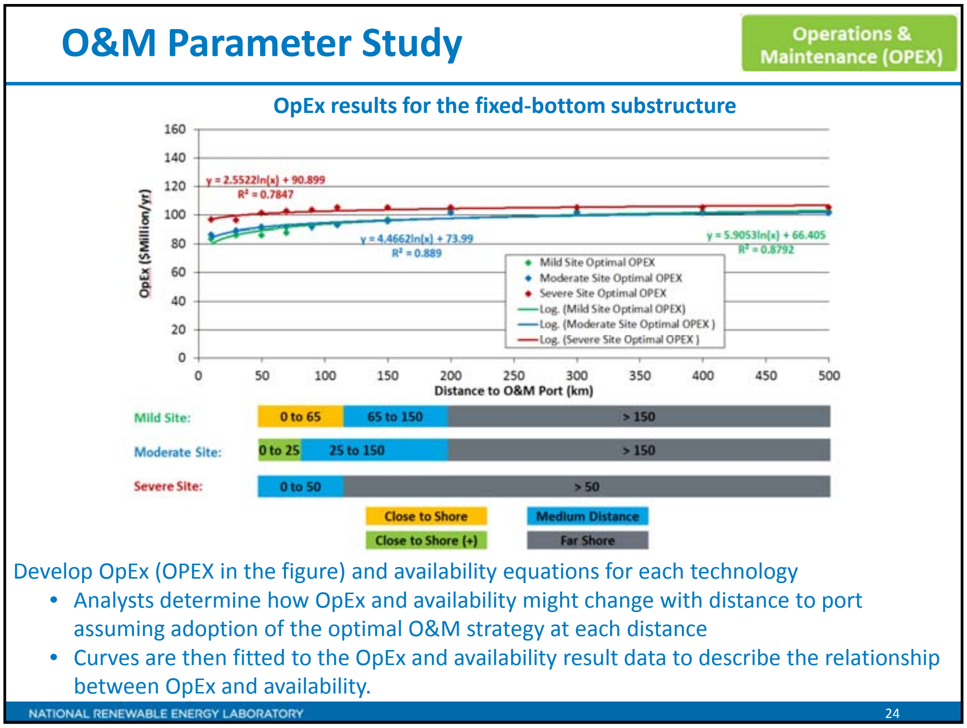
Matrix of operational expenditure modeling parameters



O&M Parameter Study

Operations & Maintenance (OPEX)

- Identifies economic breakpoints between O&M strategies for each of the three representative sites.



O&M Parameter Study

Operations & Maintenance (OPEX)

Develop OpEx (OPEX in the figure) and availability equations for each technology

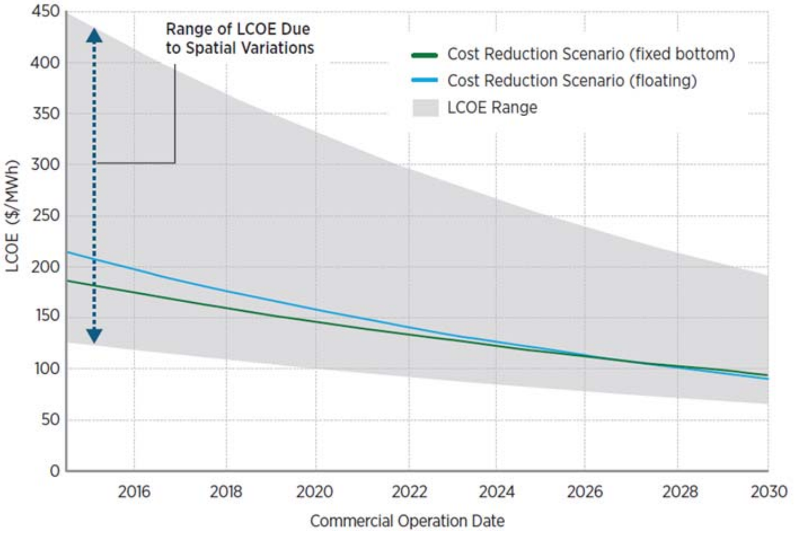
- Analysts determine how OpEx and availability might change with distance to port assuming adoption of the optimal O&M strategy at each distance
- Curves are then fitted to the OpEx and availability result data to describe the relationship between OpEx and availability.

General Limitations

General limitations of this initial assessment include the following:

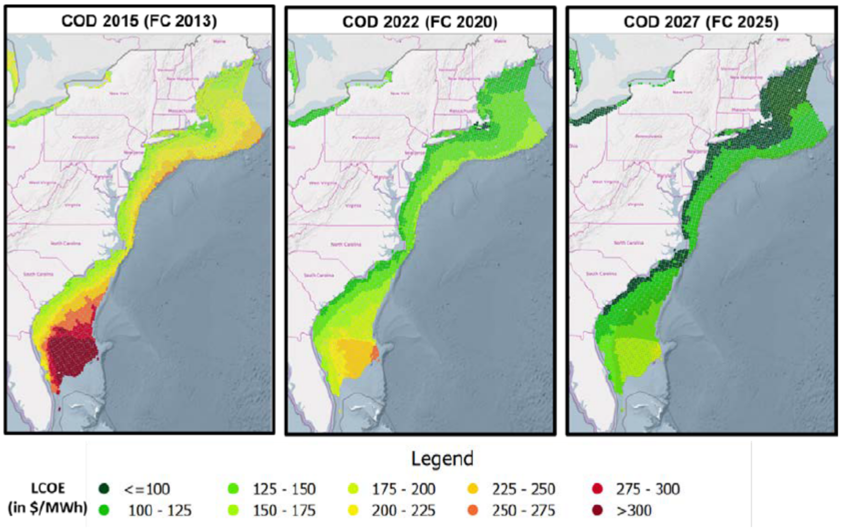
- An assumption of continued investments in technology innovation, developments, and market visibility of a robust domestic supply chain
- The need for domestic cost reductions to require additional activities to reduce risk and uncertainty of early projects, including addressing U.S.-specific challenges (e.g., hurricanes, deeper water, Jones Act requirements) and incentivizing markets
- Model simplifications, such as:
    - Models—parameter studies were conducted with first-order tools
    - Cost data— validation of assumptions
    - Suitability/availability of technology
    - Macroeconomic factors (e.g., exchange rates, commodity prices)
- Analysis does not consider several significant design variables that may contribute to variability among regions
- Preliminary assessment of the levelized avoided cost of energy ~~LACE~~ limited by available data and a set of simplifying assumptions.

Results



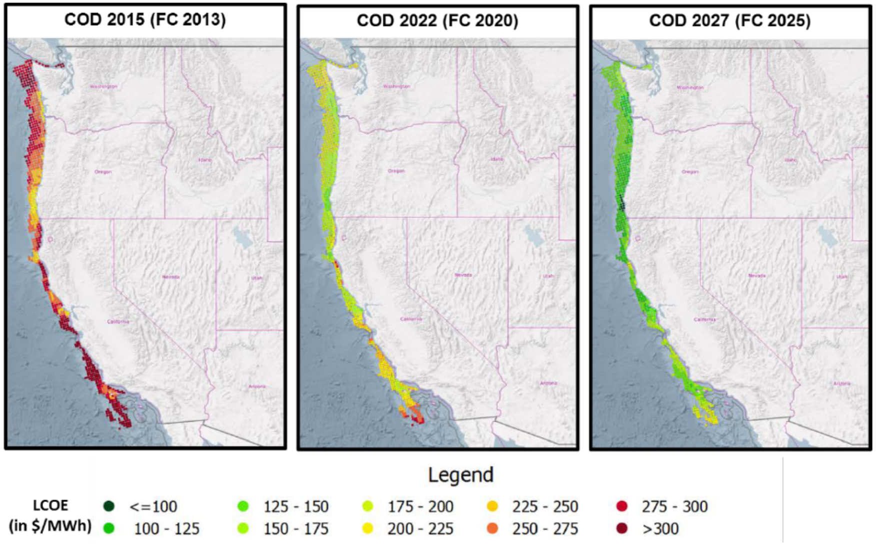
LCOE (unsubsidized) for potential offshore wind power projects from 2015-2030 (COD) throughout the technical resource area

Results: Atlantic Coast

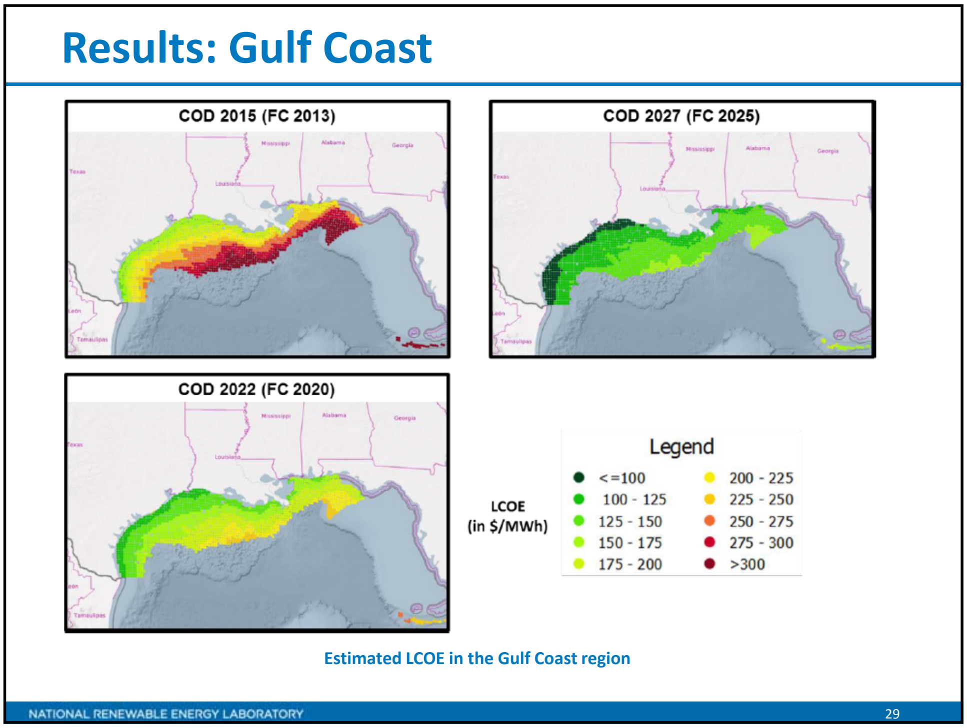


Estimated LCOE in the Atlantic Coast region

Results: Pacific Coast



Estimated LCOE in the Pacific Coast region



Results: Gulf Coast

COD 2015 (FC 2013)

COD 2027 (FC 2025)

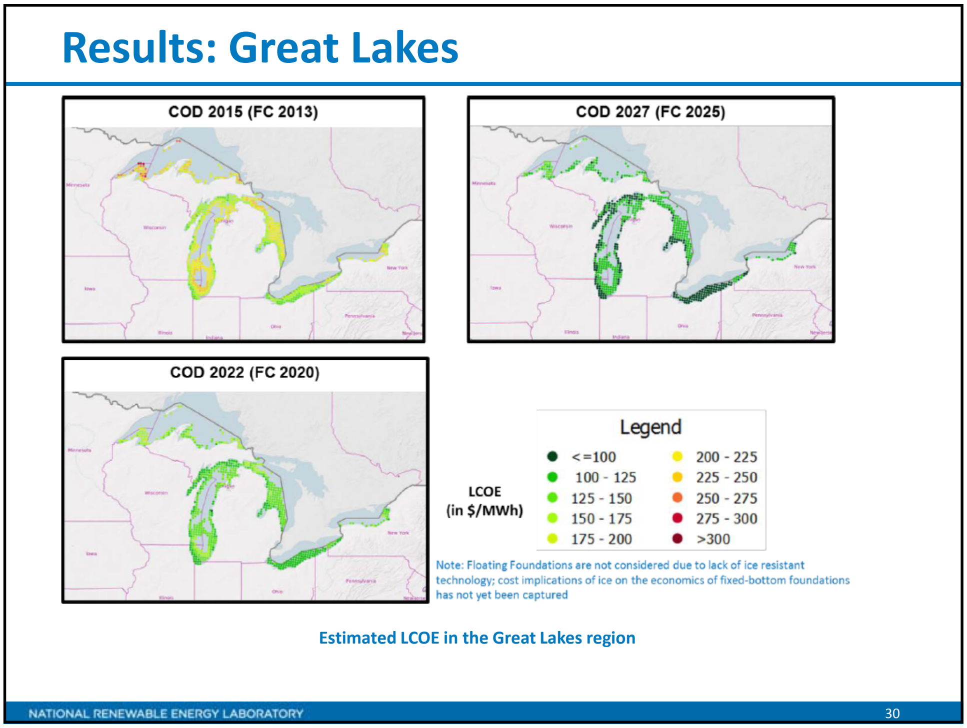
COD 2022 (FC 2020)

LCOE
(in $/MWh)

Legend

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

Estimated LCOE in the Gulf Coast region



Results: Great Lakes

COD 2015 (FC 2013)

COD 2027 (FC 2025)

COD 2022 (FC 2020)

LCOE
(in $/MWh)

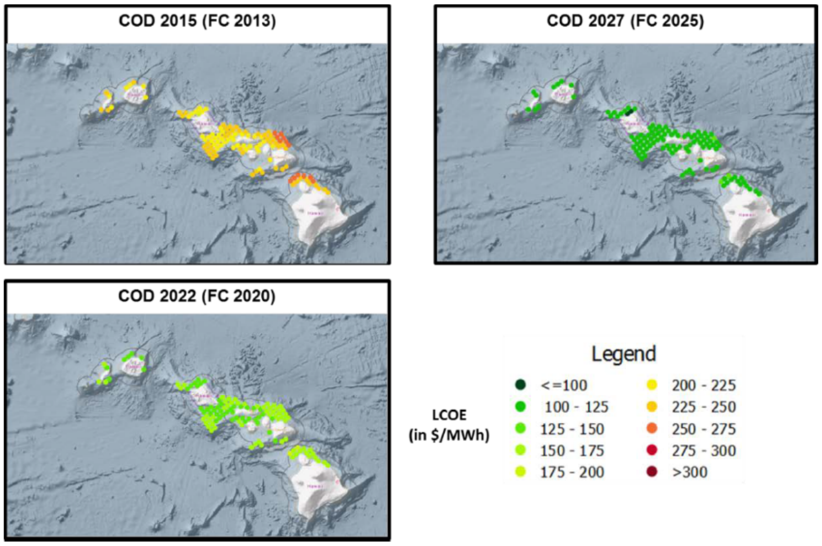
Legend

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

Note: Floating Foundations are not considered due to lack of ice resistant technology; cost implications of ice on the economics of fixed-bottom foundations has not yet been captured

Estimated LCOE in the Great Lakes region

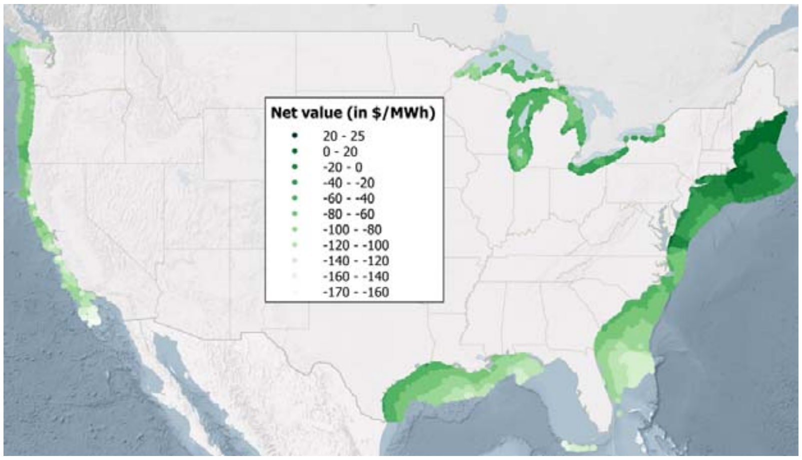
Results: Hawaii



Estimated LCOE in Hawaii

Results: Economic Viability

- **Net value ($/MWh) = LACE – LCOE**
- LACE: levelized avoided cost of energy (proxy for available revenue to a project; a combination of wholesale electricity prices and capacity value)



Economic potential (unsubsidized) of U.S. offshore wind sites in 2027 (COD)

Conclusions

- In 2015, offshore wind costs span an estimated range from $130/MWh–$450/MWh
- Cost-reduction pathway modeling and analysis of future conditions show that cost ranges are reduced by 2022 to a range from $95/MWh–$300/MWh, and they are further reduced by 2027 to a range from $80 MWh–$220/MWh among U.S. coastal sites
- By 2030, offshore wind may become economically viable in some parts of the United States, particularly in parts of the northeastern Atlantic Ocean and in a small number of locations along the mid-Atlantic Coast (without consideration for direct policy support)
- During the time period considered, the costs of the two technologies are found to converge under the cost-reduction pathway scenarios modeled
- Analyses comparing fixed and floating technology using four typical substructure types show economic break points in water depths between 45 m and 60 m.

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Beiter, P., W. Musial, A. Smith, L. Kilcher, R. Damiani, M. Maness, S. Sirnivas, T. Stehly, V. Gevorgian, M. Mooney, G. Scott. 2016. A Spatial-Economic Cost-Reduction Pathway for U.S. Offshore Wind Energy Development from 2015–2030 (Technical Report), NREL/TP-6A20-66579, National Renewable Energy Laboratory (NREL), Golden, CO (US). http://www.nrel.gov/docs/fy16osti/66579.pdf.

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A Levelized Cost of Energy (LCOE) Model for Wind Farms that Includes Power Purchase Agreement (PPA) Energy Delivery Limits

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The cost of energy is an increasingly important issue in the world as renewable energy resources are growing in demand. Performance-based energy contracts are designed to keep the price of energy as low as possible while controlling the risk for both parties (i.e., the Buyer and the Seller). Price and risk are often balanced using complex Power Purchase Agreements (PPAs). Since wind is not a constant supply source, to keep risk low, wind PPAs contain clauses that require the purchase and sale of energy to fall within reasonable limits. However, the existence of those limits also creates pressure on prices causing increases in the Levelized Cost of Energy (LCOE). Depending on the variation in capacity factor (CF), the power generator (the Seller) may find that the limitations on power purchasing given by the utility (the Buyer) are not favorable and will result in higher costs of energy than predicted. Existing cost models do not take into account energy purchase limitations or variations in energy production when calculating an LCOE. A new cost model is developed to evaluate the price of electricity from wind energy under a PPA contract. This study develops a method that an energy Seller can use to negotiate delivery penalties within their PPA. This model has been tested on a controlled wind farm and with real wind farm data. The results show that LCOE depends on the limitations on energy purchase within a PPA contract as well as the expected performance characteristics associated with wind farms.

Biographies

Maira Bruck

Maira Bruck is an undergraduate Economics student at the University of Maryland. She has worked for the Center for Advanced Life Cycle Engineering (CALCE) at the University of Maryland since 2015. She was the winner of the Best Student Paper Award at the ASME Power and Energy Conference in 2016. A paper by Maira was selected for a panel presentation at the WindEurope 2016 conference in Hamburg Germany.

Navid Goudarzi

Navid Goudarzi received his M.S. and Ph.D. in mechanical engineering from University of Maryland, Baltimore County. His research interests include renewable energy projects with a focus on novel onshore/offshore and small/large scale wind turbine designs for expanding their operational range and increasing their efficiency at lower cost, system cost modeling, system life-cycle and risk economics, computational/experimental fluid dynamics, and contract engineering with focus on performance-based logistics/outcome-based contracts. In 2015-2016 Navid was a post-doctoral researcher in the Center for Advanced Life Cycle Engineering (CALCE) at the University of Maryland, College Park. In fall 2016 he became an Assistant Professor in the Mechanical Engineering Technology Department at the University of North Carolina, Charlotte. Navid's renewable energy projects focus on novel onshore/offshore and small/large scale wind turbine designs, system cost modeling, system life-cycle and risk economics, computational/experimental fluid dynamics, and contract engineering with focus on performance-based logistics/outcome-based contracts.

A Modified Levelized Cost of Energy (LCOE) Model to Provide Bid Comparisons for Power Purchase Agreements

Maira Bruck, Navid Goudarzi, Peter Sandborn

Center for Advanced Life Cycle Engineering (CALCE), Mechanical Engineering Department, University of Maryland

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Levelized Cost of Energy (LCOE) and Power Purchase Agreements

<u>Levelized Cost of Energy (LCOE):</u>

"The Total Life-Cycle Cost (TLCC) for each unit of energy produced in the given lifetime of a project."

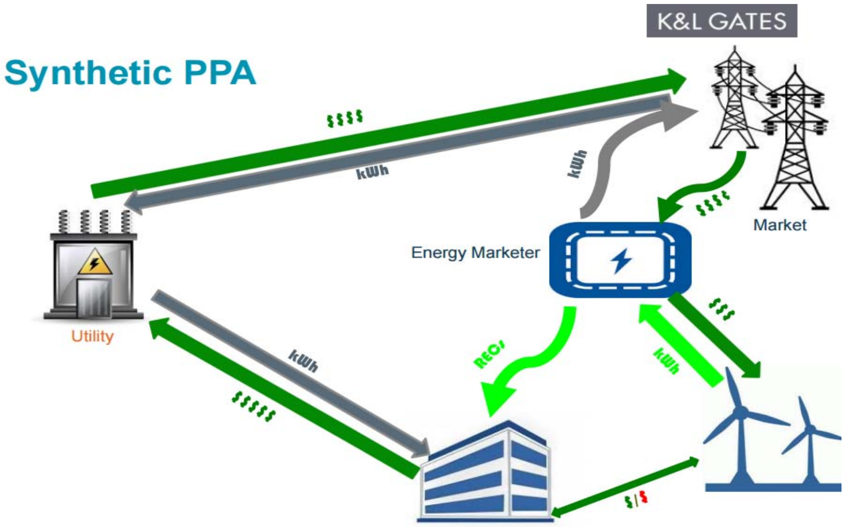
<u>Power Purchase Agreements (PPAs):</u>

- PPAs are performance-based contracts that aim to create a "fair" agreement for the purchase and sale of energy between a utility (the Buyer) and a generator (the Seller)
  - LCOE is commonly used within these energy contracts to determine a fair Cost of Energy (*COE*)
- PPAs define under (minimum) and/or over (maximum) energy delivery limits and their penalties
  - Over production causes a loss as the energy will no longer be bought (or will be bought at a reduced rate)
  - Under production will cause the Seller to be charged a penalty

Synthetic PPAs

- Synthetic PPAs work as a third party (the Hedge) financing system and are created for a short-term unlike traditional PPAs (10 or less years)
- If the energy price falls below the bid price in the contract, derived from the LCOE, than the Hedge pays the difference to the counterparty (a consumer)
- If the price falls above the bid price, the Hedge pays the Buyer the price
- Synthetic PPAs may still contain Maximum and Minimum limits
- Sometimes there is a range in which the prices have a range of indifference
- No physical exchange of power between the buyer and seller because the Buyer sells the energy into the open market
- Three types of contract:
  - Contract of differences: Sells energy at fixed price and if spot market is greater then the Seller pays the difference to the Hedge, but if it falls below the Hedge pays the Seller. The counterparty buys at floating prices
  - Put option: Buyer will purchase energy at higher than market price if market price falls below bid price, but will purchase energy at market price if it falls above the bid price
- Typically, the Hedge receives the RECs

Synthetic PPAs



The Problem with LCOE

- Energy delivery limits in PPAs increase the LCOE through production loss and penalties, which should be considered costs
  - Conventional LCOE calculations do not include the penalties
  - An accurate LCOE is vital to ensure that the project breaks even and does not fail
  - An LCOE that is too high might deter potential investors or Buyers in the PPA
  - An LCOE that is too low hurts the Seller
- In a bidding market for PPAs on a wind farm, either the wind farm or the utility bids a contract that presents an escalating (with “inflation”) price schedule or a constant price schedule
  - Utilities prefer an escalating price schedule because investors and utilities look at short-term returns instead of long-term returns
  - The wind farm needs an accurate LCOE to compare proposed price schedules in order to ensure that there is a similar total revenue from the escalating versus a flat price schedule
- Creating a price schedule in which the final net revenue equals the net revenue from a constant LCOE (throughout the contract length) is generally not possible
- Revenue has to be based on <u>purchased</u> energy, conventional LCOE is based on <u>produced</u> energy.

Modeling LCOE

The LCOE is the cost that, if assigned to every unit of energy <u>produced</u> by the system over the analysis period, will equal the total life-cycle cost when discounted back to the base year.

Conventional Model:

$$LCOE = \frac{\sum_{i=0}^{n} \frac{CPE_i}{(1+r)^i}}{\sum_{i=0}^{n} \frac{E_i}{(1+r)^i}}$$

$$CPE_i = I_i + OM_i + F_i - TC_i$$

New Model:

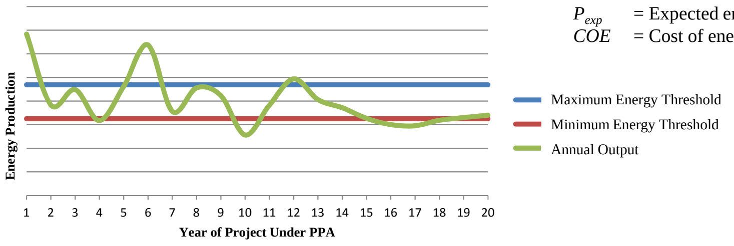
$$LCOE = \frac{\sum_{i=0}^{n} \frac{(CPE_i + PN_i + PL_i)}{(1+r)^i}}{\sum_{i=0}^{n} \frac{E_i}{(1+r)^i}}$$

$$PN_i = (Min_{lim} P_{exp} - E_i) COE_i$$

$$PL_i = (E_i - Max_{lim} P_{exp}) COE_i$$

CPE = Cost to produce energy
E = Energy generated
r = WACC
I = Initial investment cost
OM = Operation and maintenance cost
F = Fuel cost
TC = Tax credit
Max_{lim} = Maximum Energy Threshold
Min_{lim} = Minimum Energy Threshold
PN = Penalty cost
PL = Production loss
P_{exp} = Expected energy production
COE = Cost of energy

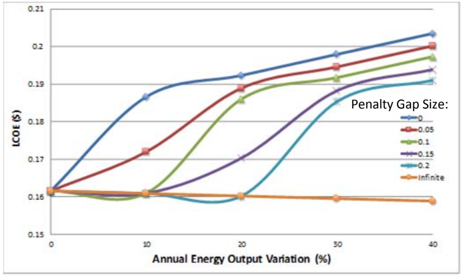
PPA Penalties:

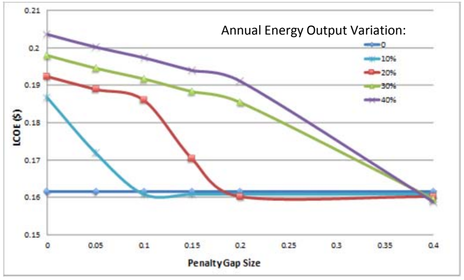


New LCOE Model Results

The new LCOE model depends the capacity factor variation and the penalty “gap” (the difference between the minimum and maximum penalty thresholds). For a symmetric gap:

Capacity Factor = 0.2
Half the time, the energy production is above or below the average production
determined by the capacity factor by the *variation* specified





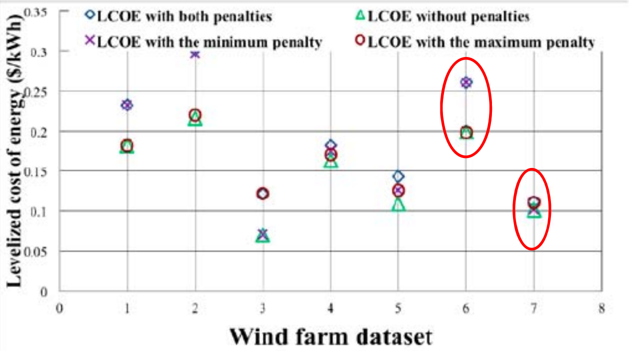
Penalty gap size = $Max_{lim} - Min_{lim}$

$$E_{per\ year} = 8760(CF)(RP)$$

I = $1500 per installed kW
OM = $0.01 per kWh produced
F = $0
TC = $0.05 per kWh sold
r = 0.089 per year
RP = rated power

Wind Farm Case Study

Actual wind farm data shows that the LCOE without penalties (conventionally calculated LCOE) is lower than the actual LCOE that includes penalties. Different wind farms have different characteristics and the gaps in the actual LCOE can vary.



Max_{lim} = 0.75
Min_{lim} = 0.52

I = $1500 per installed kW
OM = $0.01 per kWh produced
F = $0
TC = $0.05 per kWh sold
r = 0.089 per year

- Farms differ and different contracts need to be constructed for them
- The conditions in the farms determine the gap between the conventional LCOE and an LCOE that includes delivery penalties
- In the PPA bidding market, the conventional LCOE could be problem (wind farms 1,2,3, and 6)

Conclusions

- By creating mechanisms to reduce the risk of higher costs for the Buyer, PPAs create a paradox of higher LCOEs for the Seller
- The new LCOE model allows Sellers in a PPA to use expected future energy production to assist in negotiating penalties and an appropriate Cost of Energy in the PPA based on the expected costs from penalties
- The optimal PPA should focus on an appropriate Min_{lim} for projects with a low capacity factor and projects with a higher capacity factor can address having both limits or just one limit depending on the expected variation and the Buyer’s need for energy

- Energy Markets Impact: The new LCOE model also allows for the Seller to compare contract bids with differing price schedules. This allows the Sellers to choose a price schedule that results in a final net revenue that is close to the net revenue from a flat price schedule.