International Workshop on Life-Cycle Costing of Offshore Wind Turbines and Farms

October 1, 2015

University of Maryland, College Park, Maryland, USA

Offshore wind farms are capital intensive projects whose economic viability depends on many things including: the wind resources, the technology, the depth of the water, the price of energy, and the successful long-term sustainment (or operation and maintenance, O&M) of the turbines. Accurate life-cycle costing is a key enabler for making offshore wind farm business cases and optimizing their management. This workshop will focus on forecasting life-cycle costs of turbines, wind farms, and their associated infrastructure.

Topics of interest include:

- Cost of ownership
- Operations and maintenance analysis
- Maintenance infrastructure
- Condition-based health management
- Spare parts forecasting and inventory
- Economics of reliability
- Return on investment and business case analysis
- Financial modeling (e.g., WACC determination)
- Designing power purchase agreements (PPAs) and designing for PPAs
- Warranty analysis
- Life extension
- Inspection
- Energy availability
- No fault found
- Aging supply chain
- Real options analysis

University of Maryland Energy Research Center

Business Network for Offshore Wind

calce Center for Advanced Life Cycle Engineering

Agenda

Time	Title	Presenter	Organization
8:30	Introduction to the Workshop (The Sustainment of Wind Turbines and Wind Farms)	Peter Sandborn	University of Maryland
9:00	2014-2015 Offshore Wind Technologies Market Report: Progress towards Cost Reduction in Europe and Implications for the US Market	Aaron Smith	NREL
9:30	CoE Modeling for Offshore Turbines with Different Drive Train Types at Sites Varying Distances from Shore	James Carroll	University of Strathclyde (Glasgow, UK)
10:00	Break		
10:30	Offshore Wind Farm O&M Optimization Using Real Options Analysis	Xin Lei	University of Maryland
11:00	Wind Turbine Performance Analysis and Anomaly Detection based on Techniques Developed on SCADA Data	Peyman Mazidi	KTH (Sweden)
11:30	Reliability Predictions of Current OSW Turbine Designs	Aris Christou	University of Maryland
12:00	LCOE of Offshore Wind Farms - Identification & Reduction	Ashish Dewan	ECN (Netherlands)
12:30	Lunch		
1:00	Lunch		
1:30	Offshore Wind Balance of System Cost Modeling	Tyler Stehly	NREL
2:00	Power Purchase Agreement (PPA): Performance-Based Levelized Cost of Energy	Maira Bruck	University of Maryland
2:30	Maintenance and Operation Management Strategy to Reduce the Cost of Offshore Wind Power Generation	Joseph Arumala	University of Maryland Eastern Shore
3:00	Reducing Costs in the Offshore Wind Sector: From Modular Design to a Healthy Flow of Knowledge	Matei Rogin	University of Southern Denmark
3:30	Break		
4:00	Return on Investment (ROI) Modeling of Offshore Wind Farm O&M to Support Strategic Technology Insertion	Roozbeh Bakhshi	University of Maryland
4:30	Lessons Learnt from Whole Life Costing Applications	John Erkoyuncu	Cranfield University (UK)
5:00	Potential Life-Cycle Cost Reductions for Offshore Floating Wind Energy	Michael Borg	Technical University of Denmark
5:30	Wind Turbine Maintenance Optimization: The Impact of an Accurate Vertical Wind Profile Estimation	Navid Goudarzi	University of Maryland

The Sustainment of Wind Turbines and Wind Farms

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Operation and maintenance (O&M) is projected to be the second largest contributor to the life-cycle cost of offshore wind turbines accounting for 20% of the total life-cycle cost of the turbine. Therefore, optimization of the maintenance provides a significant opportunity for wind turbine cost reduction that benefits all stakeholders.

Offshore wind farms are capital intensive projects whose economic viability depends on many things including: the wind resources, the technology, the depth of the water, and the availability of the turbines. Operational availability (or availability factor) is the ability of a service or a system to be functional when it is requested for use or operation. Wind turbines cannot be depended on for energy generation if they are always “down” waiting for maintenance. Availability of a system is a function of the system’s reliability and how efficiently it can be maintained when it does fail. There are different approaches to maintenance, but fundamentally, depending on if a system has failed, when it is projected to fail, how it has failed, etc., there are decisions that need to be made about how to and when to maintain it.

Maintenance of offshore wind farms is challenging because the resources required to perform maintenance are expensive, not continuously accessible, and weather conditions are variable. Poor availability will make offshore wind farms non-viable. In addition, for infrastructure-critical systems, customers are moving towards buying the availability of a system through “availability-based contracts,” instead of actually buying the system itself. Power purchase agreements (PPAs) are one form of availability contract. Evaluating an availability requirement is a challenge for manufacturers and supporters of wind farms because determining how to deliver a specific availability is not trivial.

The long-term sustainment of wind farms suggests that:

1) O&M costs for offshore wind farms will be fundamentally driven by availability (either time or energy based). Availability-based contracts for the operation of offshore wind farms will define financials that are indexed to the performance achieved – other O&M dominated systems, such as aircraft and military systems are already moving to “availability contracts,” and wind farms are likely to follow suit.
2) Maintenance costs, although forecasted to be 20% of the total life-cycle cost of an offshore turbine, are likely to be much larger for the turbines being installed today. In today’s fervor to construct wind farms, is the reliability of key components are being compromised to obtain the lowest procurement costs?
3) There is a significant risk that 10 years from now there will be lots of wind turbines sitting idle in wind farms because maintenance resources are not available to fix them and/or the funding for maintenance does not exist because it has been significantly under-budgeted.

International Workshop on Life-Cycle Costing of Offshore Wind Turbines and Farms

Objective

- Accurate life-cycle costing is a key enabler for making offshore wind farm business cases and optimizing their management.
- This workshop focuses on forecasting life-cycle costs of turbines, wind farms, and their associated infrastructure.

Questions we would like to be able to address (all of which require the ability to accurately predict the life-cycle costs of turbines and farms):

1) How do we optimally maintain turbines (When do we do maintenance? What do we do when maintenance resources are available?)
2) How do we optimally implement condition monitoring?
3) How do we make business cases for alternative maintenance strategies?
4) How do we optimize PPAs?

Value

- Computing cost and ROI is useful, but how is cost used to define how you sustain (manage) the system?
- Sustainment involves more than just picking a maintenance approach, how do you optimally apply that approach?
- There are also other measures of value that have to be folded into the cost calculation, e.g., availability

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The Sustainment of Wind Turbines and Wind Farms

Peter Sandborn
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University of Maryland

October 1, 2015

What is Sustainment?

- The capacity of a system to endure
- Key elements of sustainment:
  - Reliability
  - Warranty
  - Maintainability
  - Availability
  - Upgradability
  - Affordability

Sustainment Definition

- Sustainment = Development, production, operation and management of systems that maximizes the availability of goods and services while minimizing their footprint.
- Where:
  - "footprint" could represent any kind of impact that is relevant to the system's stakeholders, e.g., cost (economics), human health, energy required, environmental, and/or other resource consumption (water, materials, labor, expertise, etc.)
  - "availability" represents the fraction of time that a good or service is in the right state, supported by the right resources, and in the right place when the customer requires it
  - "customer" could be an individual, a company, a city, a geographic region, a specific segment of the population, etc.

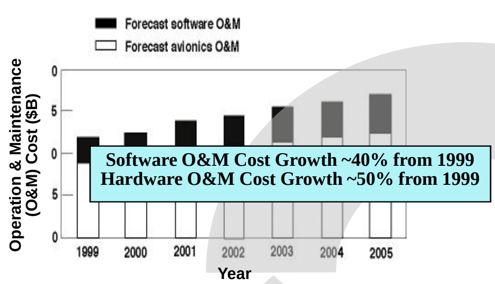
Why We Care About Sustaining Systems

- Unpredicted and unmanaged failure of critical systems can have catastrophic consequences:
  - loss of life
  - loss of critical services (or mission)
  - loss of the system
  - property damage (collateral damage)
  - economic damage
- The developed world is plagued by the prohibitive costs of supporting aging and expensive legacy systems and infrastructure, which in many cases, makes investments in new systems and infrastructure virtually impossible.

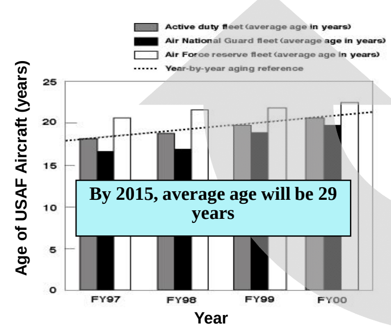
Today's Sustainment Culture

- Today long-term sustainment management organizations are rewarded for "firefighting"
- … unfortunately, you get what you measure

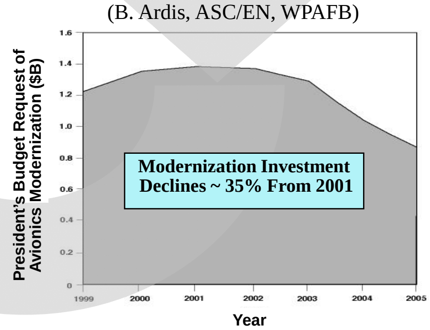
Sustainment's "Vicious Circle"



More money going into sustainment at the determent of new investment, which causes the fleet to age further, which causes more money to be required for sustainment, which leaves less for R&D, …

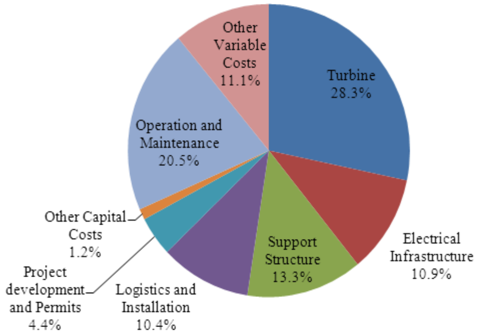


(B. Ardis, ASC/EN, WPAFB)



The Cost of Wind Energy

Projected Offshore Wind Life Cycle Cost Breakdown



Musial, W., and Ram, B., "Large-scale offshore wind power in the United Sates assessment of opportunities and barriers," *National Renewable Energy Lab*, Tech. Rep. 500-40745, September 2010

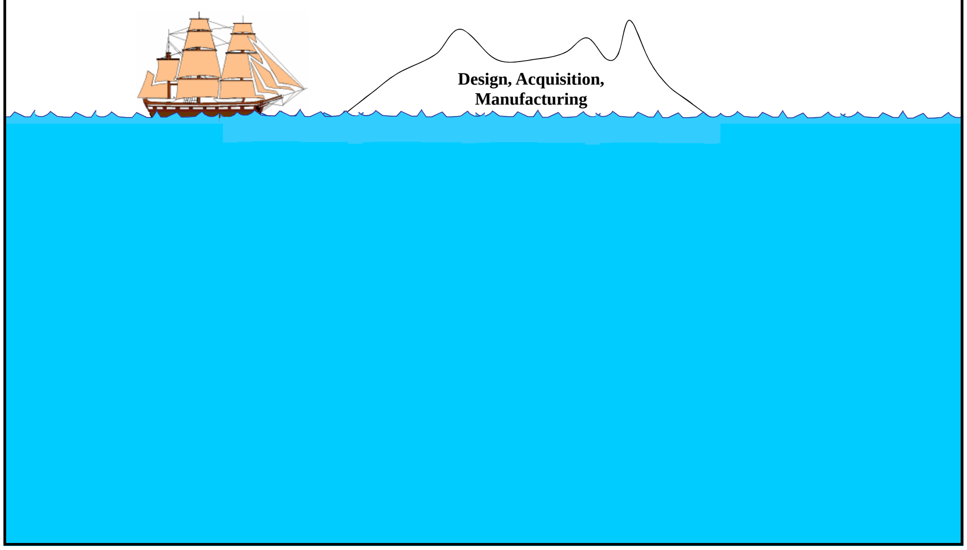
Operation and Maintenance (O&M) Costs:

- Not all wind farms are in easily accessible locations
- Turbines require non-traditional resources to maintain
- Adverse weather conditions may pose an impediment to maintenance
- The cost of unscheduled maintenance is high
- Aging supply chain effects will catch up with these systems (e.g., DMSMS)

Wishful Thinking?

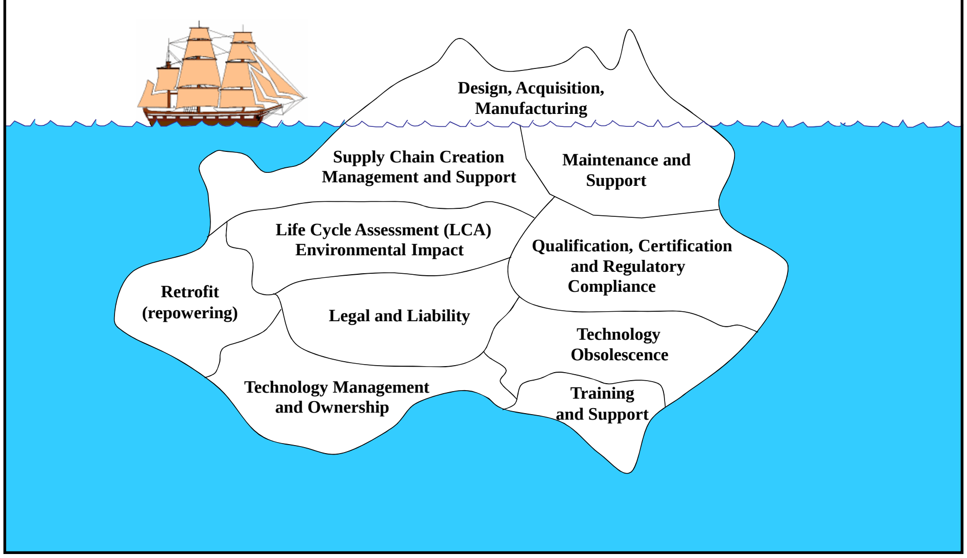
- Maintenance costs could be much larger than the forecasted 20% for the turbines being installed today.
- Many "sustainment-dominated" systems have O&M costs that reach 70% or more of the life-cycle cost of the system (airplanes, military systems, nuclear power plants, …)
- In today's fervor to construct wind farms, the reliability of key components are being compromised to obtain the lowest procurement costs.
- How many wind turbines have been abandoned due to high rates of failure and high maintenance costs?

System Cost



System Life-Cycle Costing

Reality



2014-2015 Offshore Wind Technologies Market Report: Progress towards Cost Reduction in Europe and Implications for the US Market

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The 2014-2015 Offshore Wind Technologies Market Report, funded by the U.S. Department of Energy, provides data and analysis to assess the current status of the U.S. and global markets. The scope of the report covers deployment , technology trends, and economic data to help U.S. offshore wind industry stakeholders, including policymakers, regulators, developers, financiers, and supply chain participants to identify barriers and opportunities.

The global industry is on track to set a new deployment record with nearly 4,000 GW scheduled for commissioning in 2015, which will bring the cumulative market to 11,800 MW. The announced project pipeline totals nearly 250,000 MW. The pipeline is led by Europe (63%), but development seems to be accelerating in Asia (23%), North America (9%), and the rest of the world (5%). Projects totaling 37,000 MW have announced that they will begin operations by 2020. 21 projects totaling 15,650 MW are under various stages of development in the U.S. market, which has reached a key milestone with start of offshore construction at the 30 MW Block Island Wind Project in Rhode Island.

After reviewing industry trends, the presentation will focus on the available empirical CapEx and performance data from global project data to provide insight into current cost levels. The European industry and stakeholders have set a target of reducing the LCOE for offshore wind projects by 40% for projects that close financing in 2020 from 2010 levels. NREL will present a case study on recent competitive tender results in Europe, which suggest that the industry is on track to meet these targets. The progress towards cost reduction in the Europe should translate to U.S. projects and allow developers to offer offshore wind power at increasingly competitive prices; however, there are a number of potential barriers in the domestic market that could lead to higher cost levels. The presentation will conclude with a summary of these domestic barriers and provide recommendations for how to overcome them.

NREL

2014-2015 Offshore Wind Technologies Market Report

Progress towards Cost Reduction in Europe and Implications for the US Market

Life-Cycle Cost Modeling of Wind Turbines and Wind Farms Workshop

Aaron Smith

1 October 2015

2014-2015 Market Report Background

New report that covers the global and domestic offshore wind industries:

- Market Developments and Drivers
- Deployment Status and Projections
- Technology Trends
- Economic Trends
  - Cost
  - Performance
  - Finance
- LCOE Reduction Progress

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

Outline

1. **Methodology/Approach**
2. **Overview of Offshore Wind Developments**
3. **Economic and Performance Trends (Macro)**
4. **Case Study: Empirical Evidence of LCOE Reduction**
5. **Challenges and Opportunities in the U.S. Market**

Approach/Methodology

- **NREL Offshore Wind Database (OWDB)**
  - 1,382 offshore wind projects, located in 40 countries, and totaling about 730,000 MW (including both active and dormant projects)
  - Projects in the database range in maturity and cover a time period from 1991 to 2034
- **Database scope**
  - Project characteristics (e.g., water depth, distance from shore),
  - Technical specifications (e.g., turbine type, component weights)
  - Economic attributes (e.g., project- and component-level costs, performance)
  - Detailed data on turbine models, vessels, ports, etc.
- **Normalization of Cost and Price Data to 2014 U.S. Dollars (USD)**
  - Conversion to USD using the exchange rate for the year in which the latest data were reported
  - Inflation to 2014 USD using the U.S. Consumer Price Index
  - **TAKE AWAY**: This year's report does not take into account the recent appreciation of the USD, which will likely result in lower costs for initial projects given need to import some key components from Europe

Summary of Criteria developed for the 2014-2015 market report

Criteria for reporting on Offshore Wind Project Status

Objective: Create a set of criteria to report on trends in the U.S. and Global Offshore Wind Markets:

1) Categories are generalizable across markets and regulatory regimes
2) Categories are discrete, that is they are non-overlapping
3) Categories provide an objective way to measure project status based on key project milestones
4) Categories do not require NREL to make any subjective assessments/forecasts of project likelihood

Step	Phase Name	Phase Start Criteria	Phase End Criteria
1	**Planning – Early Stage**	Starts when developer or regulatory agency initiates formal site control process	Ends when a developer obtains exclusive development rights to a site (e.g., through competitive auction or a determination of no competitive interest in the United States)
2	**Planning – Site Control**	Begins when the developer obtains exclusive development rights to a site (e.g., through competitive auction or a determination of no competitive interest in the United States)	Ends when the developer files major permit applications (e.g., a construction operations plan for projects in federal waters in the United States)
3	**Major Permits Submitted**	Starts when the developer files major permit applications (e.g., construction operation plan for projects in federal waters in the United States)	Ends when a regulatory body(s) grants authorization to proceed with construction; a rejection may cause the project sponsor to appeal (still permitting phase), place the project on hold, or cancel
4	**Approved**	Starts when project has been approved by the relevant regulatory bodies and is fully authorized to proceed with construction	Ends when sponsor announces FID, and has signed unconditional contracts for major construction work packages; achievement of this milestone generally requires that a project has secured sufficient revenue mechanisms (e.g., power offtake contracts, subsidies, or tax incentives) to be financially viable
5	**Financial Close**	Begins when sponsor announces FID and has signed unconditional contracts for major construction work packages; achievement of this milestone generally requires that a project has secured sufficient revenue mechanisms (e.g., power offtake contracts, subsidy, or tax incentives) to be financially viable	Ends when project begins offshore construction work
6	**Under Construction**	Starts when offshore construction work is initiated	Ends when project has been connected to the power grid and all units fully commissioned; COD marks the official hand-over from construction to operations
7	**Operating**	Commences when project has been connected to the power grid and all units fully commissioned; COD marks the official hand-over from construction to operations	Ends when the project has begun a formal process to decommission and stops feeding power to the grid
8	**Decommissioned**	Starts when the project has begun a formal process to decommission and stops feeding power to the grid	Ends when the site has been restored and lease payments are no longer being made, or if the site has been repowered
N/A	**On Hold/ Canceled**	Starts when sponsor stops development activities (i.e., discontinues lease payments) and/or abandons a prospective site	Ends when the sponsor announces the restart of project development activities

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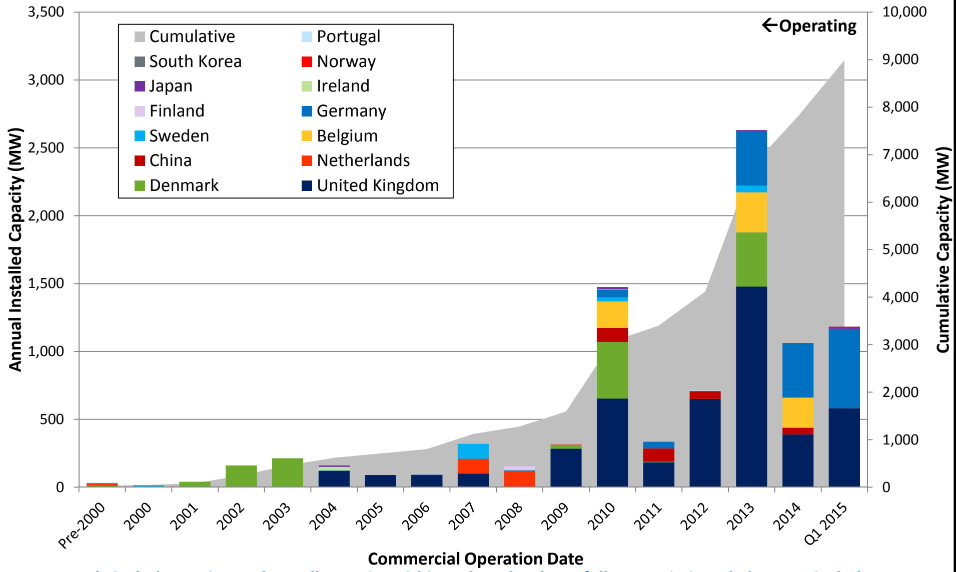
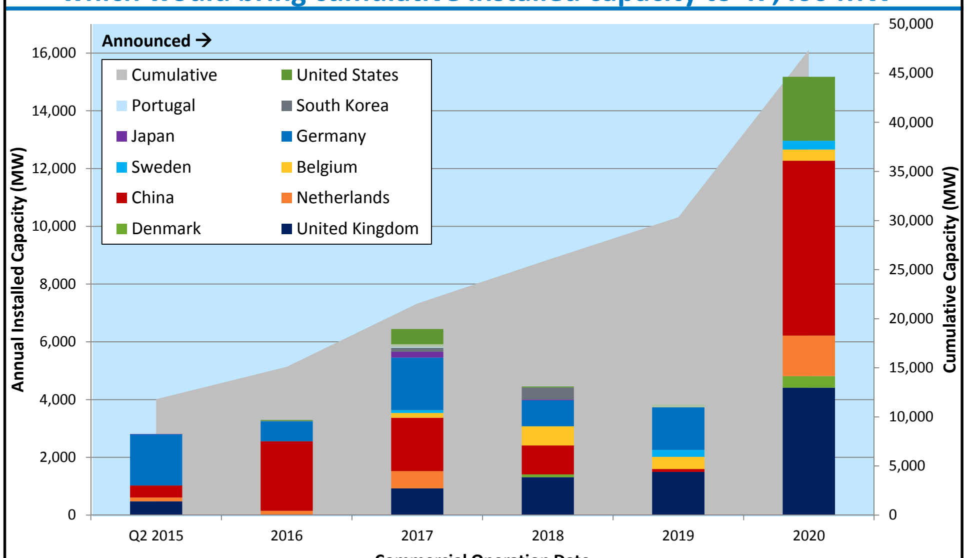
The cumulative operating offshore wind market reached 8,990 MW by June 30, 2015 (Q2)



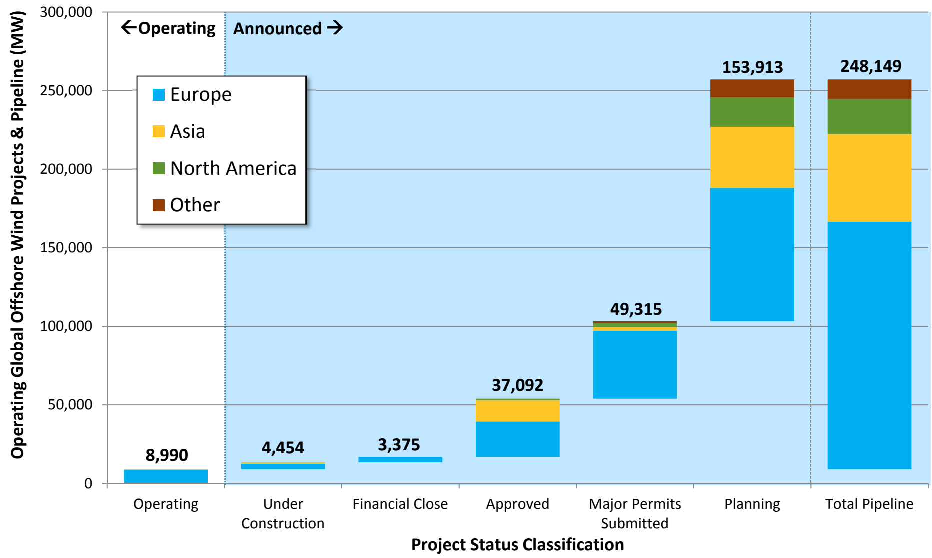
Note: Only includes projects where all capacity within a phase has been fully commissioned; does not include intertidal projects or scaled demonstration projects; Cut off for inclusion is June 30th 2015 (end Q2)

The expected global project pipeline to 2020 is nearly 38,400 MW, which would bring cumulative installed capacity to 47,400 MW



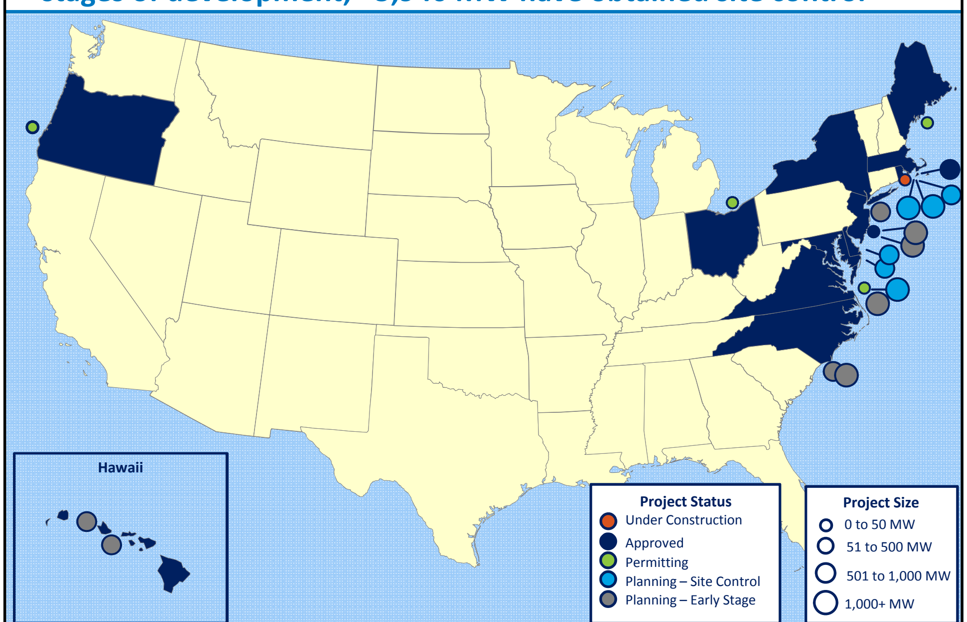
Note: Global pipeline is based on developer announced COD; NREL has not evaluated individual projects to determine likelihood of achieving announced schedule so this should not be treated as forecast

The global offshore wind pipeline totals nearly 250,000 MW of capacity; regional diversity expected to increase in the future

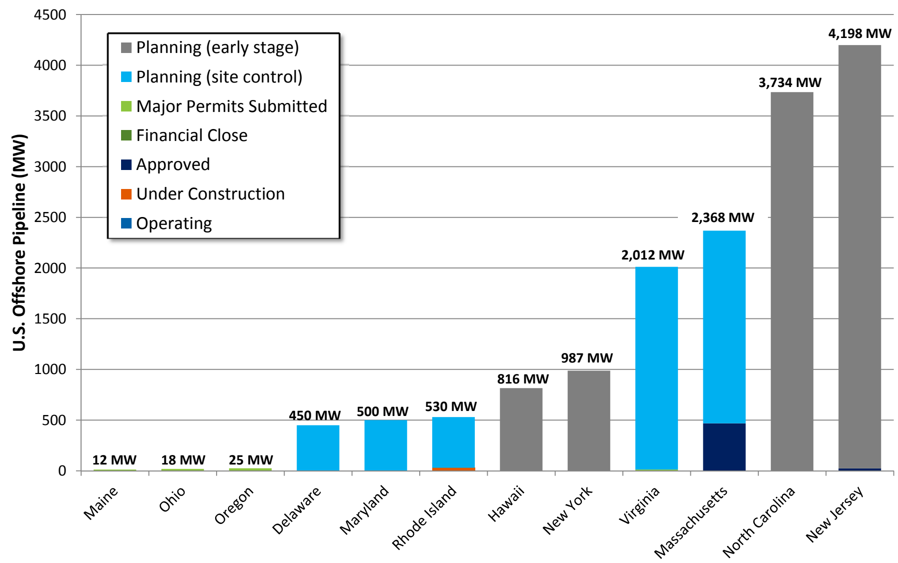


Approximately 63% of the projects in the identified pipeline are located in Europe, 23% in Asia, 9% in North America, and 5% in the rest of the world (Other)

US projects totaling 15,650 MW of potential capacity are in various stages of development; ~5,940 MW have obtained site control



21 projects have been announced in 12 states; projects tend to reduce capacity as developers refine plans for development zones



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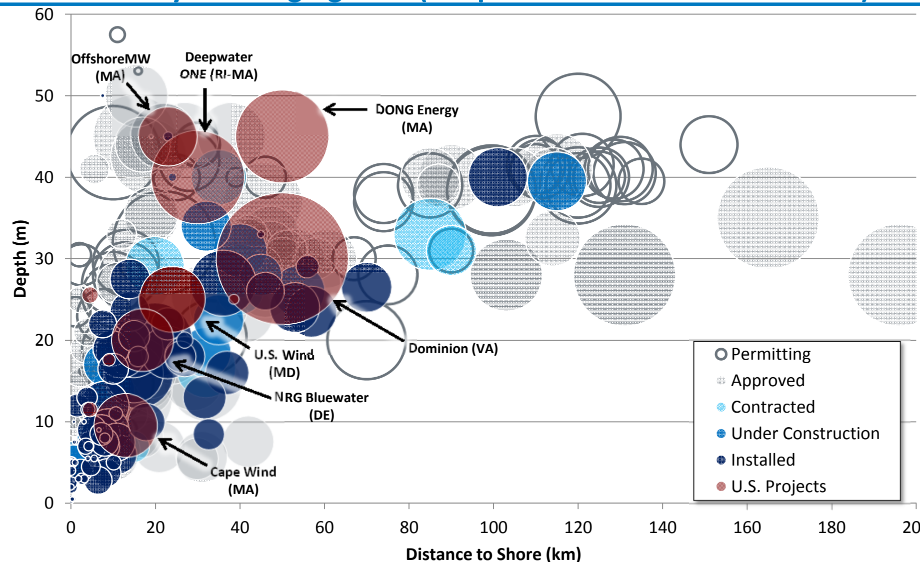
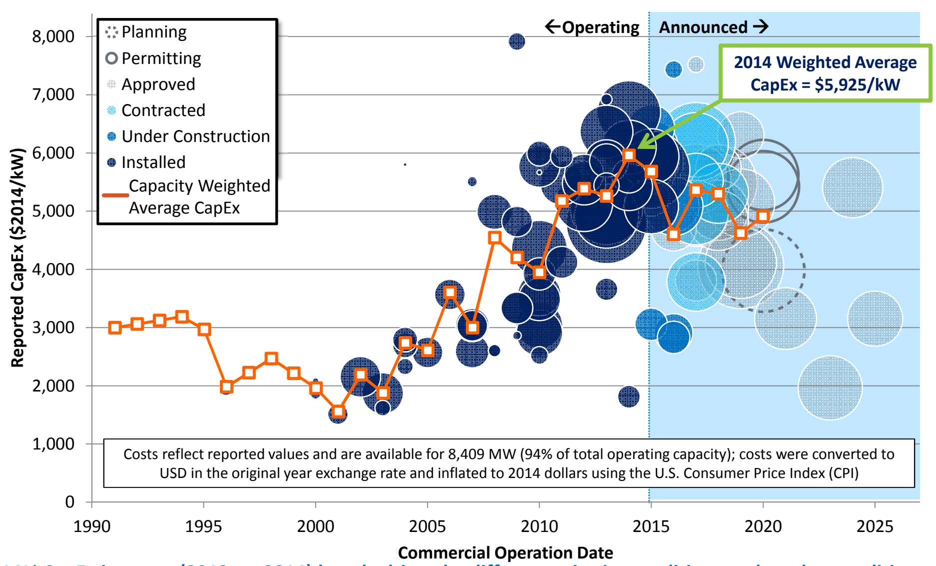
OSW projects are growing larger and are being installed in technically challenging sites (deeper water and far from shore)



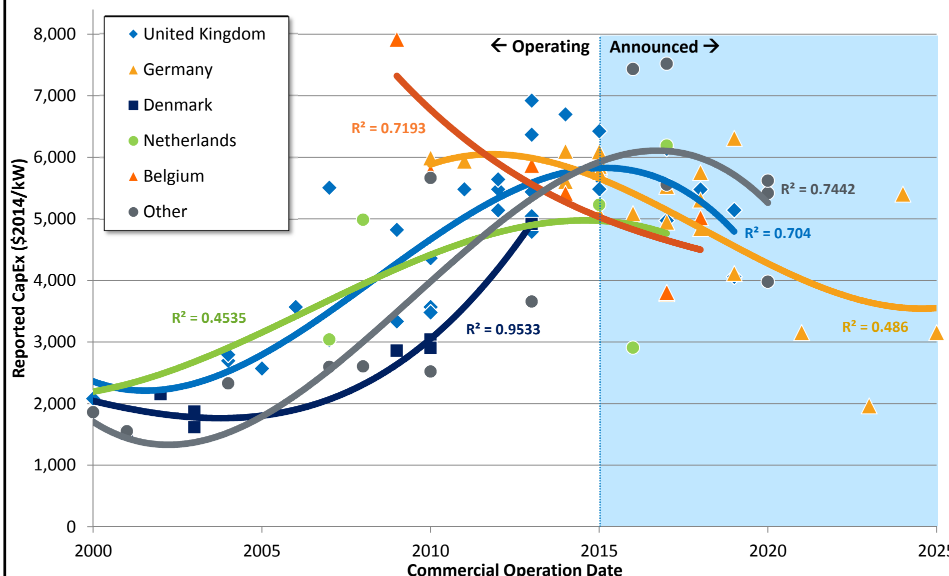
Bubble size represents project rated capacity (in MW): Proposed U.S. projects reflect the 13 projects (~5,940 MW) that have achieved site control. Note that WindFloat Pacific (OR, 350 m) and Aqua Ventus (ME, 95 m) are not shown due to truncation of the Y-axis

CapEx for E.U. projects rose significantly between 2005 and 2014; projections suggest that CapEx may be entering a period of decline



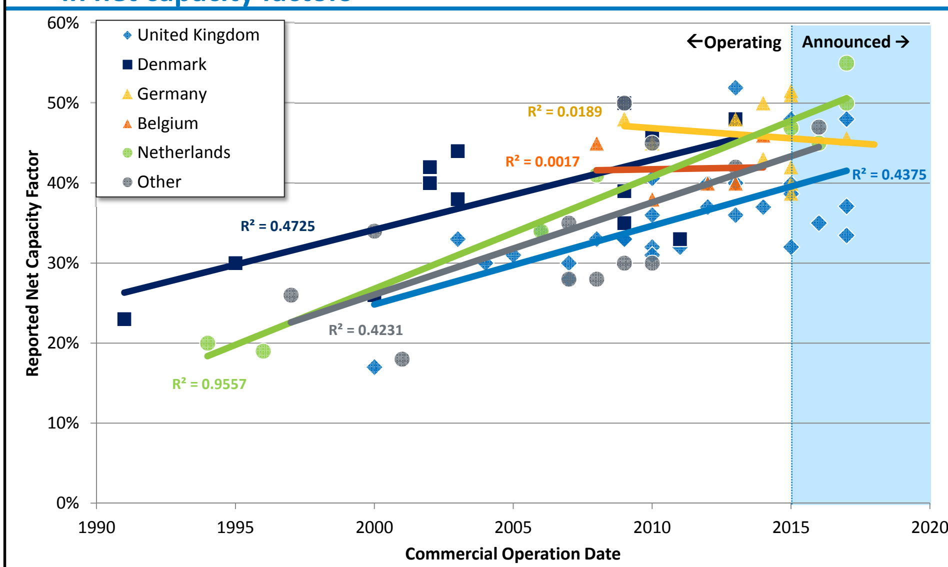
14% CapEx increase (2013 vs. 2014) largely driven by differences in site conditions and market conditions for sample of projects commissioned in each year

Segmentation of data by country shows that CAPEX is generally expected to trend downward in most markets



Denmark is the one exception in this chart and shows an increase. Note, however, that no projects in Denmark have announced CAPEX since Anholt in 2012 and that Horns Rev III was awarded at a FiT rate that is 32% below the award for Anholt. This suggest that CAPEX will be significantly lower.

Increases in CAPEX have been offset, to some extent, by increases in net capacity factors



Belgium and Germany show flat and decreasing trends, respectively, with almost no correlation between time and NCF. Unlike offshore wind projects in other countries, the first projects in BE and DE markets were installed in unsheltered, open ocean locations with high wind speeds. Average capacity factors for BE (42%) and DE (47%) are higher than the global fleet wide average of 37% for operating projects

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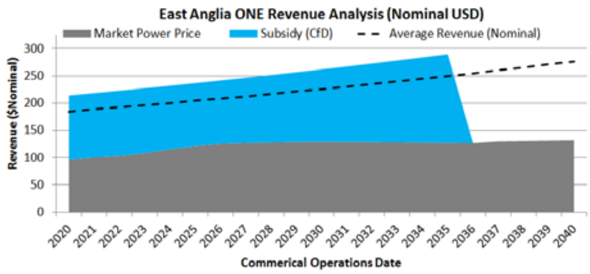
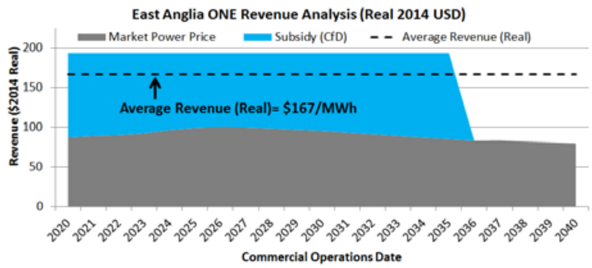
Cost Reduction Case Study: background and data sources

- **European cost reduction goals (from 2010)**
  - **UK:** £100/MWh ($164/MWh) for projects that reach Final Investment Decision (FID) in 2020 – approximate commercial operation date 2022
  - **Continental Europe:** - €100/MWh ($130/MWh) by FID 2020
  - Differences in Scope
    - UK projects responsible for transmission system costs (OFTO)
    - European generally allocate transmission system costs to Transmission System Operator
- **Two sources of empirical evidence about LCOE for Future Projects**
  1. UK Cost Reduction Monitoring Framework
     - 10 projects (3,078 MW) that reached COD between 2010 and 2014
     - 6 projects (1,793 MW) that had reached FID between 2012 and 2014
     - Average LCOE has declined from $235/MWh in 2010/2011 to $209/MWh for projects reaching FID in 2012/2014, **an 11% reduction**
  2. Competitive Tenders for Subsidy in the U.K. and Denmark

Project	Target COD	Capacity (MW)	First Year CFD/FIT ($2014/MWh)	Subsidy Term (years)	Other Subsidies ($2014/MWh)	Inflation Adjusted (Y/N)	Average Power Price ($2014/MWh)
Horns Rev III (DK)	2020	400	$134	12[a]	NA	N	$63[b]
Neart Na Gaoithe (UK)	2019	448	$184	15	NA[c]	Y	$94[d]
East Anglia ONE (UK)	2020	714	$193	15	NA[c]	Y	$94[d]

Cost Reduction Case Study: Estimating LCOE from Total Revenue

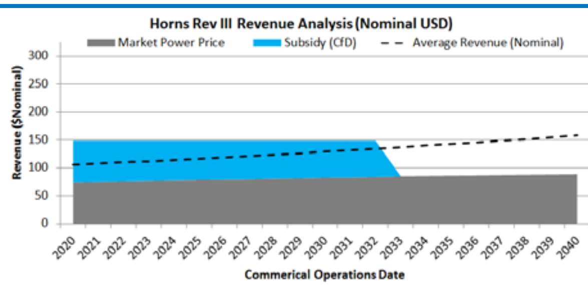


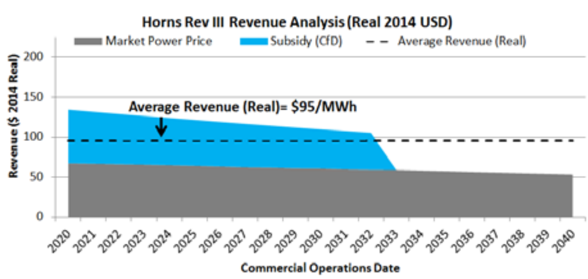


East Anglia ONE Contract for Differences (CfD) Value Analysis	
Incentive Rate	$186/MWh
Incentive Term	15 years
Inflation Index	Consumer Pricing Index
Average Electricity Price	$94/MWh
Electricity Price Source	(National Grid 2014)
Other	Levy Exemption Credit set to expire before project begins operation

Real LCOEs approximated by averaging total revenue stream (subsidy tariff + market price) over project lifetime. Converted to USD assuming 2014 exchange rates and normalized to $2014 using inflators from the US BLS

Cost Reduction Case Study: Estimating LCOE from Total Revenue





Horns Rev III Feed-in Tariff (FiT) Value Analysis	
Incentive Rate	$134.4/MWh
Incentive Term	20 million MWh (~12 years)
Inflation Index	Consumer Pricing Index
Average Electricity Price	$63/MWh
Electricity Price Source	(Energinet.dk 2013)
Other	State pays grid connection and some development costs

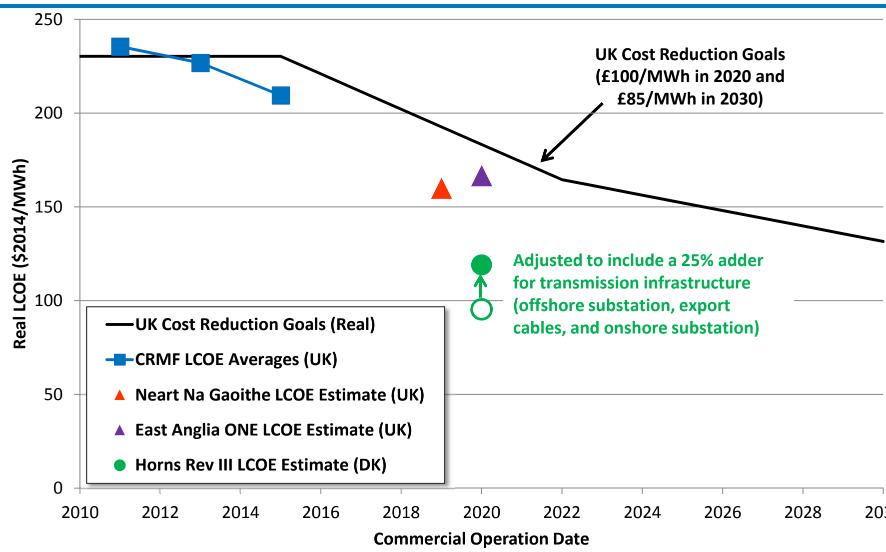
Real LCOEs approximated by averaging total revenue stream (subsidy tariff + market price) over project lifetime. Converted to USD assuming 2014 exchange rates and normalized to $2014 using inflators from the US BLS

Cost Reduction Case Study: Estimating LCOE from Total Revenue

- **Approximate LCOEs show significant spread**
  - Horns Rev III (DK) $95/MWh
  - Neart Na Gaoithe $160/MWh
  - East Anglia ONE $167/MWh

- **Drivers of Differences**
  - **Scope:** Horns Rev III is not responsible for transmission infrastructure (offshore substation, export cables, and onshore substation). Increases lifecycle cost by ~20% to ~30% to roughly $120/MWh
  - **Project Characteristics:**
    - Horns Rev III: shallow water (**15 m**), close to shore (**30 km**), and **9.8 m/s** average wind speed at 100 m
    - East Anglia ONE: deeper water (**37 m**), farther from shore (**45 km**), and **9.5 m/s** average wind speed at 100 m
  - **Technology:** Horns Rev III will use Vestas V164 8-MW turbines, whereas both Neart Na Gaoithe and East Anglia ONE will use Siemens SWT-7.0-154 turbines.
  - **Policy conditions:**
    - Development costs covered by the Danish government and no seabed lease costs
    - Final subsidy tariff is negotiated between the developer and the Danish government
  - **Market structure:** tax rates and depreciation schedules can have sizable effects on LCOE.
  - **Financial structure.** Even though no details have emerged about the financial structures for any of these projects, differences in financing rates can have a large impact on LCOE.

Cost Reduction Case Study: Results



Note: there are significant challenges associated with comparing across different contract values due to differences in scope, market structure , and site characteristics . This analysis represents a reasonable approximation of LCOE for the projects considered but may not fully capture all of the drivers.

Outline

Technologies and lessons learned from European deployment experience should translate to the U.S. Market…

- **BIWF, ATD projects, and others will provide crucial experience that will enable the U.S. Commercial projects to leverage European cost reduction, while building US capabilities:**
  - State-of-the-art turbines
  - Foundations developed by U.S. design firms and optimized to U.S. conditions, including:
    - Deepwater
    - Hurricane exposure
    - Surface icing
  - Streamline and de-risk offshore wind investment in the United States
- **Could allow the industry to merge with, or even leapfrog, the European cost reduction trajectory**

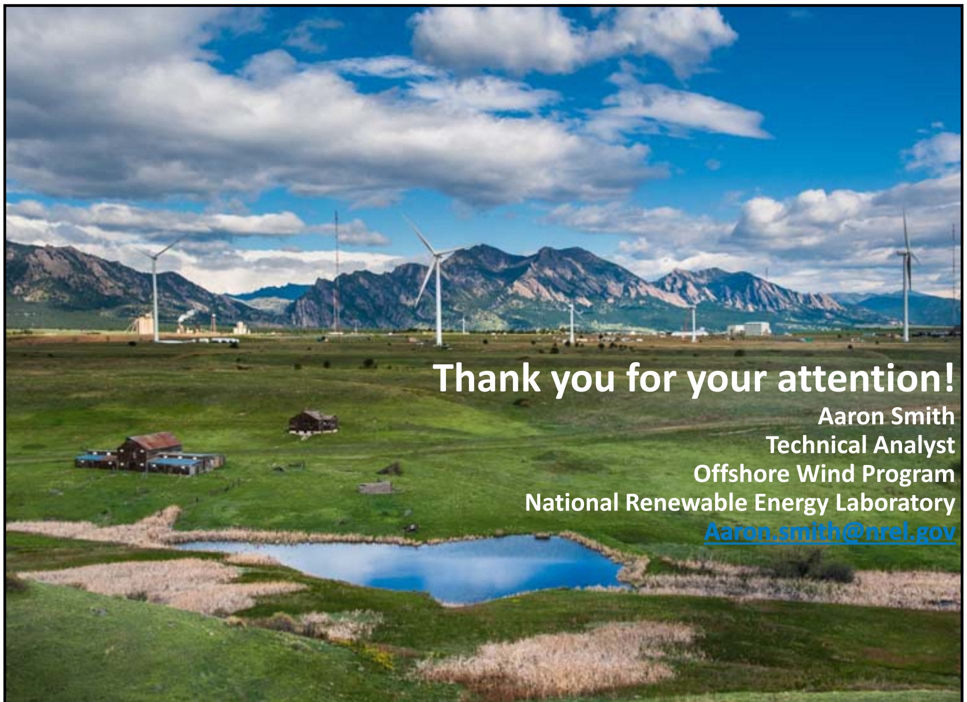
Image courtesy of Stanley White

…however, several barriers could limit the extent to which cost reductions can be realized in the United States

- **Infrastructure requires investment to handle components for larger turbine sizes and to match European industry standards for efficiency**
  - o Manufacturing facilities and/or shipyards require significant retooling
  - o Port facilities require upgrades to increase bearing capacity
  - o Jones-Act requires "creative" vessel strategies. The U.S. industry may eventually need to construct purpose-built installation vessels that comply with the Jones Act.
- **Fragmented (and uncertain) State and Federal revenue mechanisms can be made to work on a one-off basis, but do not provide the certainty needed to build an efficient industry**
  - o Site control awarded independently from revenue mechanisms
  - o Federal policy (ITC; PTC) is uncertain and is insufficient to support project economics
  - o Revenue mechanisms driven by states seeking first-mover advantages
    - – Potential for balkanized development due to focus on local, instead of regional, economic development
    - – Could result in supply chain inefficiencies and higher cost levels
- **Limited visibility into future market size makes it challenging for the supply chain to justify the necessary investments**

Summary

- **The U.S. offshore wind industry is ready for launch**
- **However, stable, coordinated policy is needed to offset high initial costs and drive deployment**
- **Costs in Europe are declining rapidly, with the industry poised to meet the targets of reducing LCOE by 40% from 2010 levels**
- **A robust project pipeline is needed to encourage the investments in technologies and infrastructure that could enable the industry to merge with, or even surpass, the European cost reduction trajectory**



Thank you for your attention!

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NREL

Back-up slides and supporting information

Bottom-up LCOE Calculations for Horns Rev III – $100/MWh seems achievable with an excellent site, large turbines, and favorable policy

No Transmission System

Baseline Levelized Cost of Energy

Expenditures	
All-in Capital Costs (CapEx; $/kW)	4000
Year 1 OpEx ($/kW)	100.0
Annual OpEx escalation (Real)	0.0%
Levelized Operations Costs (OpEx; $/kW)	100.0
Energy Production	
Net Annual Energy Production (AEP; MWh/MW)	4,600
Net Capacity Factor	53%
LCOE	
Real LCOE ($/kWh)	**$0.096**

Financing	
Project Design Life (years)	20
Tax Rate (combined state and federal)	40.0%
Debt Fraction	70%
Debt Interest Rate (Nominal)	5.0%
Return on Equity (Nominal)	15%
WACC (Nominal; After-tax)	6.6%
WACC (Real; After-tax)	4.5%
Capital Recovery Factor (Real; After-tax)	7.7%
Depreciable Basis	100%
Depreciation Schedule	5 year MACRS
Depreciation Adjustment (NPV)	84%
Tax Adjustment	111%
Real Fixed Charge Rate	8.52%

Notes:
All-in CapEx includes Turbine, BOP, Spur Line and required substations, and construction financing
OpEx includes all operating expenses: turbine O&M, BOP O&M, property tax, lease payments, etc.
With two exceptions (debt interest rate and return on equity) all values are real dollar estimates and should be estimated in the preferred baseline year dollars

Including Transmission System*

Baseline Levelized Cost of Energy

Expenditures	
All-in Capital Costs (CapEx; $/kW)	4700
Year 1 OpEx ($/kW)	120.0
Annual OpEx escalation (Real)	0.0%
Levelized Operations Costs (OpEx; $/kW)	120.0
Energy Production	
Net Annual Energy Production (AEP; MWh/MW)	4,416
Net Capacity Factor	50%
LCOE	
Real LCOE ($/kWh)	**$0.118**

Financing	
Project Design Life (years)	20
Tax Rate (combined state and federal)	40.0%
Debt Fraction	70%
Debt Interest Rate (Nominal)	5.0%
Return on Equity (Nominal)	15%
WACC (Nominal; After-tax)	6.6%
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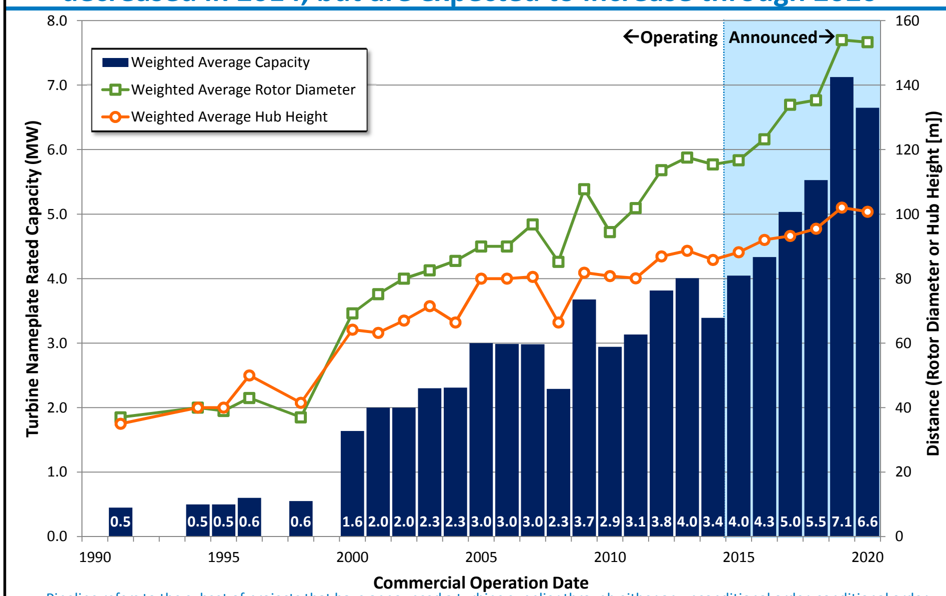
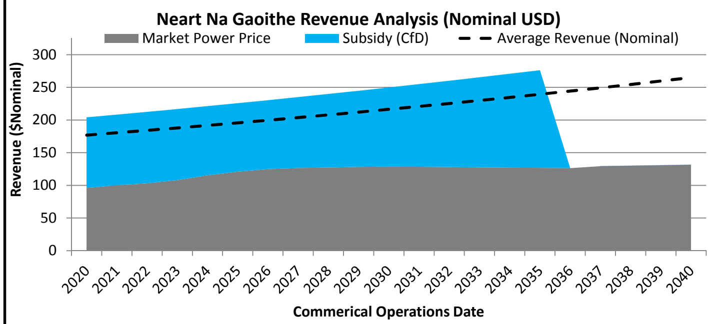
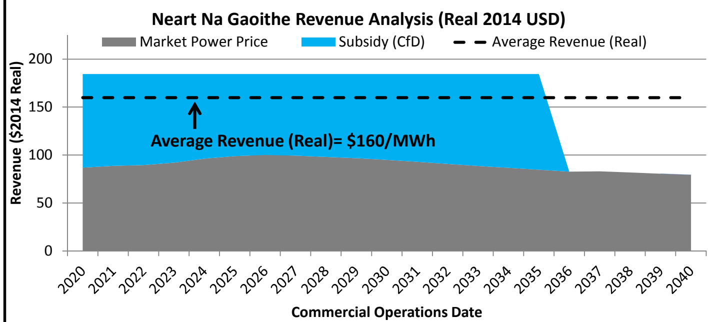
* Energinet.dk reports that transmission system costs total 1,500 DKK (~$280 M), inclusion of transmission system increases OpEx (~20/kW) and lowers capacity factor (~-4%)

Average turbine capacities, rotor diameters, and hub heights decreased in 2014, but are expected to increase through 2020



Pipeline refers to the subset of projects that have announced a turbine supplier through either an unconditional order, conditional order, preferred supply agreement, or where the turbine OEM is a partner in a development consortium. Must also have announced COD.





Neart Na Gaoithe
Contract for Differences (CfD) Value Analysis

Incentive Rate	$184/MWh
Incentive Term	15 years
Inflation Index	Consumer Pricing Index
Average Electricity Price	$94/MWh
Electricity Price Source	(National Grid 2014)
Other	Levy Exemption Credit set to expire before project begins operation

CoE Modeling for Offshore Turbines with Different Drive Train Types at Sites Varying Distances from Shore

James Carroll
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This presentation will show the results of CoE modeling and the effect of the use of different wind turbine types on the CoE at sites varying distance from shore. The CoE was modeled for 4 different wind turbine types at sites 10km, 50km and 100km from shore. The turbine types were differentiated by their drive train configurations. The drive train configurations chosen for this analysis were:

1. 3 stage, DFIG, Partially Rated Converter
2. 3 Stage, PMG, Fully Rated Converter
3. 2 Stage, PMG, Fully Rated Converter
4. Direct Drive, PMG, Fully Rated Converter

The results were obtained through the use of CoE, O&M and Balance of Station models that were both created at the University and provided by research partners. These models were populated with up to date operational and cost data for modern multi MW offshore turbines provided to the presenter by wind energy developers, manufacturers, operators, consultants and governmental research groups.

Offshore Wind Turbine Cost of Energy Analysis for Different Drive Train Types

James Carroll

UK Wind Energy Doctoral Training Centre, University of Strathclyde, Glasgow

Contents

Presenter and Research Centre

University of Strathclyde Engineering

- Past 6 years in the Wind Energy Industry
- First 3 years SoWiTec and Vestas
- Micrositings, Wind Maps, Availability and lost production analysis
- Past 3 years doing PhD
- PhD Topic
- UK Wind Energy Doctoral Training Centre (DTC)
- 10 Students from different backgrounds, common year then research
- Centre is very open to industry and academia partnership and collaboration

University of Strathclyde Glasgow
Wind Energy Systems
Centre for Doctoral Training

Introduction and Background

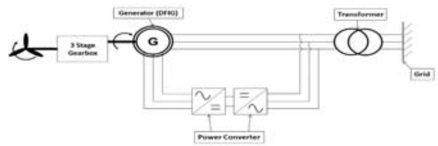
1. Presenter and Research Centre
2. Introduction and Background
3. Drive Trains Modelled in this Work
4. Overview of Work Carried Out
5. Cost of Energy and its Inputs
6. Models Used
7. Hypothetical Sites
8. Results
   - Energy Produced at each Site
   - Turbine Costs
   - BoP Costs
   - Other Capital Costs
   - O&M Costs
   - Total Cost of Energy
9. Conclusion

University of Strathclyde Engineering

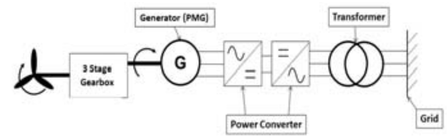
- How do you choose between different competing wind turbine models when planning an offshore wind farm?
- Many turbine types available
- Drivetrain biggest differentiator
- This work shows how the drive train choice effects the CoE of offshore wind farms
- 3 hypothetical Sites located at different distances from shore
- Each site has one of four different drive train types

Drive Trains Modelled in this Work

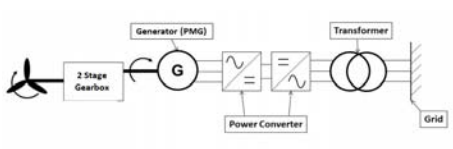
Turbine Type 1: 3 Stage, DFIG, PRC



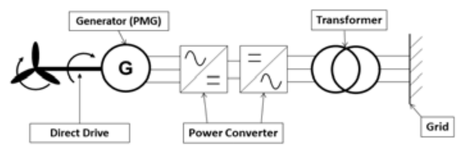
Turbine Type 2: 3 Stage, PMG, FRC



Turbine Type 3: 2 Stage, PMG, FRC



Turbine Type 4: DD, PMG, FRC



Overview of Work Carried Out

1. Obtain or create the various models required to calculate the CoE for offshore wind farms.

2. Source empirical offshore wind farm operational and cost data to populate these models

3. Adjust empirical data to represent drive train types that had no empirical data.
   - No field data for some drive train types.
   - Reliability and operational data estimated using REMM
   - Cost using methods published in past papers in which drive train component costs are estimated based on weight
   - Power curve data adjusted using past paper which provided power curve % difference between turbine types

4. Combine the models and input data to work out the CoE for one of the drive train type at each of the three offshore locations

5. Adjust inputs to represent the 3 other drive train types and determine the effect on CoE at each of the three sites.

6. Draw conclusions on which drive train type offers the lowest CoE at each distance from shore.

Cost of Energy and its Inputs

- In this analysis as in [X] the CoE is defined as:

$$\frac{(Initial\ Capital\ Costs\ x\ Fixed\ Charge\ Rates) + (O\&M\ Costs)}{Energy\ Production}$$

Where:

- Initial Capital costs include:
    1. Turbine costs
    2. BoS costs (port and staging, substructure and foundation, electrical infrastructure, assembly and installation, commissioning, engineering and management costs)
    3. Other capital costs (insurance during construction, decommissioning, finance costs, contingency etc.).

- O&M costs include the staff costs, repair costs and transport costs.

- Fixed Charge Rate is 10.1% as in NREL CoE analyses.

- The energy production is the amount of energy produced by the wind farm or wind turbine in the given time period.

Models Used

Model and Output	Description	Input and source of input
O&M Cost Model. Output: O&M costs for each drive train type at each site	The O&M cost model used in this work was the AM02 model created at the university of Strathclyde [1]	Empirical failure rates, repair times, no. of technicians required for repair, repair costs and so on, from a population of ~350 offshore modern multi MW turbines from between 5-10 offshore wind farms throughout Europe.
Energy Production Model. Output: Energy produced by each turbine type at each site.	The energy production model used in this work was the AM02 model created at the University of Strathclyde [1]	Empirical power curves from wind turbines with different drive train types, wind and wave data from a north sea site
BoS Model Output: BoS costs for each turbine type at each site	The balance of station model from which results were obtained was created by NREL [2]	Costs of: ports, staging, substructure, foundation, electrical infrastructure, assembly, installation, development, engineering, management and commissioning. Model populated by Garrad Hassan
Other outputs:	Wind Turbine Costs for different turbine types. Component cost for different wind turbine types.	Provided by a leading wind turbine manufacturer who was the PhD industrial partner to the author

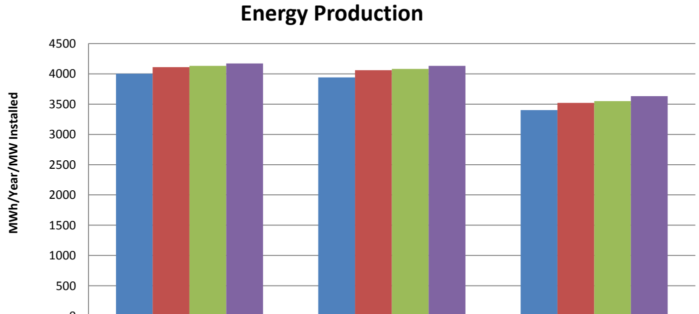
Hypothetical Sites

- 12 Wind Farms
- 4 at 10km, 4 at 50km, 4 at 100km
- 100 modern MW offshore wind turbines of the same rated power
- Each of the 4 at 10km will have one of the 4 turbine types described earlier
- FINO climate and sea state data used
- FINO representative of a North Sea Site

Energy Produced

- Energy per installed MW per year
- 3MW = ~12,000 MWh @ 10km
- Availability drives difference between distances and turbine types
- All costs will be shown / MWh so production plays an important role

Energy Production

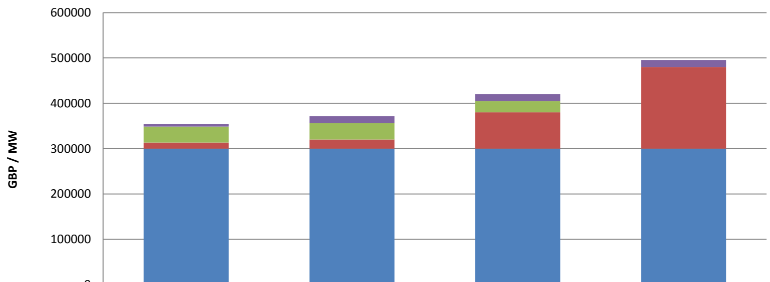


	10km	50km	100km
3 Stage DFIG PRC	4002	3940	3400
3 Stage PMG FRC	4110	4060	3520
2 Stage PMG FRC	4130	4080	3550
DD PMG FRC	4170	4130	3630

[3]

Turbine Costs

- DFIG Configuration has the lowest CoE
- Driven by the lowest cost generator and converter
- PMG configuration cost increases with the speed of the generator

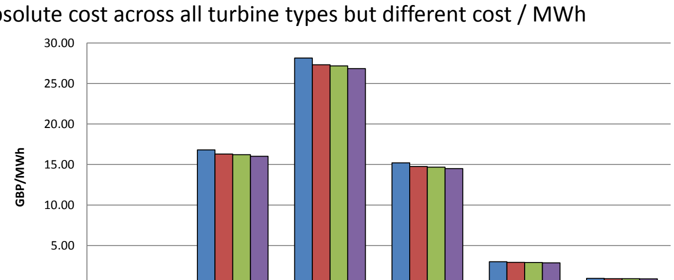


	3 Stage DFIG PRC	3 Stage PMG FRC	2 Stage PMG FRC	DD PMG FRC
Converter	6000	15500	15500	15500
Gearbox	35000	36000	25000	0
Generator	13500	20000	80000	180000
Rest of Turbine	300000	300000	300000	300000

[4]

BoS Costs Further Analysis

- BoS costs for 50km offshore
- Includes port and staging, foundation, ….
- Electrical Infrastructure is the highest cost followed by … (Same across all distances from shore
- Same absolute cost across all turbine types but different cost / MWh

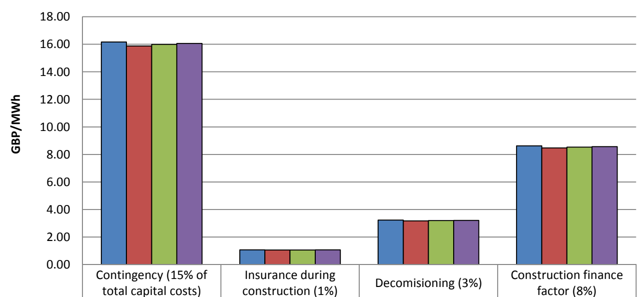


	Port and Staging	Substructure and Foundation	Electrical Infrastructure	Assembly and Installation	Development, Engineering & Management	Commisioning
3 Stage DFIG PRC	0.57	16.80	28.14	15.20	3.01	0.94
3 Stage PMG FRC	0.55	16.30	27.31	14.75	2.92	0.91
2 Stage PMG FRC	0.55	16.22	27.17	14.68	2.90	0.90
DD PMG FRC	0.54	16.02	26.84	14.50	2.87	0.89

[4]

Other Capital Costs

- Other Capital costs for 50km offshore
- Includes contingency, insurance etc.
- Contingency and the cost of finance are the highest cost
- Calculated as a % of overall capital costs

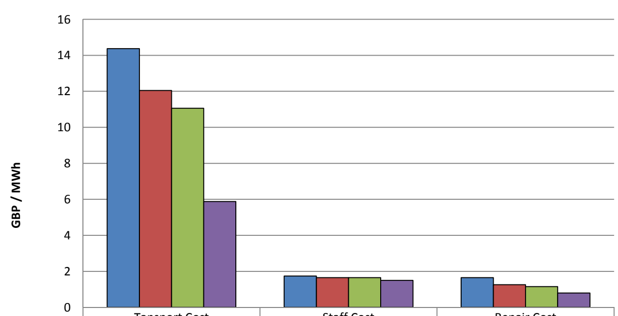


	Contingency (15% of total capital costs)	Insurance during construction (1%)	Decomisioning (3%)	Construction finance factor (8%)
3 Stage DFIG PRC	16.17	1.08	3.23	8.62
3 Stage PMG FRC	15.88	1.06	3.18	8.47
2 Stage PMG FRC	15.99	1.07	3.20	8.53
DD PMG FRC	16.06	1.07	3.21	8.56

[4]

O&M Costs

- O&M costs for 50km offshore
- Includes transport cost, staff cost and repair cost
- Transport cost is the highest cost and main differentiator between drive train types
- HLV is required the most for the DFIG and least for the DD configuration



	Tansport Cost	Staff Cost	Repair Cost
3 Stage DFIG PRC	14.37	1.74	1.65
3 Stage PMG FRC	12.05	1.65	1.26
2 Stage PMG FRC	11.06	1.65	1.15
DD PMG FRC	5.88	1.5	0.80

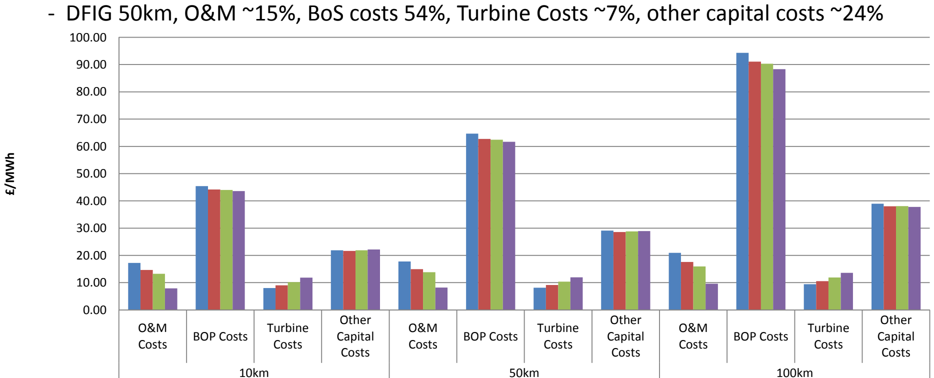
[3]

CoE Further Analysis

- O&M, BoS, Turbine Costs and other Capital Costs shown for all turbine types for each of the 3 sites

- BoS costs rise the most as sites move further offshore, turbine costs go up due to lower production

- DFIG 50km, O&M ~15%, BoS costs 54%, Turbine Costs ~7%, other capital costs ~24%



	10km				50km				100km			
	O&M Costs	BOP Costs	Turbine Costs	Other Capital Costs	O&M Costs	BOP Costs	Turbine Costs	Other Capital Costs	O&M Costs	BOP Costs	Turbine Costs	Other Capital Costs
3 Stage DFIG PRC	17.27	45.40	8.01	21.90	17.76	64.65	8.13	29.10	20.92	94.31	9.43	38.97
3 Stage PMG FRC	14.64	44.21	9.03	21.66	14.96	62.73	9.14	28.58	17.60	91.10	10.54	38.03
2 Stage PMG FRC	13.27	43.99	10.23	21.89	13.86	62.43	10.35	28.78	15.93	90.33	11.90	38.10
DD PMG FRC	7.94	43.57	11.87	22.15	8.18	61.67	11.98	28.90	9.62	88.34	13.63	37.80

[4]

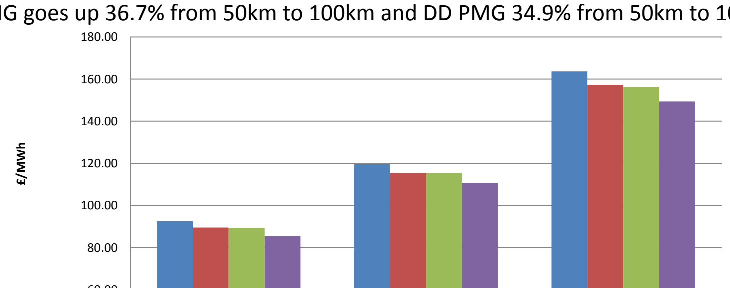
CoE Final Result

- Total CoE for each drive train shown at all 3 distances from shore

- Focusing on the DFIG we see that it is ~8% at 10km ~ 8% at 50km and ~9.5% at 100km higher cost than the lowest costing DD configuration.

- DFIG goes up 29.25% from 10km to 50km and DD PMG 29.5% from 10km to 50km

- DFIG goes up 36.7% from 50km to 100km and DD PMG 34.9% from 50km to 100km



	10km	50km	100km
3 Stage DFIG PRC	92.58	119.64	163.63
3 Stage PMG FRC	89.53	115.41	157.27
2 Stage PMG FRC	89.38	115.42	156.25
DD PMG FRC	85.52	110.74	149.38

[4]

Conclusion

- "How do you choose between different competing wind turbine models when planning an offshore wind farm?"
- Direct drive, permanent magnet generator and a fully rated converter provided the lowest CoE across all sites in this analysis.
- Little difference between the CoE from 3 stage and 2 stage PMG FRC configurations across all sites.
- The 3 stage, DFIG partially rated converter configuration had the highest CoE across all sites.
- DFIG configuration's CoE (£119.64/MWh) was ~8% higher than the DD configurations (£110.74/MWh).
- The authors plan further work of introducing different O&M vessel strategies and turbine design modifications (redundancy, in built lifting mechanisms etc.) and analysing the effects on CoE.

Acknowledgements and Contact

- The authors would like to thank the industrial partners that provided operational and cost data for this work and all parties involved in creating the models referenced in this presentation

- Contact: j.carroll@strath.ac.uk

Questions

References

[1] Dalgic Y, Dinwoodie I, Lazakis I, McMillan D, Revie M. Optimum CTV fleet selection for offshore wind farm O&M activities. 2014. Paper presented at ESREL 2014, Wroclaw, Poland

[2] Saur G, Maples B, Meadows B, Hand M, Musial W, Elkington C, Clayton J. Offshore Wind Plant Balance-of-Station Cost Drivers and Sensitivities NREL Report No. PO-5000-56132.

[3] Carroll J, McDonald A, McMillan D. Failure Rate, Repair Time and Unscheduled O&M Cost Analysis of Offshore Wind Turbines. Wiley Wind Energy Journal, August 2015.

[4] Carroll J, McDonald A, McMillan D. Cost of energy for wind turbines with different drive train types, EWEA, Paris, 2015

University of Strathclyde Glasgow

Offshore Wind Farm O&M Optimization Using Real Options Analysis

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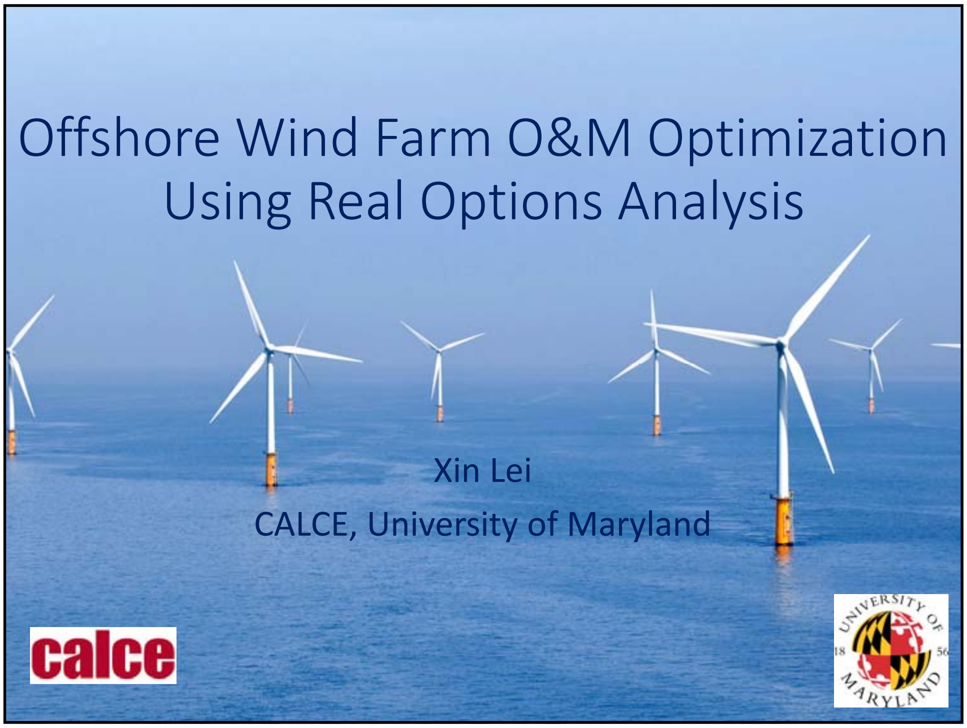
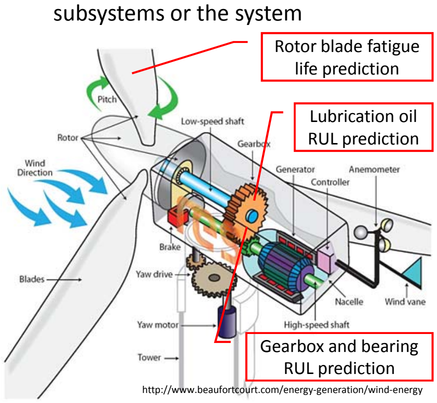
A simulation-based real options analysis (ROA) approach is used to determine the optimum predictive maintenance opportunity for turbines in an offshore wind farm managed under a power purchase agreement (PPA). In this analysis, the major subsystems in the turbines have remaining useful life (RUL) predictions generated using condition monitoring (CM) or prognostics and health management (PHM). When an RUL is predicted for a subsystem in a single turbine, a predictive maintenance option is triggered giving the decision-maker the flexibility to decide if and when to exercise the option (i.e., perform maintenance) before the turbine fails. Possible predictive maintenance value paths are simulated by considering the uncertainties in the RUL predictions and future wind speeds that govern the turbine's revenue earning potential. By valuating a series of European-style options expiring at all possible predictive maintenance opportunities, a series of option values can be obtained, and the optimum predictive maintenance opportunity can be selected. The ROA approach assumes that the predictive maintenance will only be implemented if the predictive maintenance value is higher than the predictive maintenance cost.

The optimum opportunity for a turbine under a PPA is not the same as the result for the same turbine under an "as-delivered" contract. For a wind farm managed via a PPA with multiple turbines indicating RULs concurrently, the predictive maintenance value for each turbine with a predicted RUL depends on the operational state of all the other turbines, and the amount of energy to be delivered by the whole wind farm. The optimum predictive maintenance opportunity for the farm is different from the results for the individual turbines managed in isolation. When the number of non-operating turbines in the wind farm changes, the optimum predictive maintenance opportunity for the farm may also change.



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



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

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

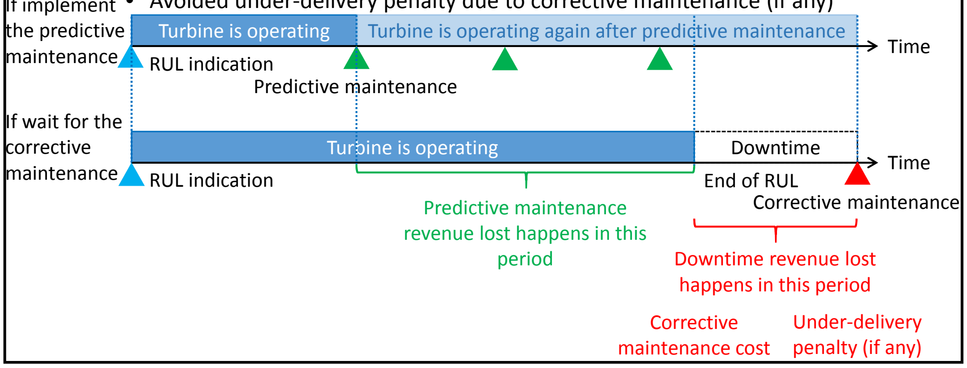
If I could determine the value of each of the options, I would have a basis upon which to make a decision about what action to take in response to the RUL prediction

A Real Options View of Predictive Maintenance

- Real Options: the right, but not the obligation to undertake certain business initiatives, such as investing, deferring, abandoning, expanding, or staging a project at the future date
- Real Options enable the flexibility to alter the course of an action in a real assets decision depending on future developments, assuming the value-maximizing decisions will always be made at each decision point with the managerial flexibility
- 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 = predictive maintenance revenue lost + cost avoidance
  - Representing the additional value obtained by implementing the predictive maintenance instead of waiting for the corrective maintenance

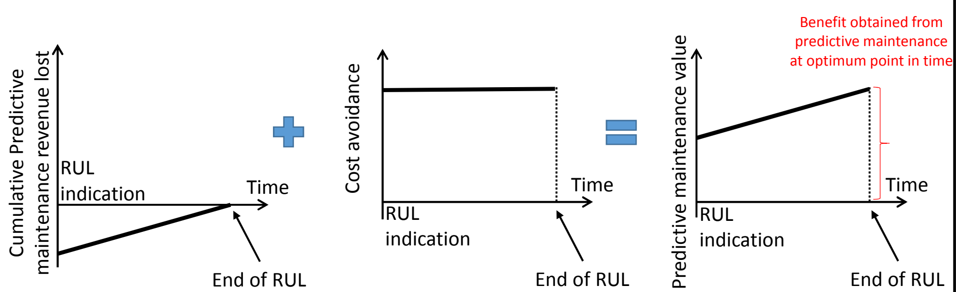
Predictive Maintenance Value Simulation for a Single Turbine

- Predictive maintenance revenue lost
  - The difference between the cumulative revenue from the RUL indication to the predictive maintenance event, and to the end of the RUL
- Cost avoidance including:
  - Avoided corrective maintenance cost (parts, service, labor, etc.)
  - Avoided downtime revenue lost
  - 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



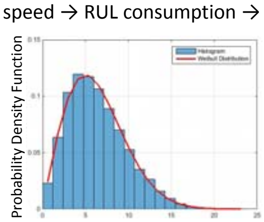
Determining the optimum predictive maintenance opportunity is trivial if there is no uncertainty

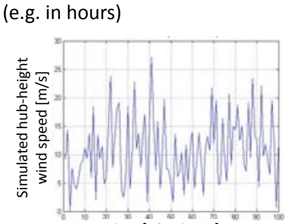
Path Simulation with Uncertainties

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

Wind Speed and TTF Simulation

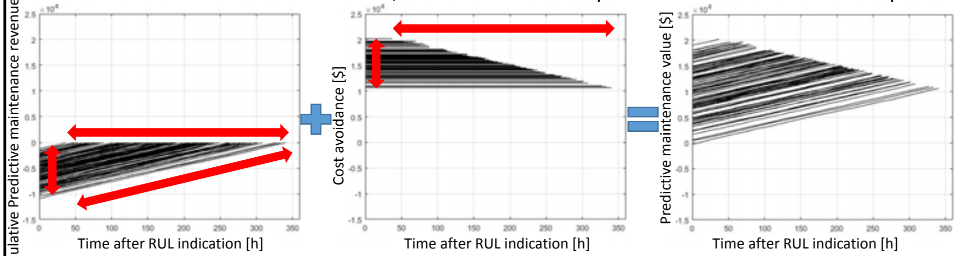
- Wind turbine: Vestas V112-3.0 MW Offshore
- Wind speed simulation
  - 2003 to 2012 wind data of NOAA Buoy 44009 (in the Maryland Offshore Wind lease area) fit with a Weibull distribution
  - Monte Carlo simulation used to get buoy height wind speed paths
  - Power Law used to transfer buoy height wind speed to hub height
- Time to Failure (TTF) simulation
  - A TTF represents a possible calendar time (e.g., in hours) for the subsystem with the RUL prediction to fail (assuming turbine fails thereafter) considering the uncertain PHM predictions and future wind speeds
  - A triangular 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

Predictive maintenance revenue lost, cost avoidance and predictive maintenance value paths



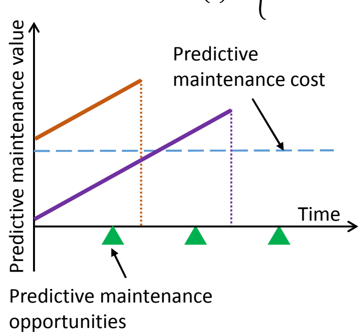
- Due to the uncertainties in RUL predictions and wind speeds, each path terminates at a different point
  - The point is the last predictive maintenance opportunity before the *TTF*
  - The shorter the *TTF*, the sooner the predictive maintenance revenue lost and the cost avoidance path terminate
- Due to the uncertainties in RUL predictions and wind speeds, each path starts at a different point
  - The shorter the *TTF*, the higher the predictive maintenance revenue lost path starts, because the revenue lost due to predictive maintenance is lower
  - The shorter the *TTF*, the higher the cost avoidance path starts, because the downtime revenue lost is higher
- The fluctuations of the paths represents the uncertainties in future wind speeds

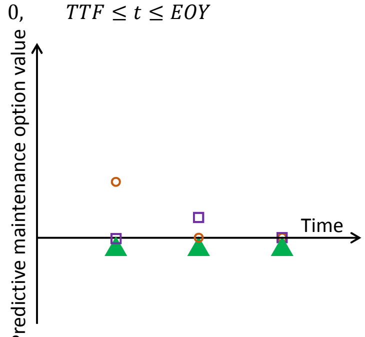
So how do we schedule the predictive maintenance based on this set of paths?

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

- Predictive maintenance can only be performed on specific dates
- Assume on each date, 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:

$$OV(t) = \begin{cases} max(V(t) - C_{PM}, 0), & t_0 < t < TTF \\ 0, & TTF \leq t \leq EOY \end{cases}$$

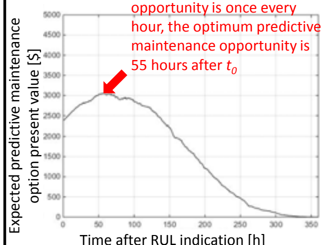




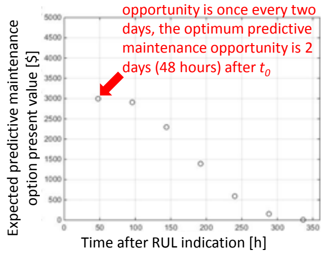
Case Study for a Single Turbine under an "As-delivered" Contract

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

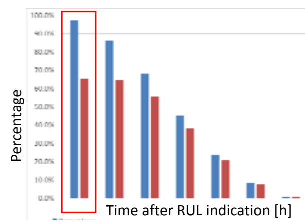
If predictive maintenance opportunity is once every hour, the optimum predictive maintenance opportunity is 55 hours after t_0



If predictive maintenance opportunity is once every two days, the optimum predictive maintenance opportunity is 2 days (48 hours) after t_0



At the optimum date:
- The predictive maintenance will be implemented on 65.3% of the paths
- 32.0% of the paths choose not to implement predictive maintenance since the predictive maintenance value is lower than the predictive maintenance cost
- In 2.7% of the paths the turbine failed prior to the predictive maintenance



Blue: percentage of the paths with the turbine still operating
Red: percentage of the paths choosing to implement predictive maintenance

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"

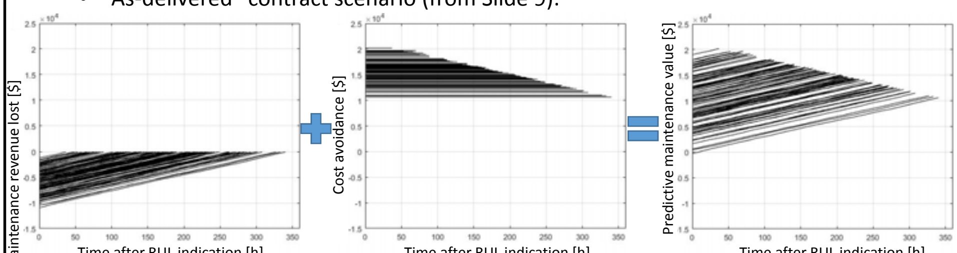
Nothing in the contract says "only when the wind blows" or "only if the turbines are operational"

Power Purchase Agreement (PPA) Modeling

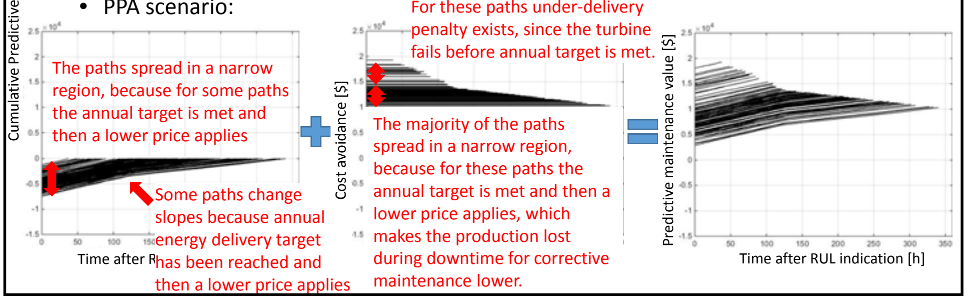
- PPA Modeling:
  - An annual energy delivery target is agreed by the seller and the buyer at the beginning of the year to reflect the buyer's annual wind energy demand, which will not change through the year
  - Constant contract energy price applies for each MWh generated before the annual target is 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

Case Study for a Single Turbine under a PPA

- "As-delivered" contract scenario (from Slide 9):

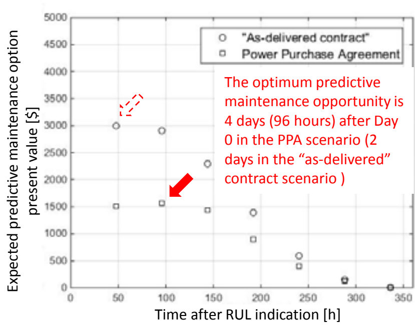


- PPA scenario:

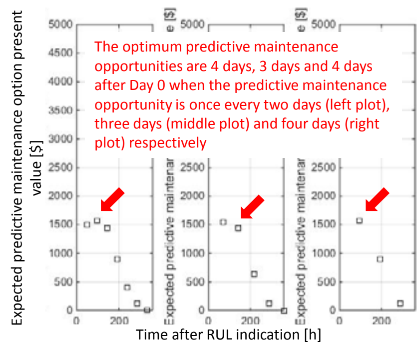


Case Study for a Single Turbine under a PPA (cont.)

- Scheduling method is same as the "as-delivered" contract scenario
- Optimum predictive maintenance opportunity for a single turbine under PPA vs. under "as-delivered" contract



- Optimum predictive maintenance opportunity for a single turbine under PPA when the maintenance calendar changes



Conclusions from the Single Turbine Case Studies

- 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
- The optimum predictive maintenance opportunities for a single turbine may be different between an "as-delivered" contract and a PPA
- When the predictive maintenance calendar changes, the optimum predictive maintenance opportunity may also change

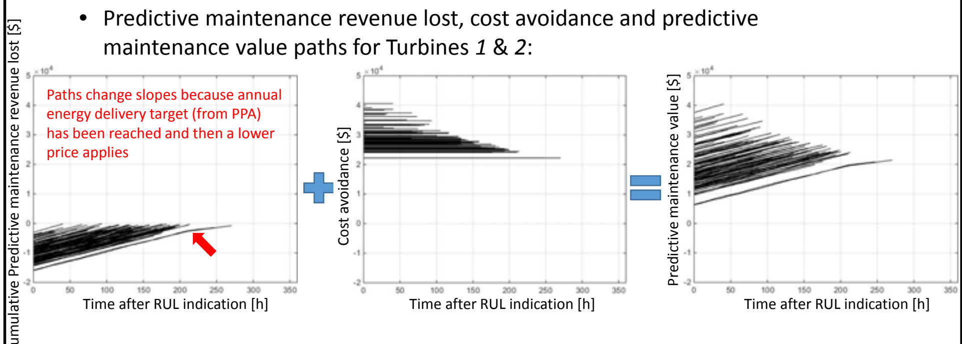
Extension the Predictive Maintenance Value Simulation Method to Wind Farms

- 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, Turbine *3* operates normally, Turbines *4* & *5* are down
- Predictive maintenance revenue lost, cost avoidance and predictive maintenance value paths for Turbines *1* & *2*:



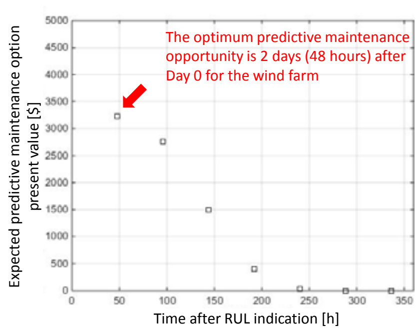
Predictive Maintenance Scheduling for a Wind Farm under a PPA

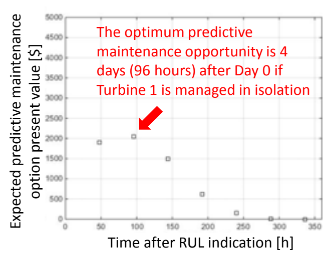
- European Real Option Analysis (ROA) is performed for the option valuation, where $C_{PM,k}$ is the predictive maintenance cost at t for Turbine k, TTF_{min} is the shortest TTF_k of all K turbines
- It is assumed that all K turbines will be maintained together before TTF_{min}, once the first turbine failure happens, the predictive maintenance option expires

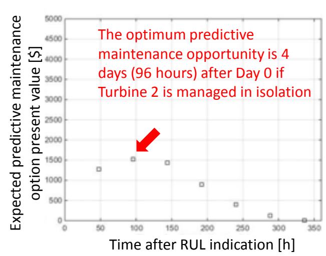
$$OV(t) = \begin{cases} max\left(V(t) - \sum_{k=1}^{K} C_{PM,k}\,, 0\right), & t_0 < t < TTF_{min} \\ 0, & TTF_{min} \leq t \leq EOY \end{cases}$$

Case Study for a Wind Farm under a PPA

- Optimum maintenance date for the turbines with RULs in a farm subject to a PPA may not be the same as individual turbines managed in isolation

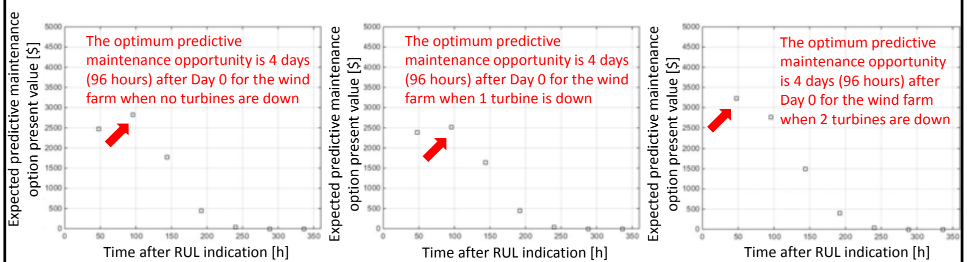






Case Study for a Wind Farm under a PPA (cont.)

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



Conclusions from the Wind Farm Case Studies

- 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
- The optimum predictive maintenance opportunity for the multiple turbines indicating RULs in a farm under a PPA is not the same as the results for the individual turbines managed in isolation
- 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

Summary of Work to Date

- The proposed work this paper enables optimum maintenance scheduling for wind farms with PHM that are subject to a PPAs may including variable prices and penalties
- Optimum maintenance scheduling = maintenance dates and actions that minimize the part of RUL wasted and minimize the risk of corrective maintenance
- Uncertainties in wind and the accuracy of the RULs forecasted by the PHM approach are included

Publications from this Work to Date

- X. Lei, P. Sandborn, and N. Goudarzi, "PHM Based Predictive Maintenance Option Model for Offshore Wind Farm O&M Optimization," to be published 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," to be presented on 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.
- N. Goudarzi, X. Lei, A. St. Pe, S. Rabenhorst, R. Delgado, and P. Sandborn, "Maintenance Optimization of a Wind Turbine: The Impact of Wind Speed Measurement Accuracy," Presented at ASME 2015 Power Conference, San Diego, CA, 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.

Wind Turbine Performance Analysis and Anomaly Detection based on Techniques Developed on SCADA Data

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Generally, approaches on condition monitoring and health analysis of wind turbines build a model to detect abnormalities in the behavior of the wind turbines. Later when the abnormality is found, the origin of the abnormality is exposed through intensive man-hour investigations and then the problem is cleared. This results in long and expensive maintenance time with sustained down-times. This paper takes one step further in this path and creates an algorithm that acts as a top-to-bottom analyzer. In the first stage of the proposed algorithm, a model is created that finds anomalies in the performance of the wind turbine (top/system layer). In the second stage, an approach is applied to analyze the discovered anomalies and uncovers the root of the anomaly (bottom/component layer). Hence, this algorithm presents a complete path in fault diagnosis of wind turbines. To validate and demonstrate the accuracy and efficiency of the algorithm, SCADA data obtained from online monitoring of a wind turbine are utilized. Reducing time and cost of maintenance and increasing up-time and availability are some of the benefits of this algorithm. The algorithm is codded in MATLAB software.

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Anomaly Detection and Performance Analysis in Wind Turbines through Neural Networks

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International Workshop on Life-Cycle Costing of Offshore Wind Turbines and Farms

University of Maryland, College Park, USA 1/Oct./2015

Presentation Outline

1. Objective
2. Overview
3. Data Processing
    3.1. Preprocessing
    3.2. Dimension Reduction
4. Anomaly Detection
    4.1. Model Parameters
    4.2. Training Stage
    4.3. Model Results
5. Conclusion
6. Continued Research

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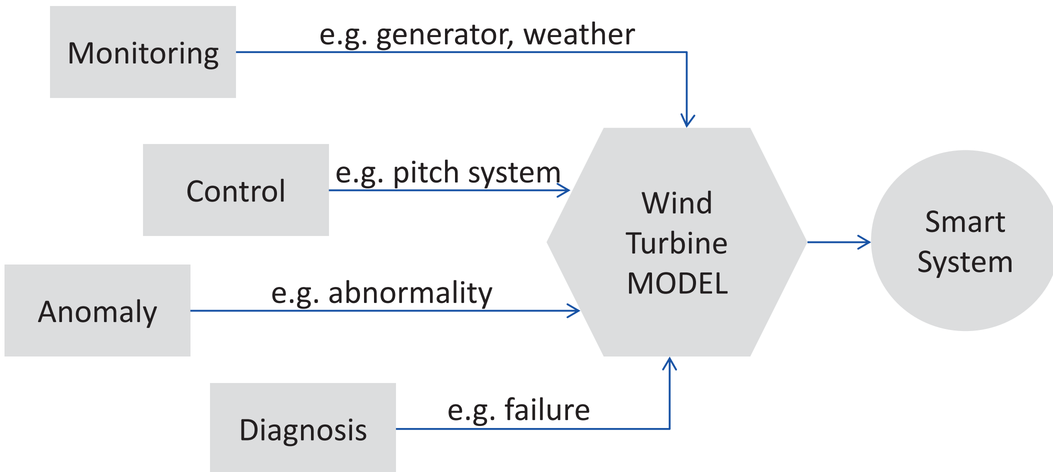
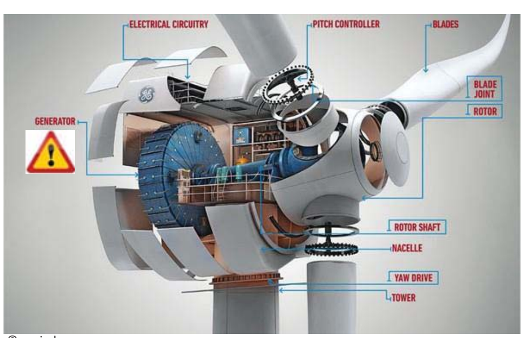
Objective



Overview



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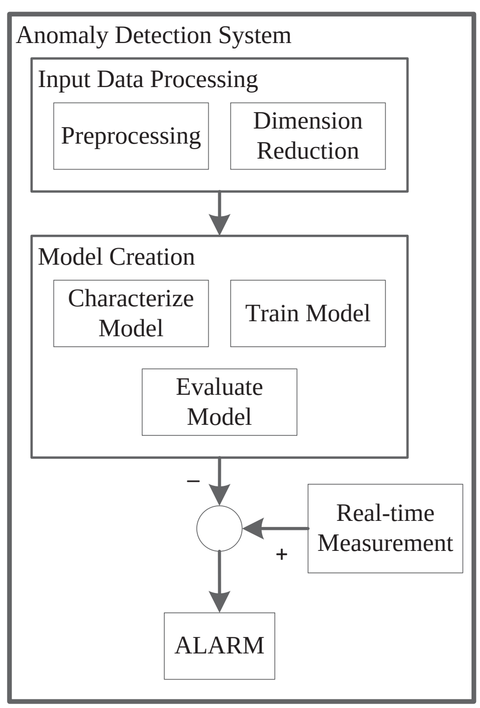
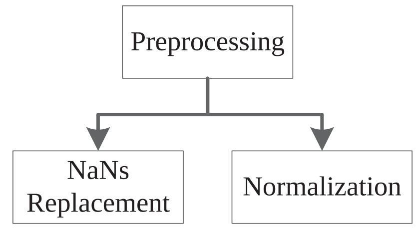


Preprocessing



3.1.1. NaN Replacement:

e.g. sensor error

Delete vs. Replace

a. Replacement1 b. Replacement2

-4	0	4	8	10	6	NaN	0	-2	-6

Avg1: NaN=1.8 Avg2: NaN=3

3.1.2. Normalization

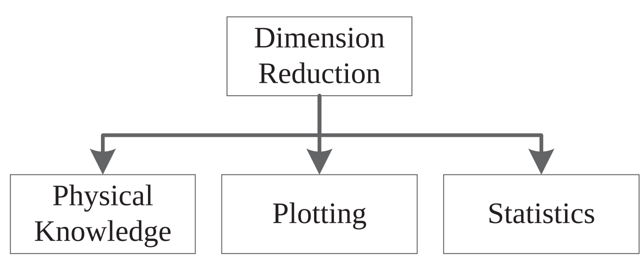
Wind Speed = [0:30]

Pitch Angle = [0:90]

Rotor Speed = [0:16] …

Dimension Reduction

- More than 50 signals recorded
- Complex model
- High computing power
- Response speed

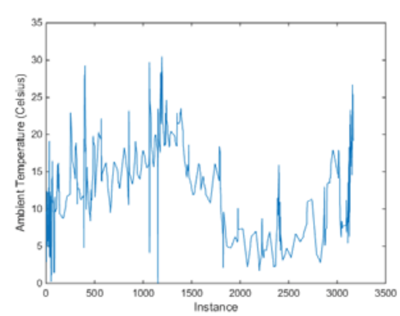


a. Physical Knowledge

- variations ratio
- “cause and effect” relationship

b. Plotting

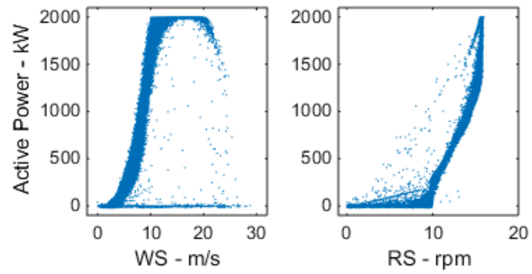
- apparent behavior



c. Statistics

Dimension Reduction – cntd.

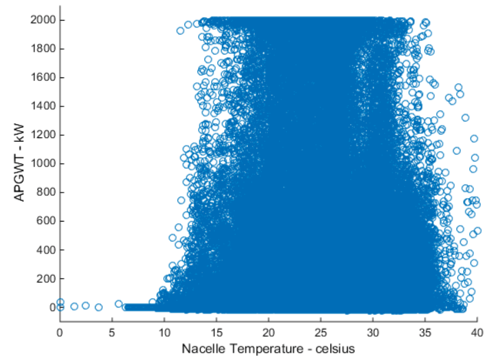
b. Plotting



c. Statistics

- Pearson Correlation

	Active Power
Ambient Temperature	-0.416
Nacelle Temperature	-0.081
Pitch Angle	-0.207
Gearbox Temperature	+0.363
Temperature of Oil in Gearbox	+0.392
Rotor Speed	+0.728
Wind Speed	+0.876

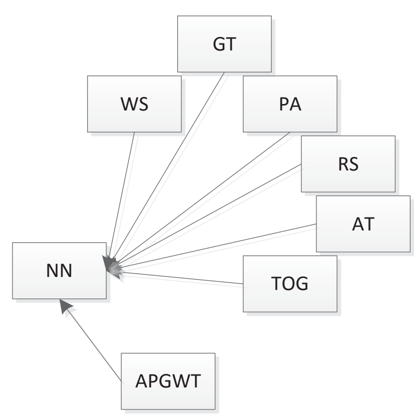


Data Processing

Final parameters to be used in the model training:

- Active Power generated by Wind Turbine (APGWT)
- Pitch Angle (PA)
- Rotor Speed (RS)
- Ambient Temperature (AT)
- Gearbox Temperature (GT)
- Temperature of Oil in Gearbox (TOG)
- Wind Speed (WS)

*NaNs replaced
*Normalized
*Dimension reduced



Anomaly Detection

- Define Anomaly:

  Abnormal behavior; Deviations from expected output

- How many components to analyze the WT? Only one?
  - lacks entire system representation
  - relations among various components are neglected
  - indirect impact on the performance
  - inaccurate modelling
  - incorrect interpretation of outcomes

➡ Power-Curve (active power vs. wind speed)

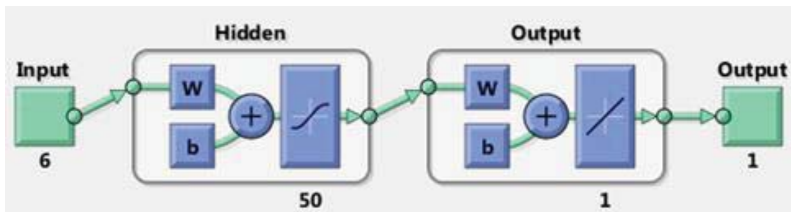
Model Parameters

- What is the optimal configuration for a NN model?
  - input variable (which parameter?)
  - the number of input variables (how many parameters)
  - training methods
  - number of hidden layers (the more the better?)
  - performance evaluation methods (a new complex one?)
  - training time (pick the fastest?)
  - the number of iterations (high or low?)
  - accuracy of the NN (in training, validation, testing)

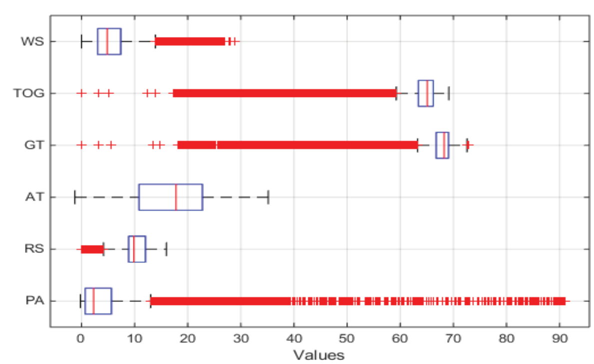
Model Parameters – cntd.

60 different NN models were built

- input: PA, WS, TOG, WS+PA, WS+PA+TOG+RS+AT+GT
- target output: active power generated by the wind turbine
- training method: Scaled Conjugate Gradient (fast, low memory)
- number of hidden layers: 10, 20, 50
- performance evaluation methods: MAE, MSE, SAE, SSE



Training Stage



- training time: Shortest: 1s , Longest: 169s
- the number of iterations: Smallest: 6 , Biggest: 952
- performance:

Best performance: each evaluation method, a different network

- accuracy of the NN (in training, validation, testing, overall):

Lowest: 67.39% , Highest: 99.73%

Training Stage – cntd.

- Optimum model results:

43 iterations; 17s; 99.73%

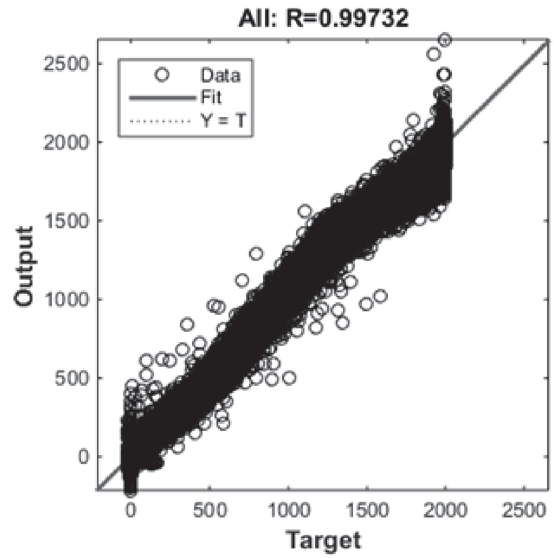
- Optimum configuration:

Input: WS+PA+TOG+RS+AT+GT

Hidden layers: 50#

Performance evaluation method:

SSE (Sum Squared Error)

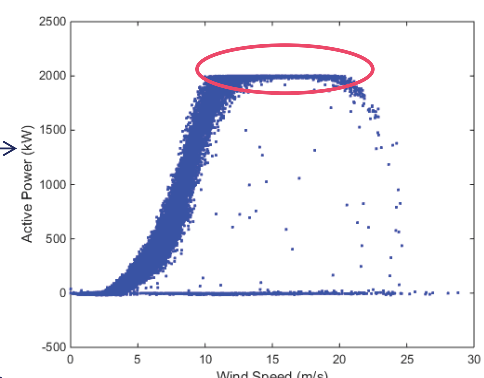


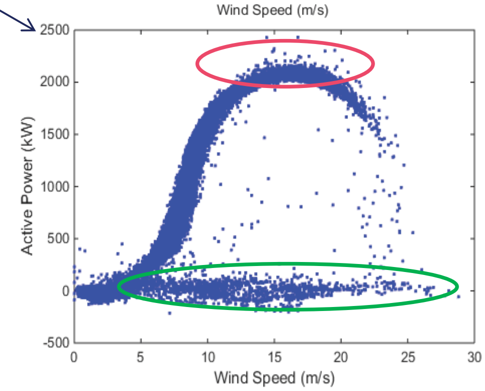
Model Results

Measurements:

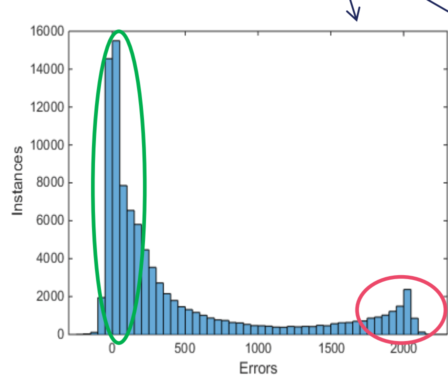
Model Output:

Errors Distribution:





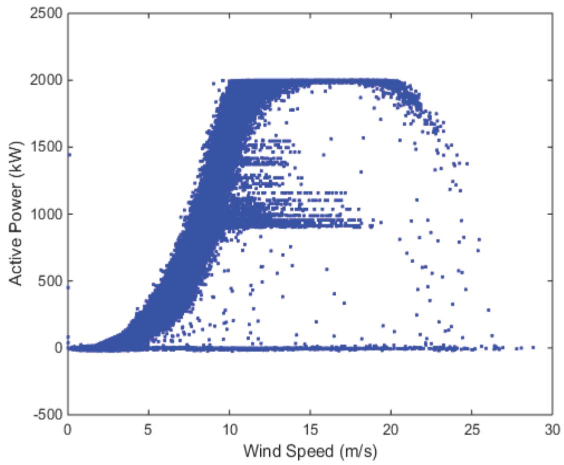
Less accuracy at low power



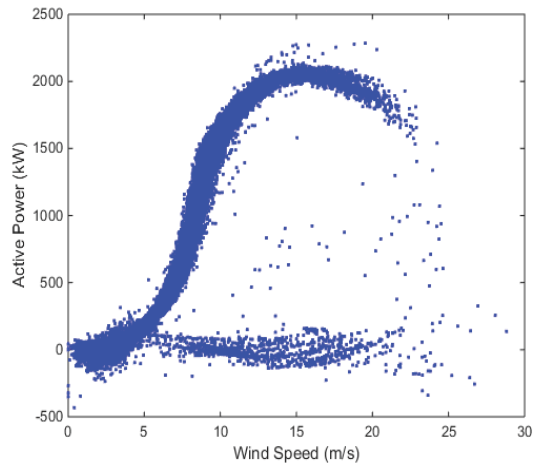
Threshold!

Model Results – cntd.

New Measurements

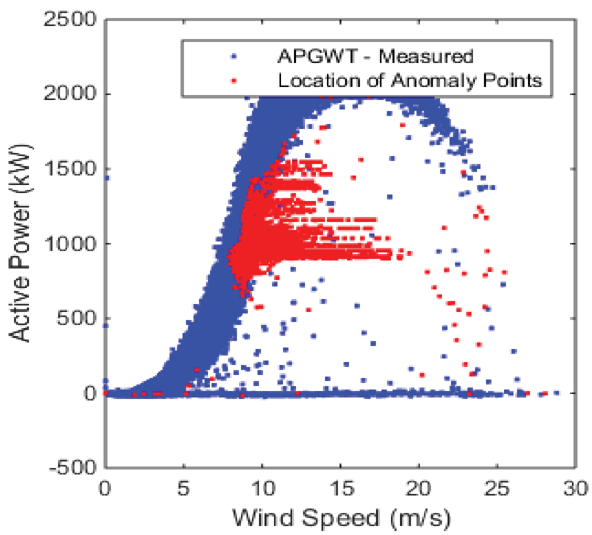


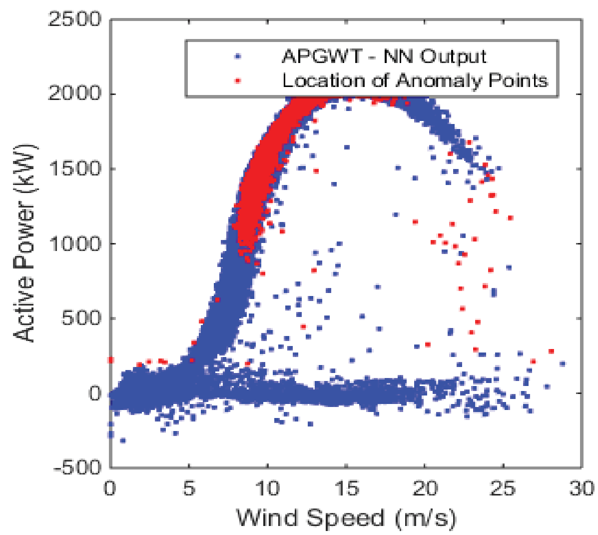
Model Output



Model Results – cntd.

After applying the threshold and comparing the differences:

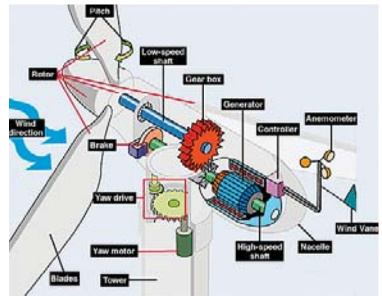


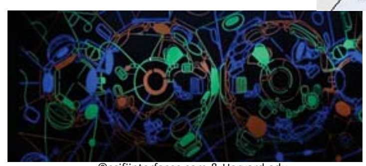


Conclusion

Neural Network Model for WT Anomaly Detection:

- Trained with about 20 months of SCADA data
- Fast learning
- High accuracy
- Real-time application
- Can be very detailed
- Easy to use
- Adaptability
- Under-performance





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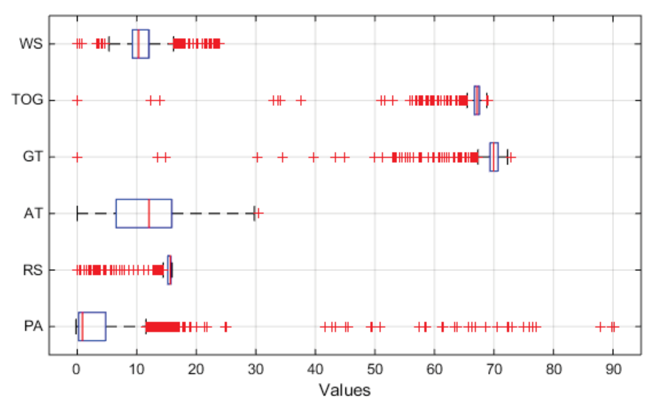
Continued Research

What to do next?
Where to go from here?

- Find the root of an anomaly

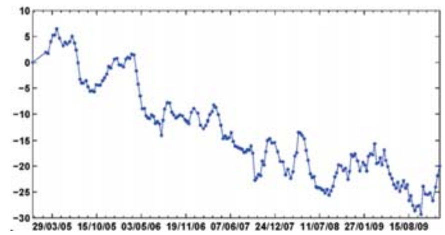
Results from the model :



Continued Research – cntd.

- Trade off between the input data & accuracy
- Increase complexity of the model (impact on noise)
- Performance index
- Development of an anomaly
- Signature identification
- Maintenance quality/impact
- Evolution of the model >> a prognosis model

...



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THANK YOU

Questions?

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Comparisons of Offshore Wind Turbine Reliability

Yizhou Lu, Aristos Christou
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Department of Mechanical Engineering
University of Maryland, College Park MD USA
lyz75820@gmail.com, christou@umd.edu

The results of a comparative probabilistic reliability model applied to offshore wind turbine systems is presented. The model calculations are based on surrogate failure rate data from industrial onshore wind turbine technologies, related marine environment technologies and generic databases. Data are adjusted for the offshore marine environment and integrated with functional as well as reliability block diagrams. The developed models are applied to five generic horizontal-axis offshore wind turbine designs. Predicted subsystem failure rates and total system failure rates are reported and critical reliability limiting sub-assemblies are identified.

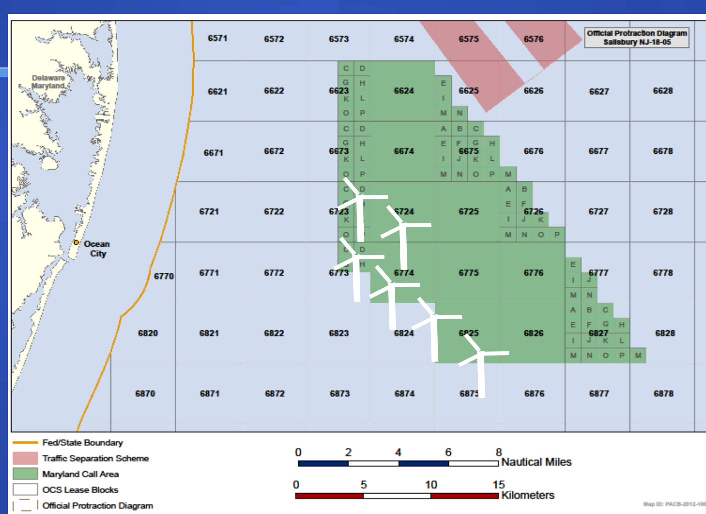
Comparison of Offshore Wind Turbine Reliability

Yizhou Lu and A. Christou

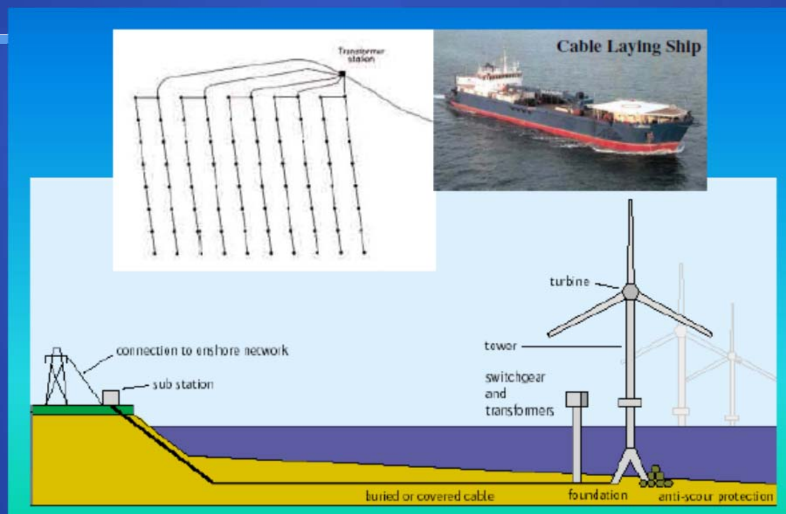
University of Maryland

College Park MD

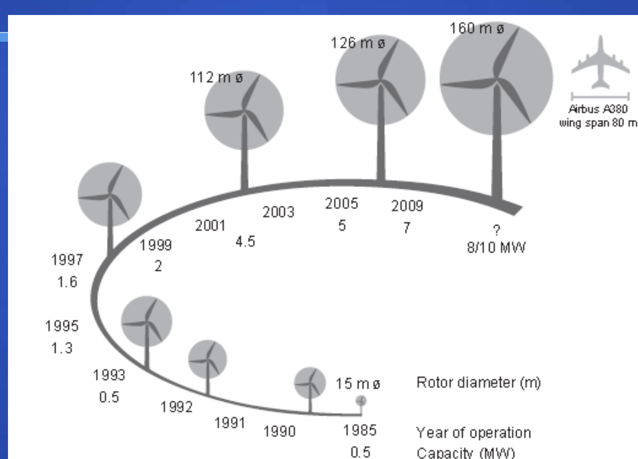
Maryland Context



Typical Offshore Wind Farm Layout



Growth in size of Commercial WT Designs (from EWEA)



Off Shore Access is Difficult, and Costly: Require Minimum Maintenance and High Reliability

The "Marine Environment"

- The "marine environment" refers to the physical, chemical, and biological stressors acting on offshore wind turbines
- The primary concern is the effect of salt and moisture content, as sea water, sea air, or salt spray, on corrosion of the electronics.
- This concern is partially mitigated by the practice of "normalizing the turbine internal atmospheric environment" by removing salt from all air inflows and providing a positive pressure
- There are, however, other physical and electrical stresses related to location offshore that can cause failures as well.
  - highly variable temperatures
  - powerful storms and lightning strikes.
- These can cause failures resulting from solder fatigue due to temperature cycling or due to the shock or vibration caused by high winds or waves during storms.

Main Issue is Reliability and Maintainability

- Develop reliability models for comparison of key technologies.
- Integrate Physics of Failure Models to Predict Reliability
- Assess life expectancy of wind turbine hardware under anticipated life cycle loading conditions and accelerated stress test conditions.
- Predict Effect of turbine degradation on grid performance

OWT Reliability

- Main question - which OWT architecture is most reliable and more appropriate for a specific site?
- What might go wrong? How does failure affect grid connections
- Root Causes & Failure mechanisms?
- Reliability prediction and comparison?
- Predicted failure rates?

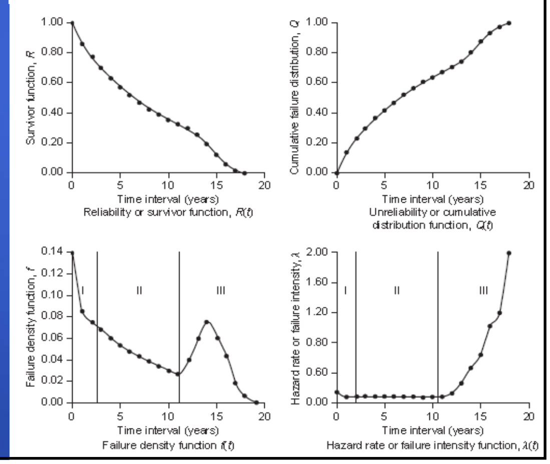
Reliability Concept

Probability density function and Reliability function assuming Weibull distribution

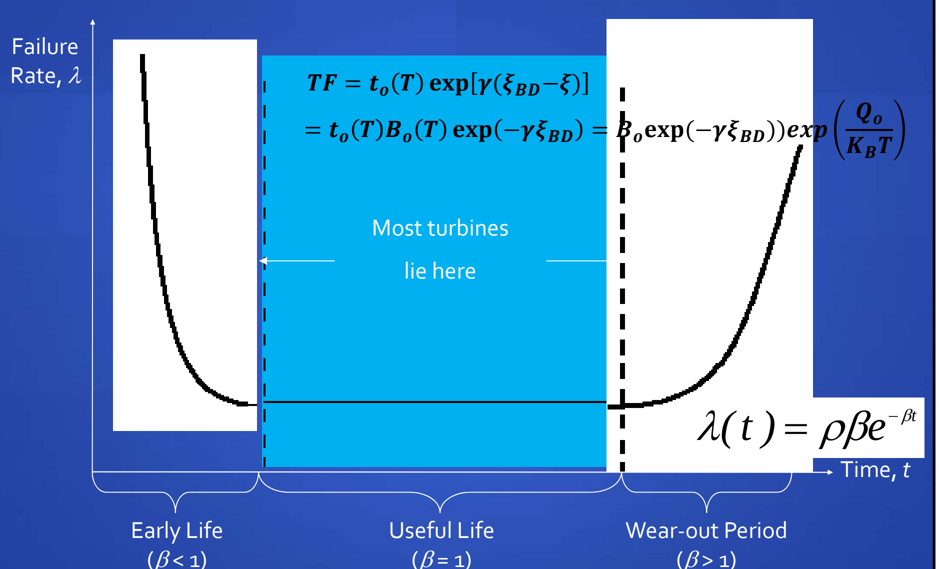
$$f(t) = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

$$R(t) = \int_t^{\infty} f(\theta)\, d\theta = \int_t^{\infty} \frac{\beta \theta^{\beta-1}}{\alpha^{\beta}} e^{-\left(\frac{\theta}{\alpha}\right)^{\beta}} d\theta = - e^{-\left(\frac{\theta}{\alpha}\right)^{\beta}} \Big|_t^{\infty}$$

Empirical Reliability Functions from 1000 OSW Turbines



Failure Rate over the WT Life

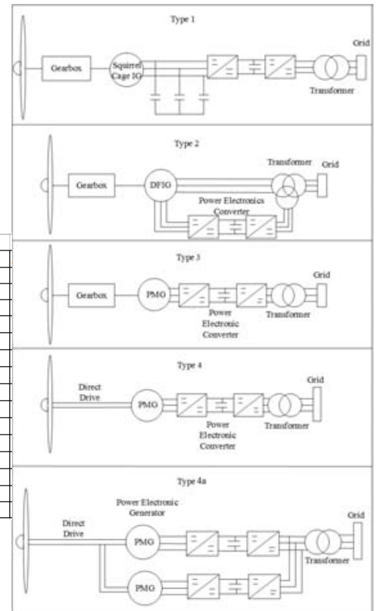


Reliability Comparison Models for Offshore Wind Turbines(OWT)

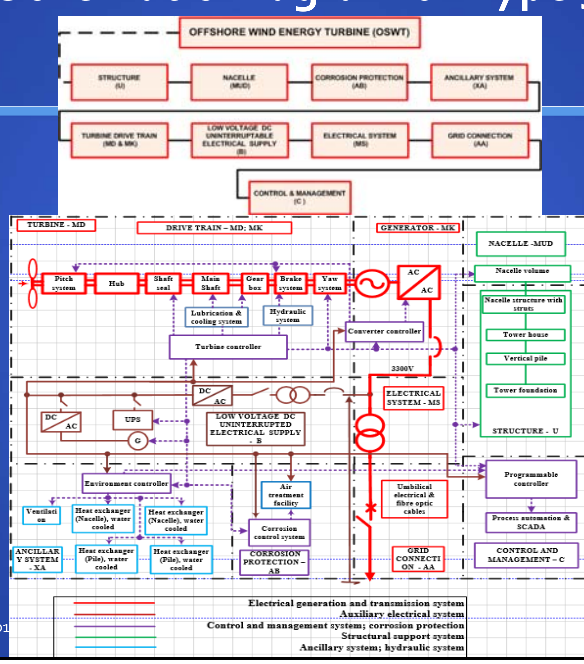
- 5 Types of OWTs (Types1-4a) were chosen for reliability modelling using Reliability Block Diagrams and Parts Count Prediction technique, based on surrogate data from wind turbines, marine and other generic databases

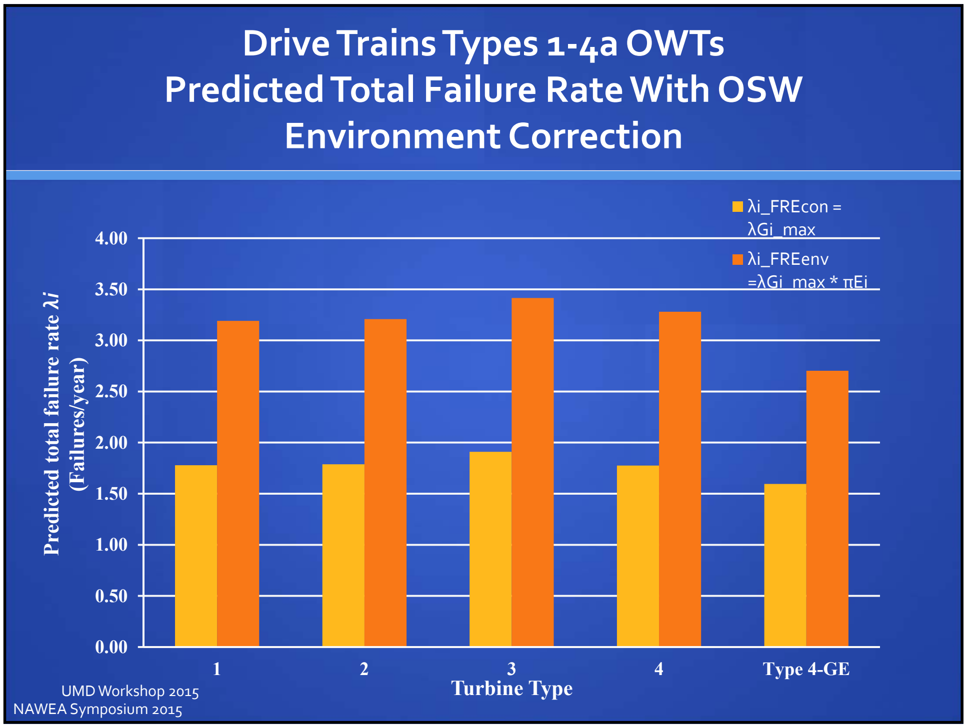
Table: Concept Types

Concept type	Drive train configuration	Manufacture	Turbine	Power MW
Type 1	GB + IG	Siemens	SWT-3.6-107	3.60
			SWT-3.6-120	3.60
			SWT-4.0-130	4.00
Type 2	GB +DFIG	Vestas	V90-3.0	3.00
		General Electric	GE 3.6	3.60
		Senvion	5M	5.00
			6.2M126	6.15
			6.2M152	6.15
Type 3	GB+PMG	Vestas	V112-3.3	3.30
			V164-8.0 MW® IEC S	8.00
		AREVA	M5000-116	5.00
			M5000-135	5.00
Type 4	PMG+Direct Drive	NORDEX	N150/6000	6.00
Type 4a	2 PMG*+Direct Drive	General Electric	GE 4.1-113	4.10
		Siemens	SWT-6.0-154	6.00



Schematic Diagram of Type 3




Drive Trains Types 1-4a OWTs
Predicted Total Failure Rate With OSW Environment Correction
λi_FREcon = λGi_max
λi_FREenv =λGi_max * πEi
Predicted total failure rate λi (Failures/year)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1
2
3
4
Type 4-GE
Turbine Type
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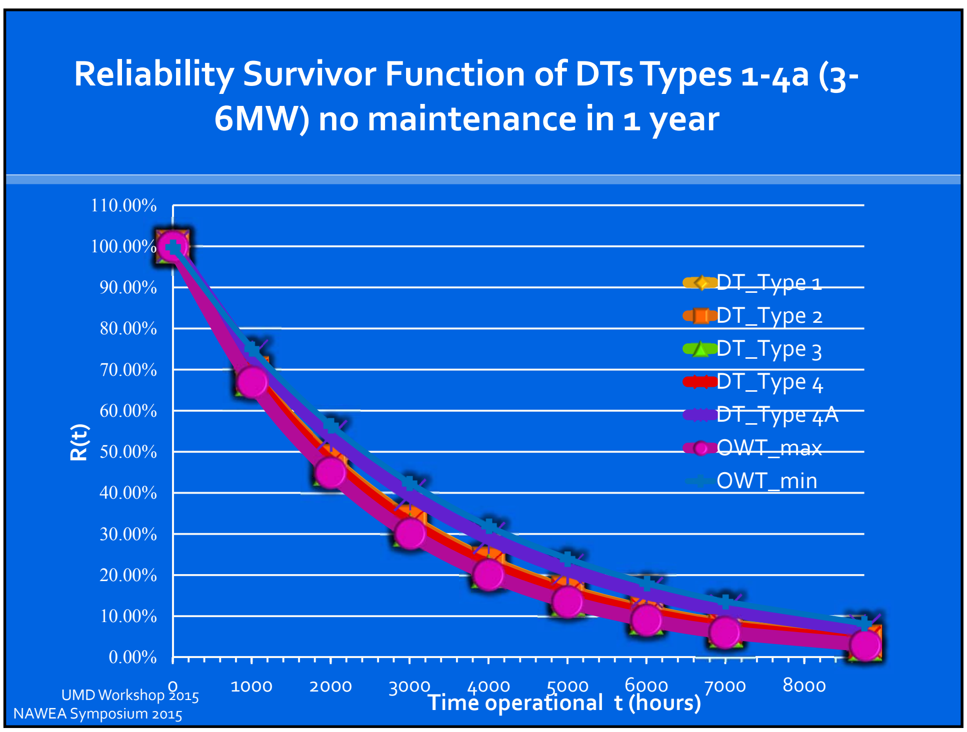
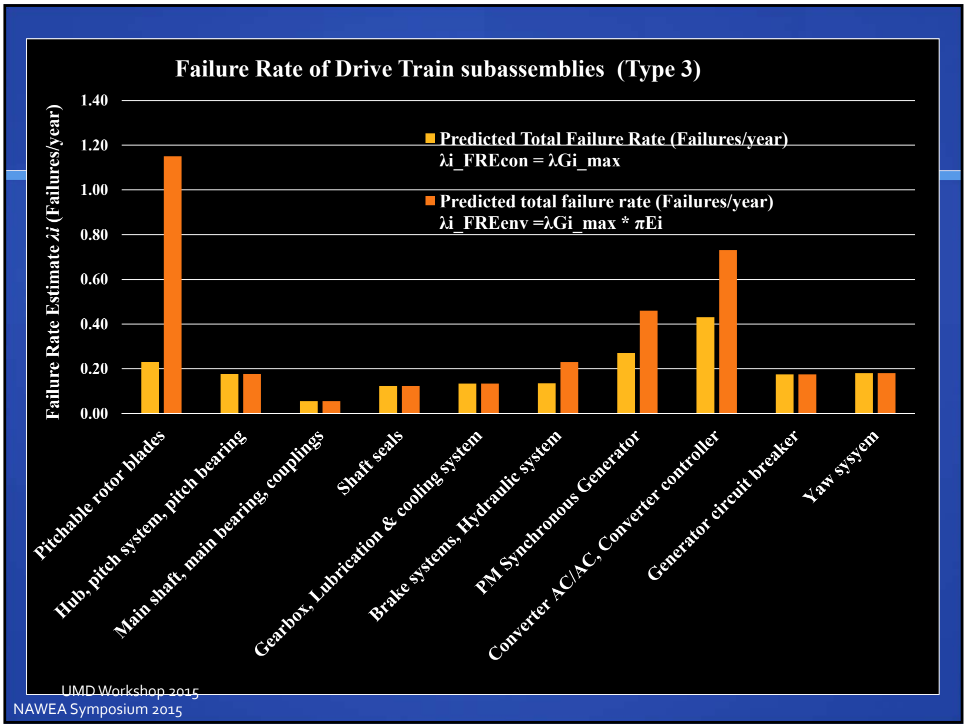
NAWEA Symposium 2015


Reliability Survivor Function of DTs Types 1-4a (3-6MW) no maintenance in 1 year
110.00%
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
R(t)
DT_Type 1
DT_Type 2
DT_Type 3
DT_Type 4
DT_Type 4A
OWT_max
OWT_min
0
1000
2000
3000
4000
5000
6000
7000
8000
Time operational t (hours)
UMD Workshop 2015
NAWEA Symposium 2015



Failure Rate of Drive Train subassemblies (Type 3)
Failure Rate Estimate λi (Failures/year)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Predicted Total Failure Rate (Failures/year)
λi_FREcon = λGi_max
Predicted total failure rate (Failures/year)
λi_FREenv =λGi_max * πEi
Pitchable rotor blades
Hub, pitch system, pitch bearing
Main shaft, main bearing, couplings
Shaft seals
Gearbox, Lubrication & cooling system
Brake systems, Hydraulic system
PM Synchronous Generator
Converter AC/AC, Converter controller
Generator circuit breaker
Yaw sysyem
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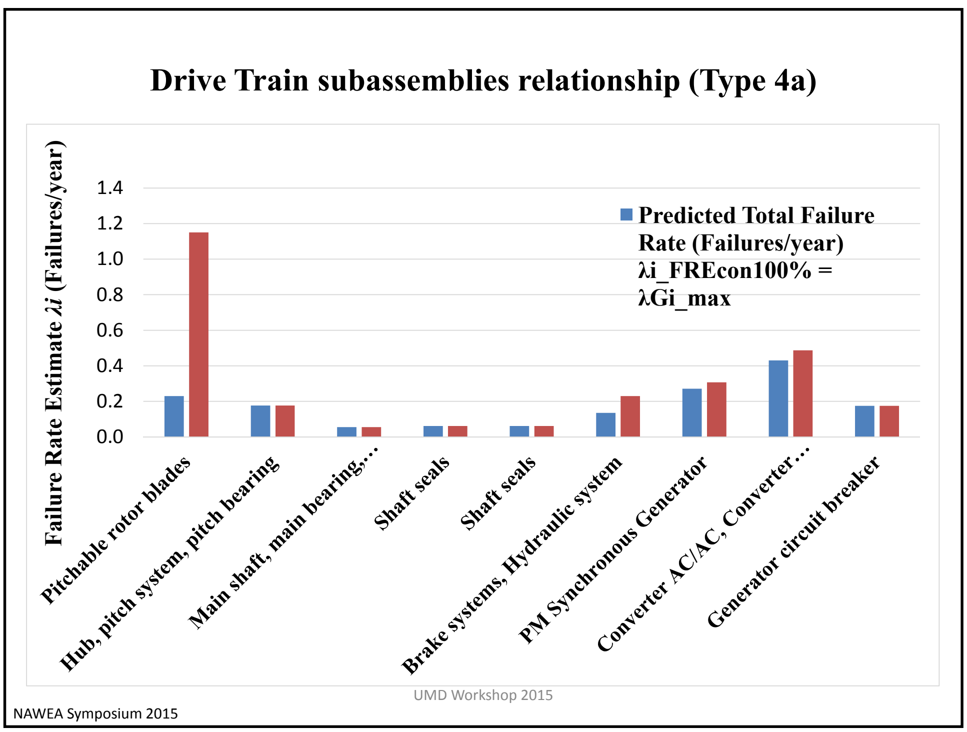

Drive Train subassemblies relationship (Type 4a)
Failure Rate Estimate λi (Failures/year)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Predicted Total Failure Rate (Failures/year)
λi_FREcon100% =
λGi_max
Pitchable rotor blades
Hub, pitch system, pitch bearing
Main shaft, main bearing,…
Shaft seals
Shaft seals
Brake systems, Hydraulic system
PM Synchronous Generator
Converter AC/AC, Converter…
Generator circuit breaker
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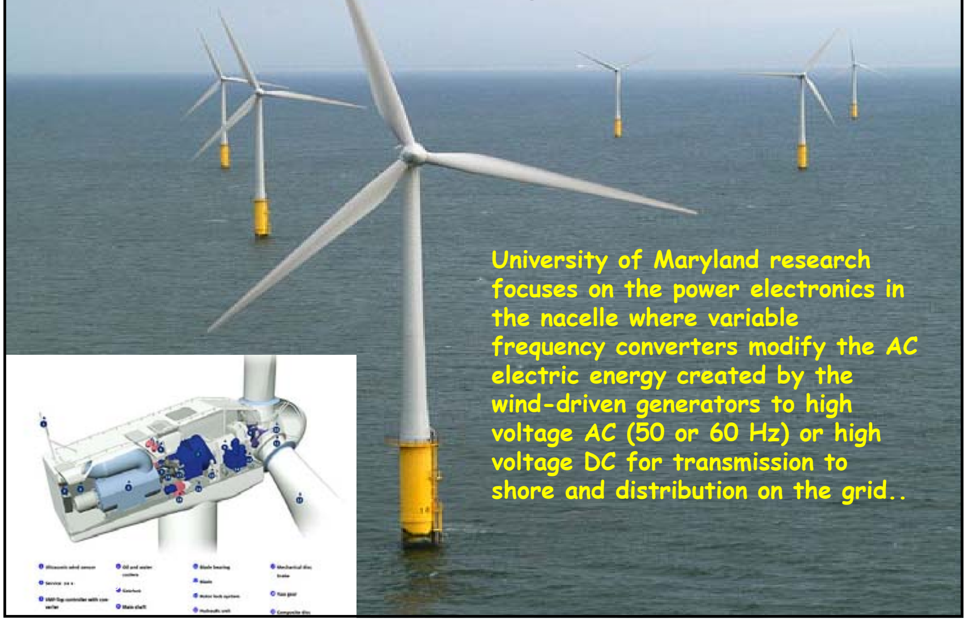
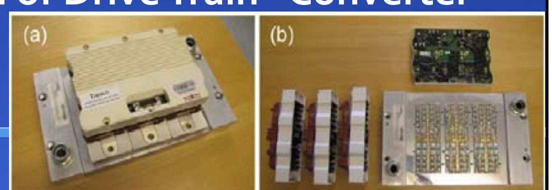
Power electronics are an integral part of offshore wind turbine energy production



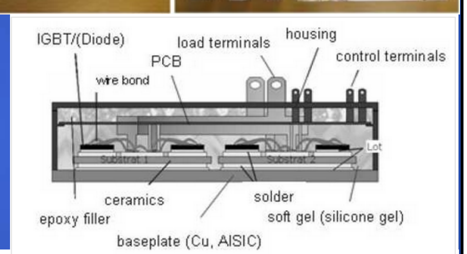
University of Maryland research focuses on the power electronics in the nacelle where variable frequency converters modify the AC electric energy created by the wind-driven generators to high voltage AC (50 or 60 Hz) or high voltage DC for transmission to shore and distribution on the grid..

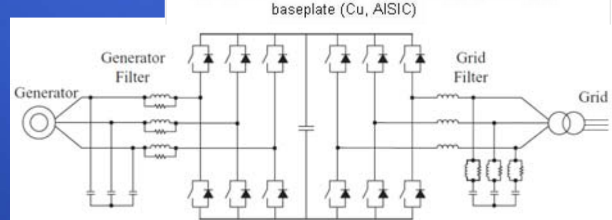
Critical Subsystem of Drive Train--Converter



Converter Module with driver board, connections, housing, and power electronic chips with heat sink.

Failure Mechanisms:
Corrosion of interconnects,
Bond wire liftoff,
Electromigration and
Solder Joint Fatigue





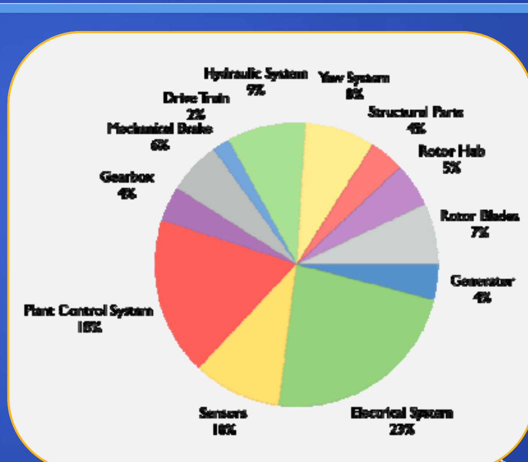
Back to back connected power module

Addressing Corrosion Failures

- Design information has been collected for power electronics used in offshore wind turbines.
- Developed models and mitigation approaches for key failure mechanisms in power electronics in marine environments:
  - Electrochemical Migration on Power/Gate Driver Boards
  - Conductive Filament Formation in Power Boards
  - Corrosion of the Direct Bond Copper (DBC) Substrate
  - Corrosion of Copper Leads

Failure Sites

- Statistical failure studies indicate electronics are a major cause of unscheduled maintenance.
- Electronics have short repair times but harsh environmental conditions can make wind turbines inaccessible.
- Power Electronic Failures can propagate to the grid.



Corrosive Environments and Interconnect Corrosion: Copper Interconnects

- Structures located over or within 2500 feet of a body of water containing chloride above 2000 ppm are considered to be marine structures.
- Marine environments are characterized by sodium chloride that is easily carried by sea spray, mist or fog.
- Temperature, relative humidity, and wet/dry time all effect the corrosion potential
- Corrosion of copper in the atmosphere results in a thin layer of corrosion, typically referred to as the patina.
- Higher concentrations of chlorides in marine air ~~cause~~ copper to acquire a patina sooner than other locations.
- The rate of copper corrosion layer formation varies in different environments:
  - Land ≈ 0.5 µm/year
  - Marine ≈ 1 µm/year

Conclusions: OSW Reliability Research

- Significant reliability problems remain
  - Off-shore posseses new challenges
  - Present investigations is a start in understanding the offshore environment and reliability of wind turbines.
- Future Work: System level impact of corrosion, fatigue and Power Electronics Issues
- Research into ways to resist corrosion
  - Extend Reliability Models to Multiple OSW Configurations, Through System Fault trees and Dynamic Baysian Analysis
  - Incorporate refined CALCE Physics of Failure Models

LCOE of Offshore Wind Farms - Identification & Reduction

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Netherlands
dewan@ecn.nl

Wind industry is a rapidly growing industry with huge potential and massive developer interest. 2014 was a record year for the wind industry as annual installations crossed the 50 GW mark for the first time. The global wind sector saw investments rise 11% to a record $99.5bn during the same period. The possibility of offshore wind is enormous. It could meet Europe's energy demand seven times over and the United States energy demand four times over. However, with the potential it has, the economics of offshore wind farms are currently less favorable than onshore wind farms. While electricity from onshore wind farms at windy sites can almost compete with the cheapest fossil fuel based electricity production, offshore wind farms still need significant cost reductions in order to so compete. The larger costs are due to large investment costs. Also operation and maintenance costs are higher than for onshore farms. Thus, policy makers, energy companies and the wind turbine industry need to know the total cost reduction potentials and trends of offshore wind farms, including technological developments, and when these may be achieved.

LCOE (Life Cycle Cost of Energy) for the offshore wind farms can definitely be reduced significantly. EU (European Union) aims to reduce the cost of offshore energy by as much as 40% by 2020. When reducing the LCOE, it is important to not only concentrate on individual wind turbine components, but the entire wind farm optimization. The different components of this cost are- Annual energy production, Capital Expenditure (CAPEX), Operational Expenditure (OPEX), Weighted Average Cost of Capital (WACC) and Lifetime extension. Change in 10% of either of the cost components can lead to a reduction of 2-9% in the LCOE for offshore wind farms.

OPEX, being one of the key identifier of the LCOE can be optimized during the operational phase by following a smart and integral solution. Monitoring the wind farm parts, obtaining reliable maintenance and production forecasts, shifting to predictive maintenance are all keys factors leading to a reduction of OPEX and hence LCOE. Further, structuring and analyzing maintenance information to get relations between events and maintenance actions are all causes for better O&M approach. Moreover, it is of significant purpose to keep evaluating the O&M strategy with the data that is gathered in form of structured maintenance reports. This will in turn help to estimate the near-future O&M costs to identify the most viable options for improving availability and reducing costs. A case study done for optimizing the O&M strategy on a real wind farm in North Sea led to 10% reduction in OPEX, leading to 1.7% reduction in LCOE.

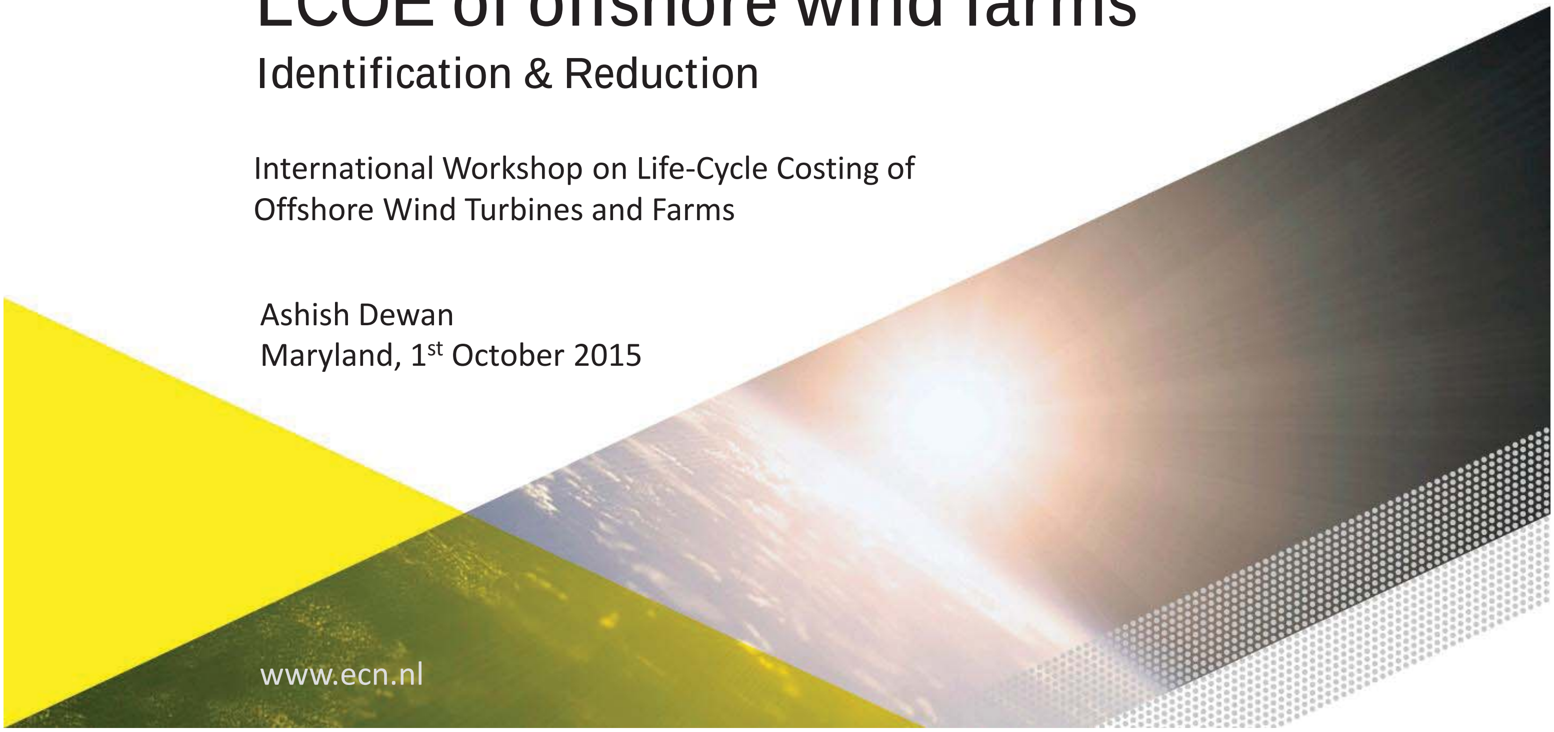
To conclude, offshore wind energy besides being expensive, has the potential to lower its overall cost by following an integral wind farm optimization procedure.

LCOE of offshore wind farms

Identification & Reduction

International Workshop on Life-Cycle Costing of Offshore Wind Turbines and Farms

Ashish Dewan
Maryland, 1st October 2015



Contents

- ECN in general
  - ECN at glance
  - Research activities (WE)
- Integral Wind farm design
- Lowering LCOE
  - Increasing Yield
  - Reduction of CAPEX & Cost of Capital
  - Lifetime Extension
  - Reduction of OPEX
- O&M System
  - O&M Data Analysis
  - O&M Cost Modelling
- Case Studies
  - RWE Case Study
  - North Sea Case study

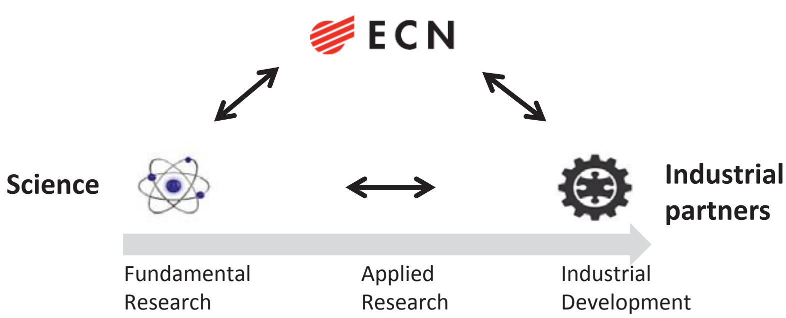
ECN at a glance

Founded in 1955
5 Commercial licensing deals p/y
600 Employees
+/-20 patents a year
€ 80 M annual turnover

ECN Focus Areas

Solar energy	Biomass	Policy studies	Energy efficiency	Wind energy	Environment & energy engineering

ECN acts as a bridge between science and corporate innovation



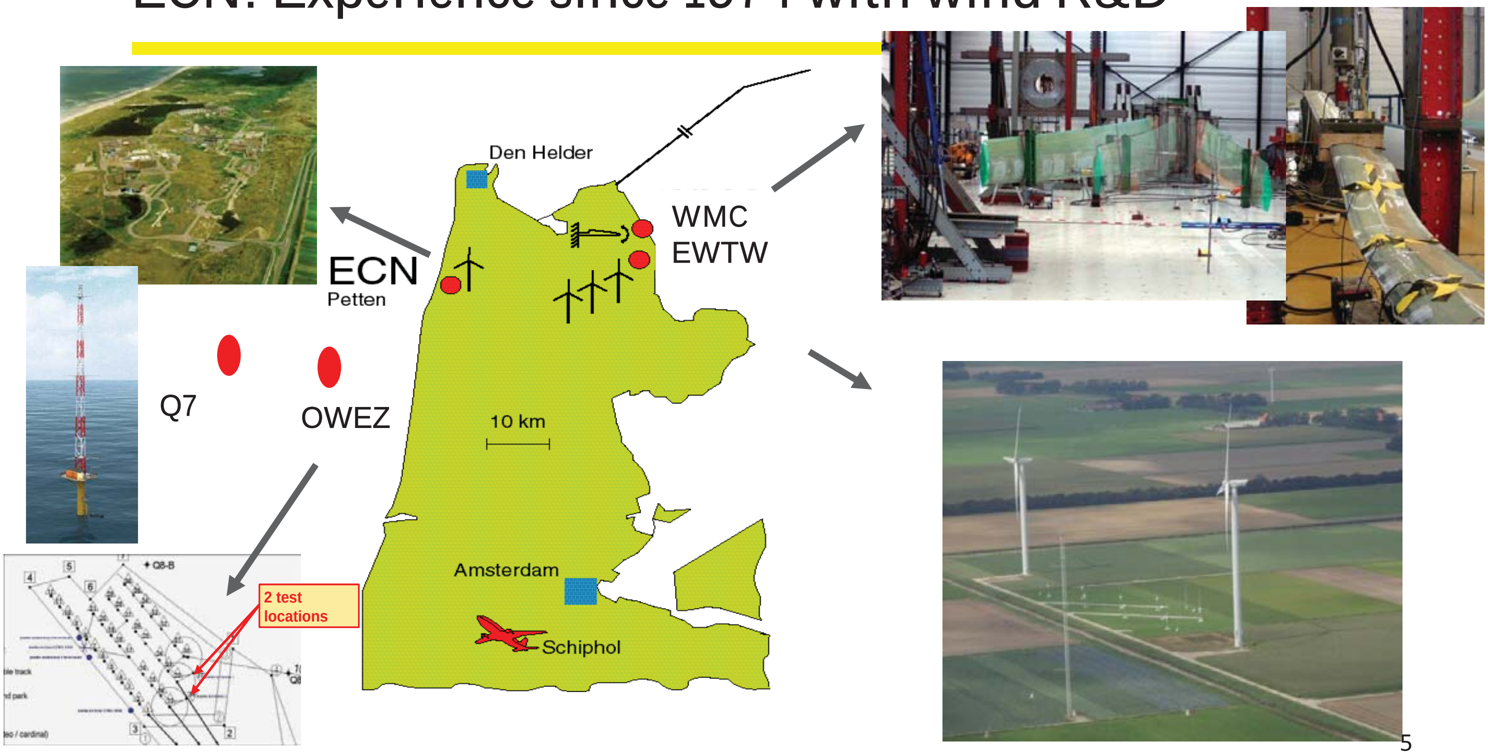
What we do

- Problem Solving
- Technology development
- Studies & Policy Support

How we can work with you

- Consultancy & Services
- Contract R&D
- Tech development & Transfer
- Joint Industry Projects

ECN: Experience since 1974 with wind R&D

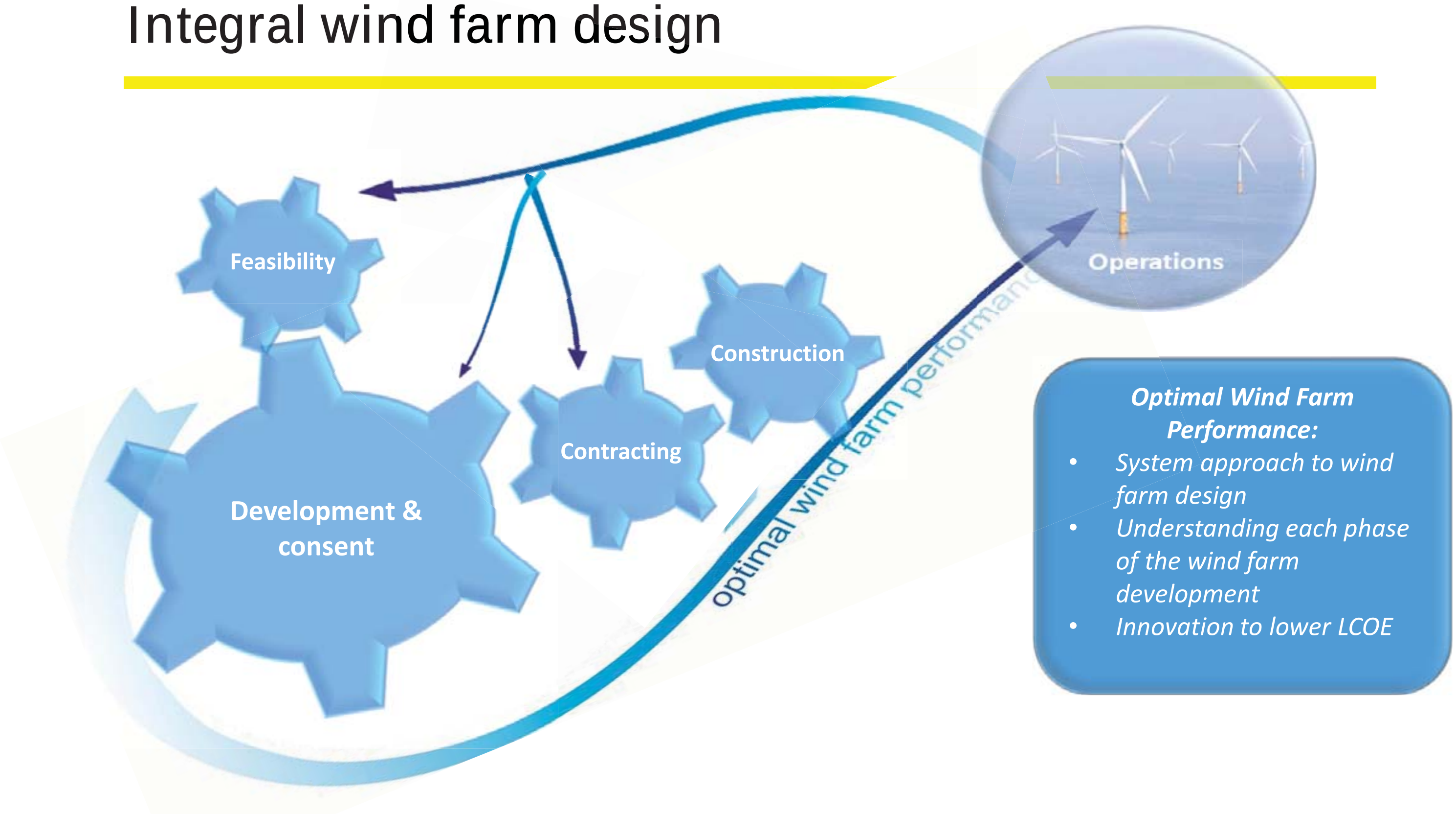


Europe's offshore Wind Energy market: The Dutch Experience

North Hoyle	2003	60
Arklow Bank	2004	25
Scroby Sands	2004	60
Kentish Flats	2005	90
OWEZ	2006	108
Barrow	2006	90
Lillgrund	2007	110
Burbo Bank	2007	90
Prinses Amalia	2008	120
Inner Dowsing	2009	97
Lynn	2009	97
Rhyl Flats	2009	90
Horns Rev II	2009	209
Robin Rigg	2009	180
Gunfleet Sands	2009	173
Alpha Ventus	2010	60
Belwind I	2010	165
Rødsand II	2010	207
BARD 1	2010	400
Thanet	2010	300
Walney I	2010	184
Greater Gabbard	2010	504
EnBW Baltic I	2010	630
Ormonde	2011	150
Sheringham Shoal	2011	317
Walney II	2011	184
London Array	2011	185
Thornton Bank II	2012	48
Anholt	2013	111
Thornton Bank III	2013	400
Lincs	2013	270
Borkum West II	2014	200

ECN Involvement

Integral wind farm design



Putting LCoE into context

The simplified cost equation is :

$$LCoE = \frac{\left(\frac{CapEx}{a} + OpEx\right)}{AEP}$$

Where (Reference values 2010 FID)

CAPEX = Capital requirement
= 4600 €/kW

OPEX = Annual operational cost
= *125 €/kW/year*

a = Annuity = $\left(1-(1+r)^{-n}\right)/r$

r = average discount rate

n = economic lifetime = 15 years

AEP based on Load Factor of 47,5%

Parameter variations show that =>

Capital Cost Assumptions

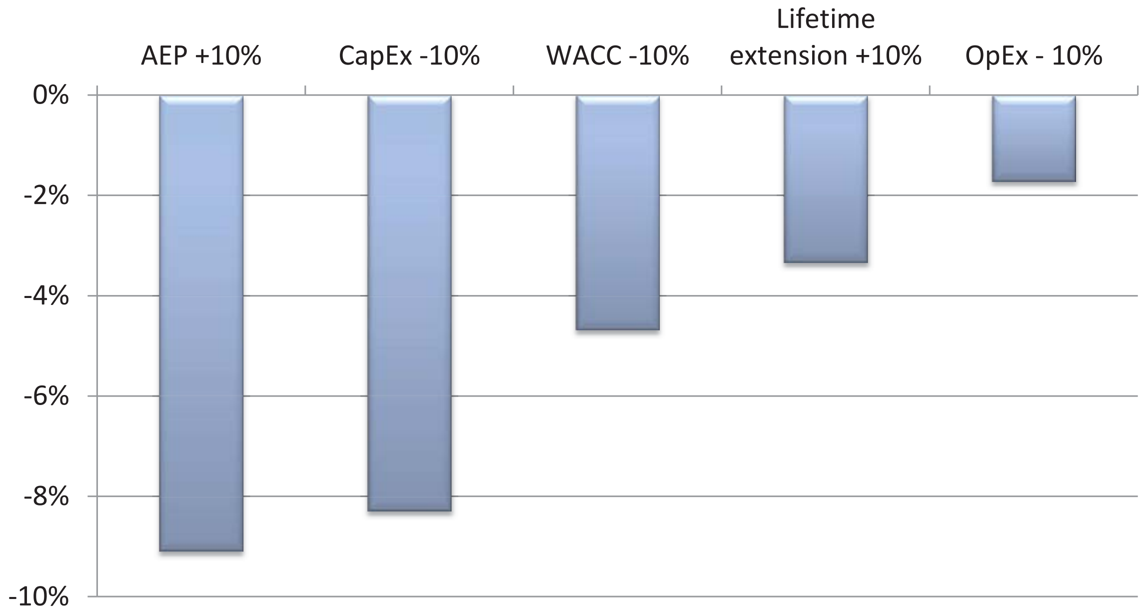
		interest /IRR
Equity	33,3%	15%
Debt	66,7%	7,5%
Average discount rate		10,0%

	variation	reference price € /MWh	LCoE variation
		€ 175	
AEP	10%	€ 159	-9,1%
CAPEX	-10%	€ 161	-8,3%
WACC	-10%	€ 167	-4,7%
Lifetime Extension	+10%	€ 169	-3,3%
OPEX	-10%	€ 172	-1,7%

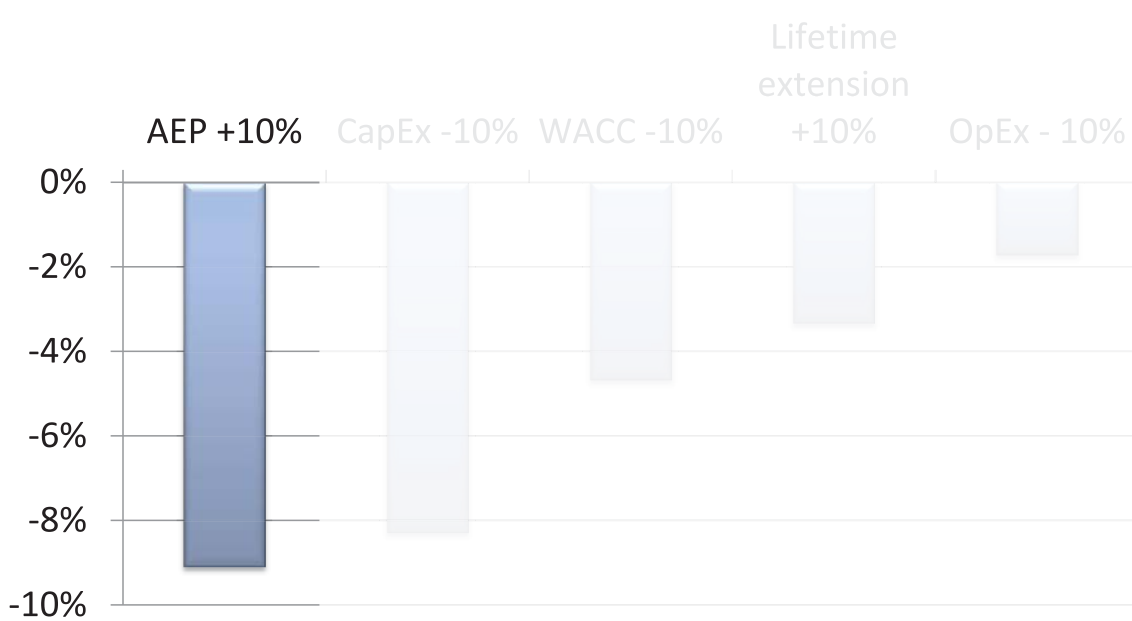
So AEP and CAPEX have the highest influence!

Lower LCoE, what to target?

Sensitivity of LCoE for 10% changes in Cost Components



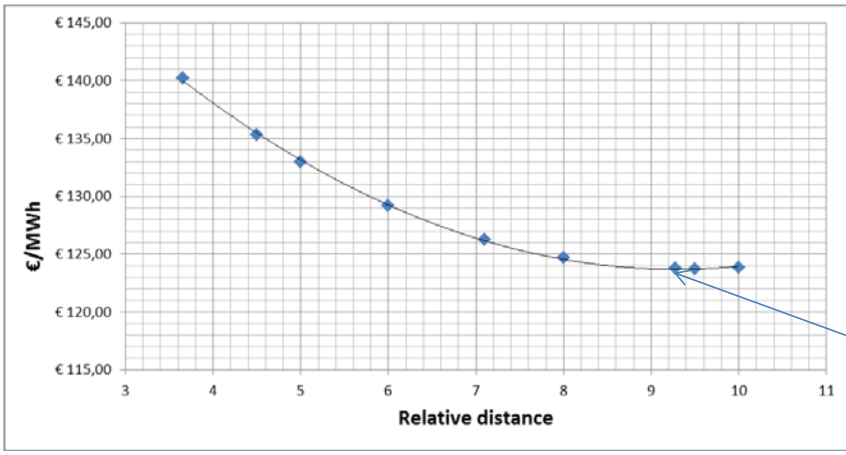
Lowering LCOE: Increasing Yield



ECN

Lowering LCOE: Increasing Yield

Finding the sweet spot – layout (wake) vs electrical costs
1 GW Wind farm, 100 large scale WT's, in high wind speed regime.

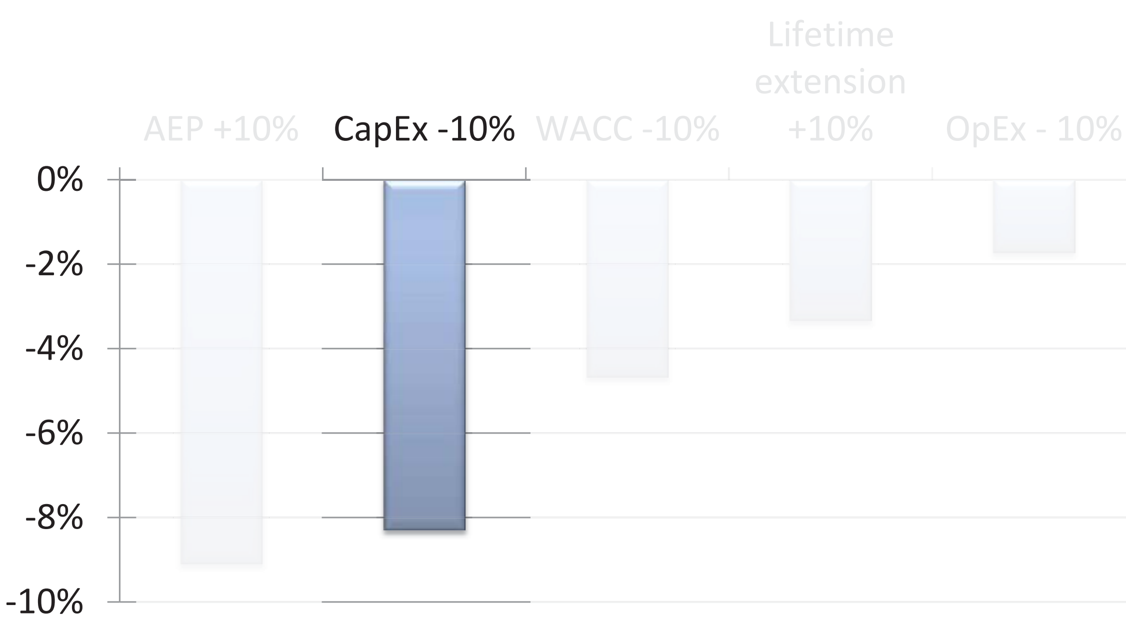


Optimum for this site 9,25 D

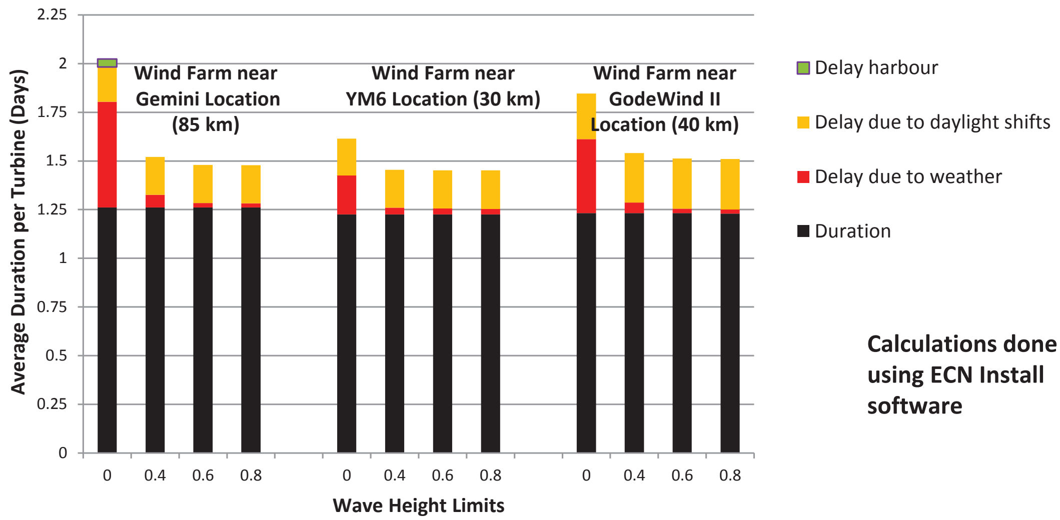
Cost reduction from 6 D spacing to optimal spacing - 6%

ECN

Lowering LCOE: Reduction of CAPEX



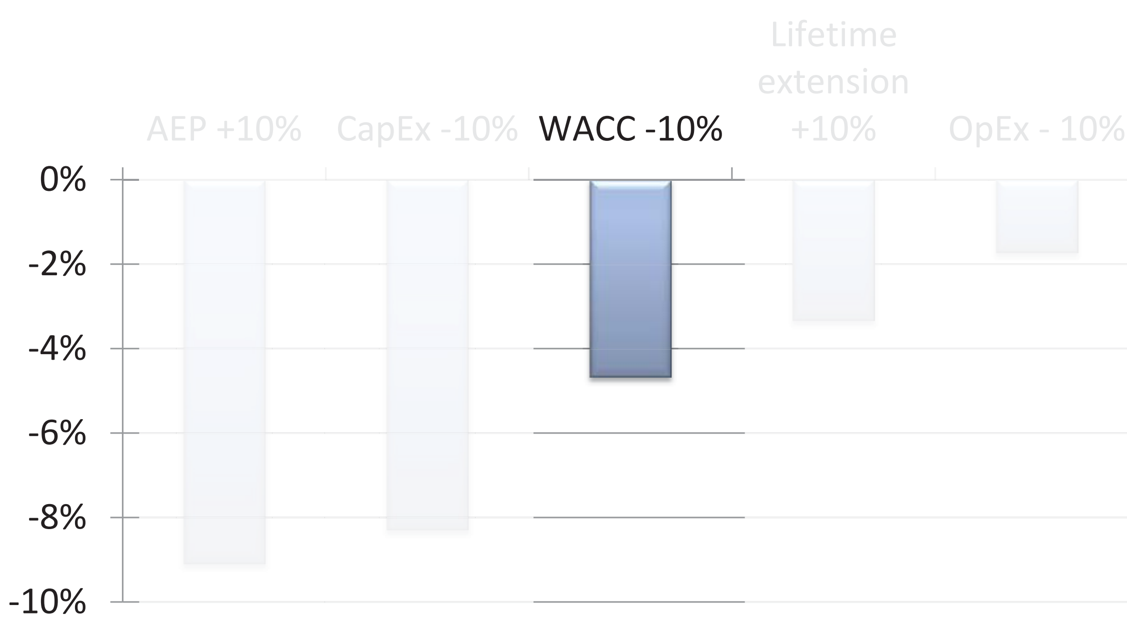
Lowering LCOE: Reduction of CAPEX



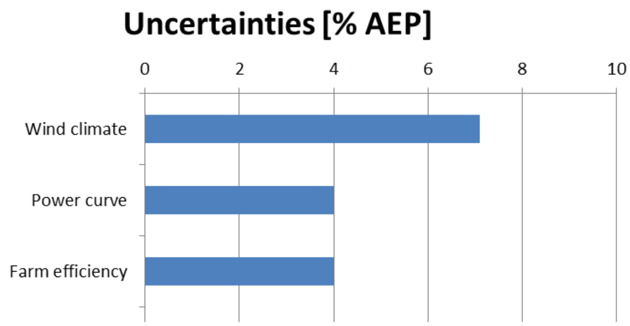
Calculations done using ECN Install software

Cost reduction with breakwaters concept - 4%

Lowering LCOE: Reduction of Cost of Capital

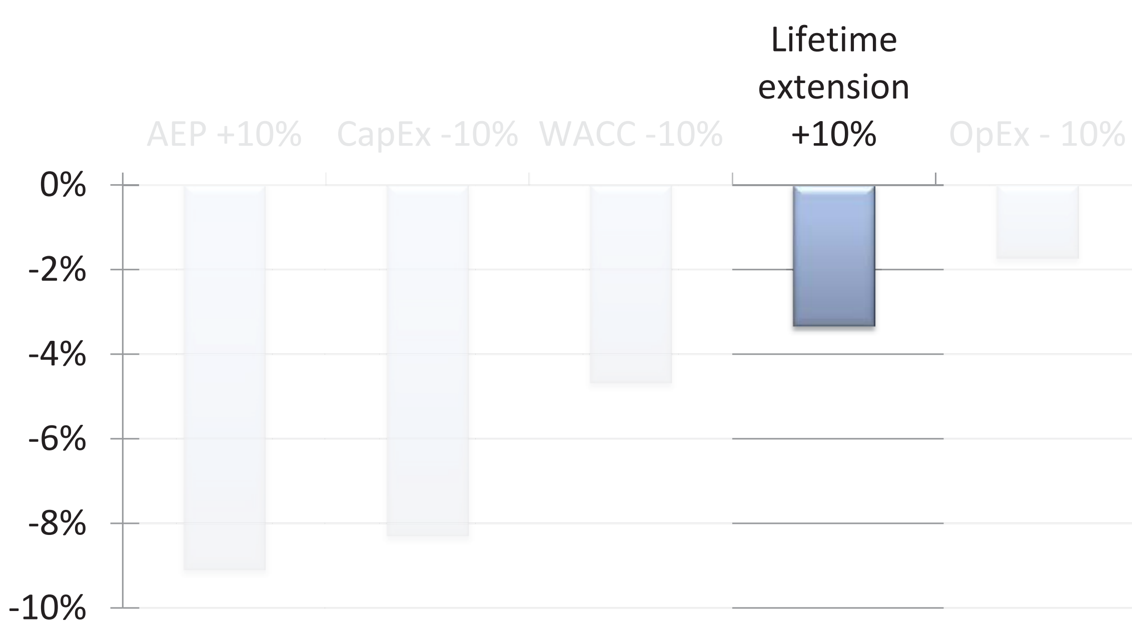


Lowering LCOE : Reduction of Cost of Capital



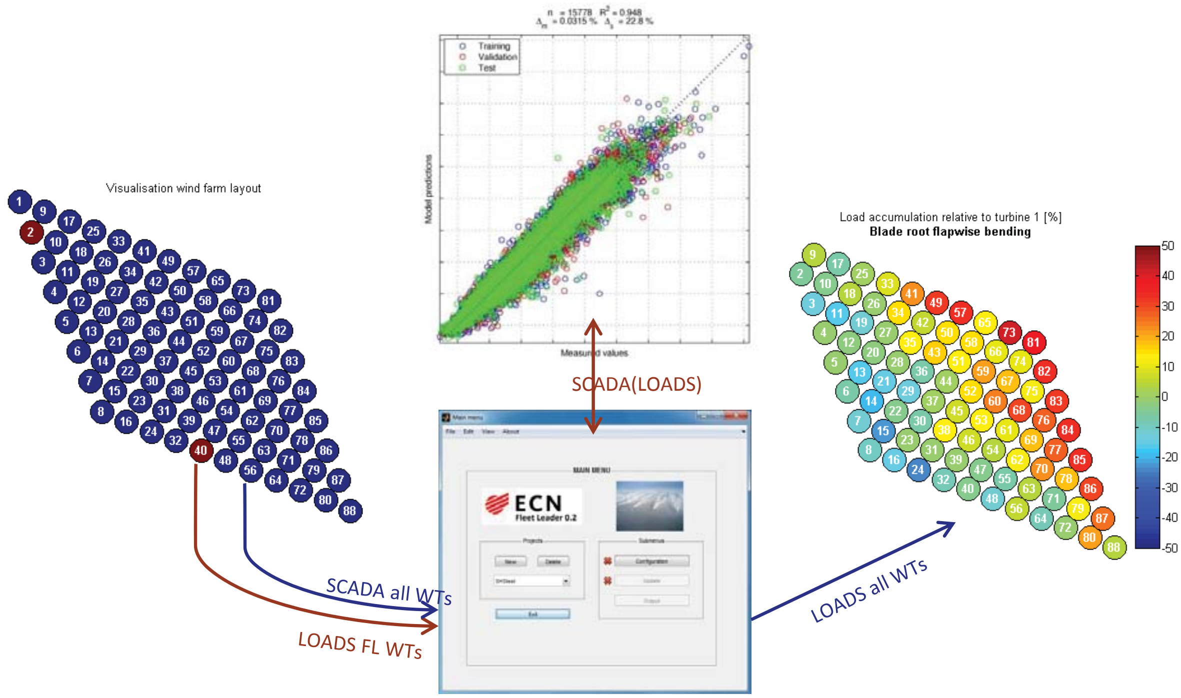
- **Wind climate**:
  Onsite measurements with latest technolgies to reduce the ratio P50/P90
- **Power Curve**:
  Verification through Metmasts & LiDAR measurements on site
- **Farm efficiency:**
  Computation of Yield calculation & Electrical losses of the wind farm

Lowering LCOE: Lifetime Extension



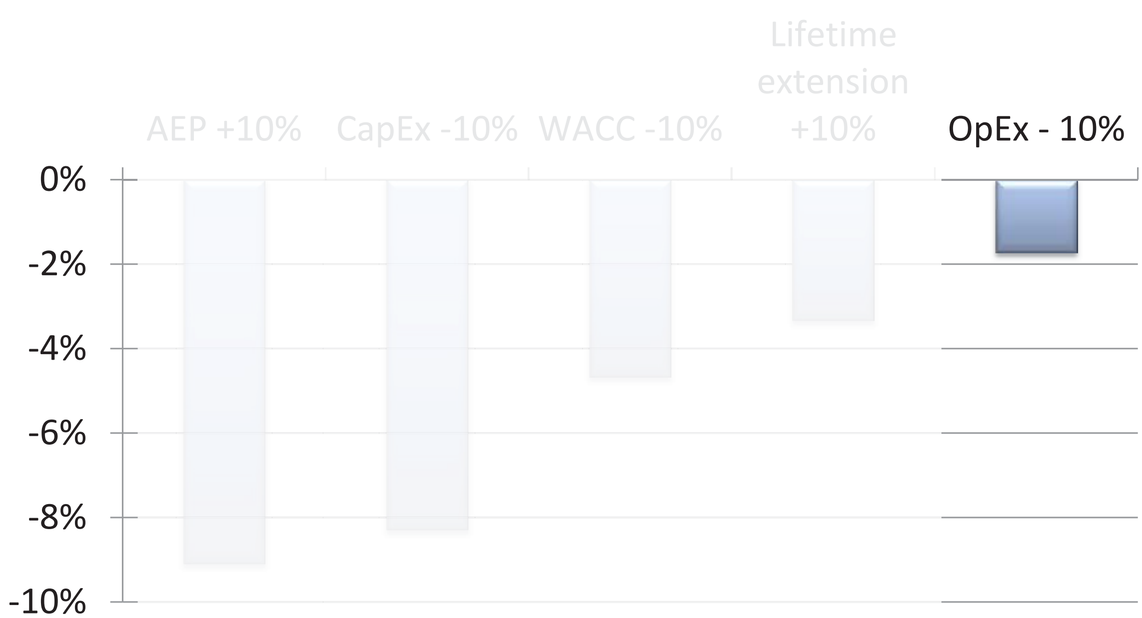
ECN

Lowering LCOE: Lifetime Extension

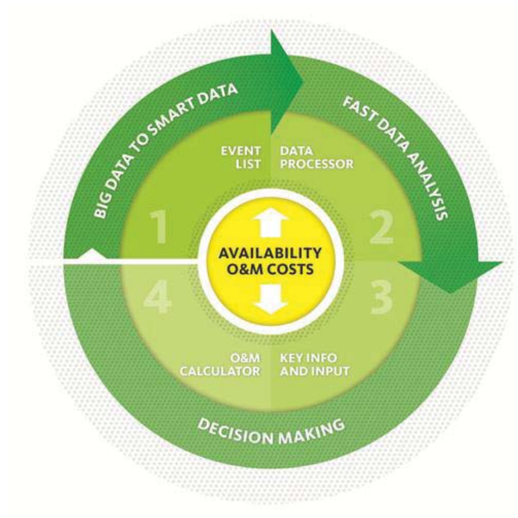


ECN

Lowering LCOE: Reduction of OPEX

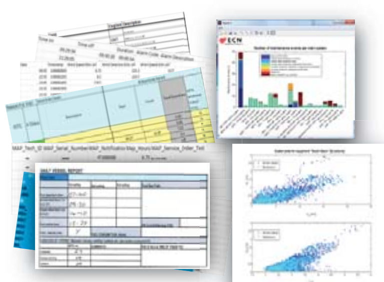


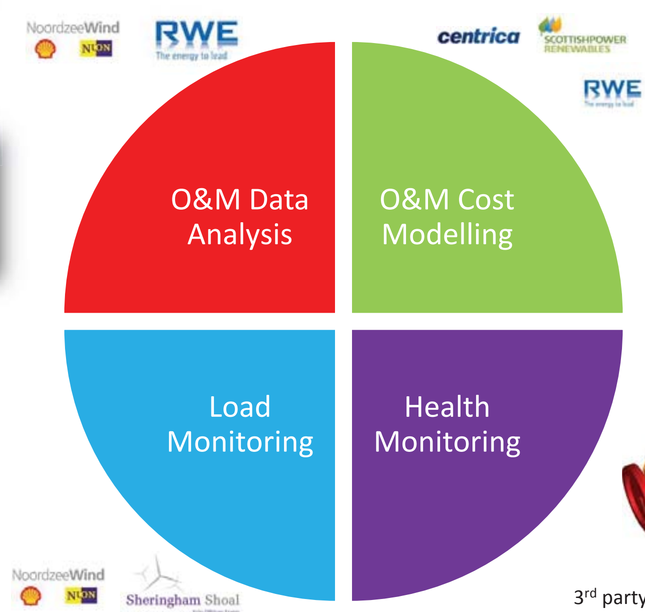
Lowering LCOE: Reduction of OPEX



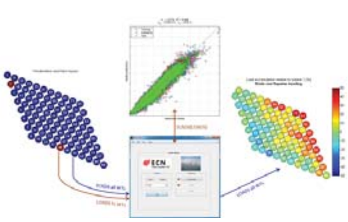
- Integral solution aimed at O&M optimisation during operational phase
- Smart analysis of wind farm operations and monitoring data
  - Obtain reliable maintenance and production forecasts
  - Support the shift to predictive maintenance
- Objective:
  - **Maximise production and minimise OPEX**

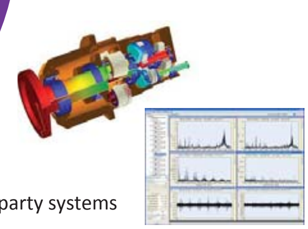
ECN O&M System Key elements


EventList & Data Analyser



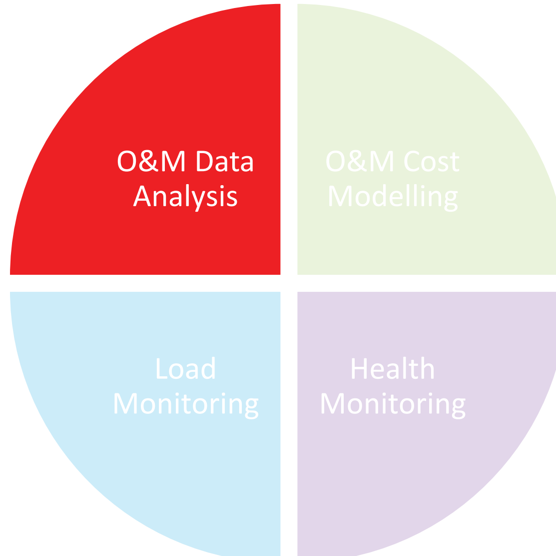

ECN O&M Calculator


FleetLeader


3rd party systems

Big data to smart data: Event list

- Event definition (≈ Workflow):
  - A (sequence of) maintenance action(s) to prevent or to correct malfunctioning.
- Data needs to be structured into a standard and repeatable format:
  - Combine data from various data sources
  - Relations between event and maintenance action(s)
  - Events per turbine in chronological order
  - Contain sufficient details to determine input parameters for O&M modelling
  - Integrated in works management system (e.g. SAP, Ultimo)



Event List: *Experience with RWE data*

- Observations:
  - Over 90% of required data is available
  - Engineering judgement for interpretation
  - Free format instead of pre-defined answers and classification
- Implementation issues
  - Ensure that Maintenance Management System contains the required fields
  - Automate export from MMS to Event List

Event nr.		*1*	
Start event	[date/time]	15-2-2013 9:33	
Event type		Corrective maintenance	
Turbine ID or BOP ID		1. Turbine A	
Nr. maintenance action		*1.1*	*1.2*
Start	[date/time]	15-2-2013 9:33	16-2-2013 8:30
End		15-2-2013 14:33	16-2-2013 17:00
Duration	[h]	1.05	8.50
Downtime	[h]	5.00	8.50
Type of maintenance		Inspections	Replacement (finalisation)
Weather downtime	[h]	4.00	0.00
Scada alarm code		0001	0010
Scada description		Temperature error	Turbine stopped by operator
Reported labour hours	[h]	2.00	
Crew size		2	
Access equipment		Access vessel	
- travel time (heading out)	[h]	0.75	
- travel time (return)	[h]	1.00	
- fuel consumption	[dm^3]	200	225
Second equipment		n.a.	n.a.
- travel time (one way)	[h]		
- mobilisation time	[h]		
Third equipment		n.a.	n.a.
- travel time (one way)	[h]		
- mobilisation time	[h]		
Explanations		Pitch motor overheated	Replaced pitch drive blade A
Main system_ID		MDC Blade adjustment	
Component ID		GL001 Pitch drive assembly A	
Work carried out		*Replacement*	
Spare part in stock		Yes	
Logistic time spare part	[h]	2	
Consumables		n.a.	
# consumables			
Total labour hours	[h]	*27.50*	
End event		*16-2-2013 17:00*	
Duration event	[h]	*31.44*	
Downtime event	[h]	*31.44*	

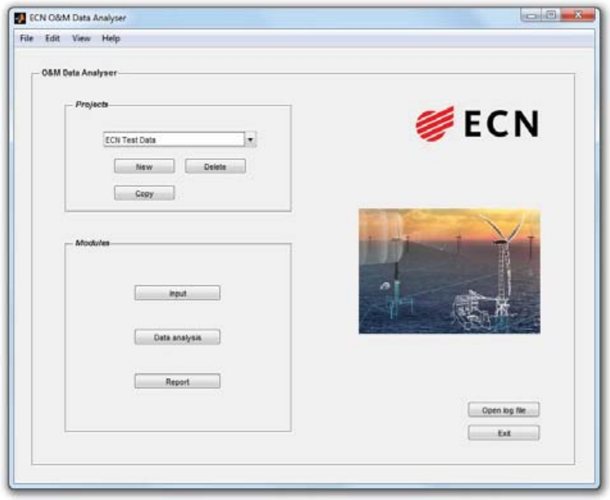
Start and definition of event

Definition of individual maintenance actions

End of event and reporting

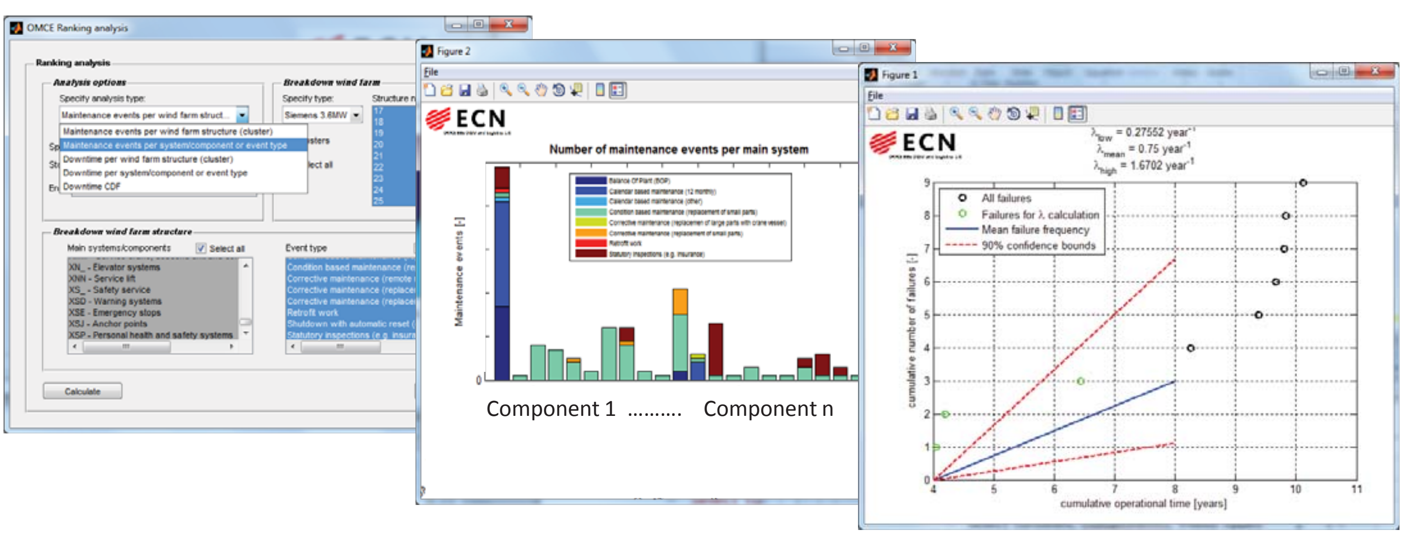
O&M data analysis: Data Analyser

- To ensure fast data analyses ECN developed dedicated data analysis software.
- Using the data stored in the Event List the software produces:
  1. Input parameters for O&M cost modelling software.
  2. Insight in the reliability & maintainability of the wind farm and its components.



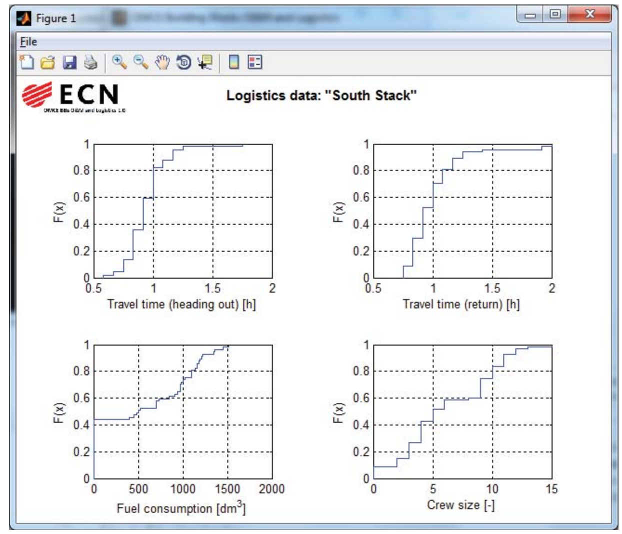
Data analysis: *'Reliability'*

- **Ranking Analysis** to create a general overview of wind farm performance in terms of downtime and number of maintenance events.
- **Trend Analysis** to determine (updated) failure frequencies of components.



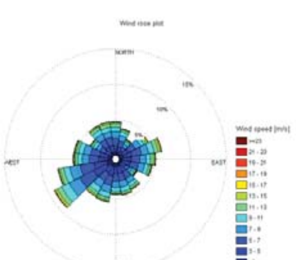
Data analysis: *'Logistics'*

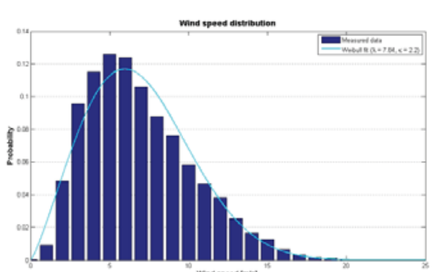
- **Equipment Analysis:** travel time, mobilisation/demobilisation time, number of technicians transported and amount of fuel used.
- **Spare Parts Analysis:** number and type of spare parts used, time for (re)ordering and transport, stock size and components maintained.
- **Repair Class Analysis:** number of phases, time to organise the repair, duration, number of technicians, equipment used and components maintained.

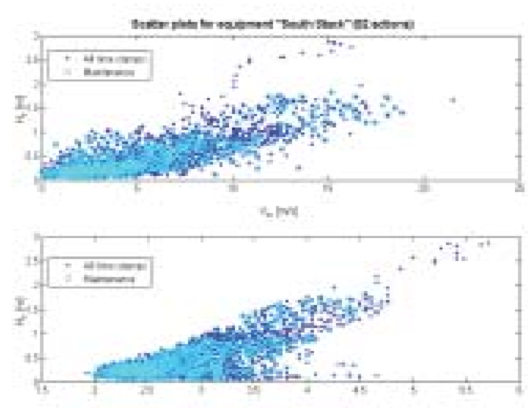


Data analysis: *'Met-ocean'*

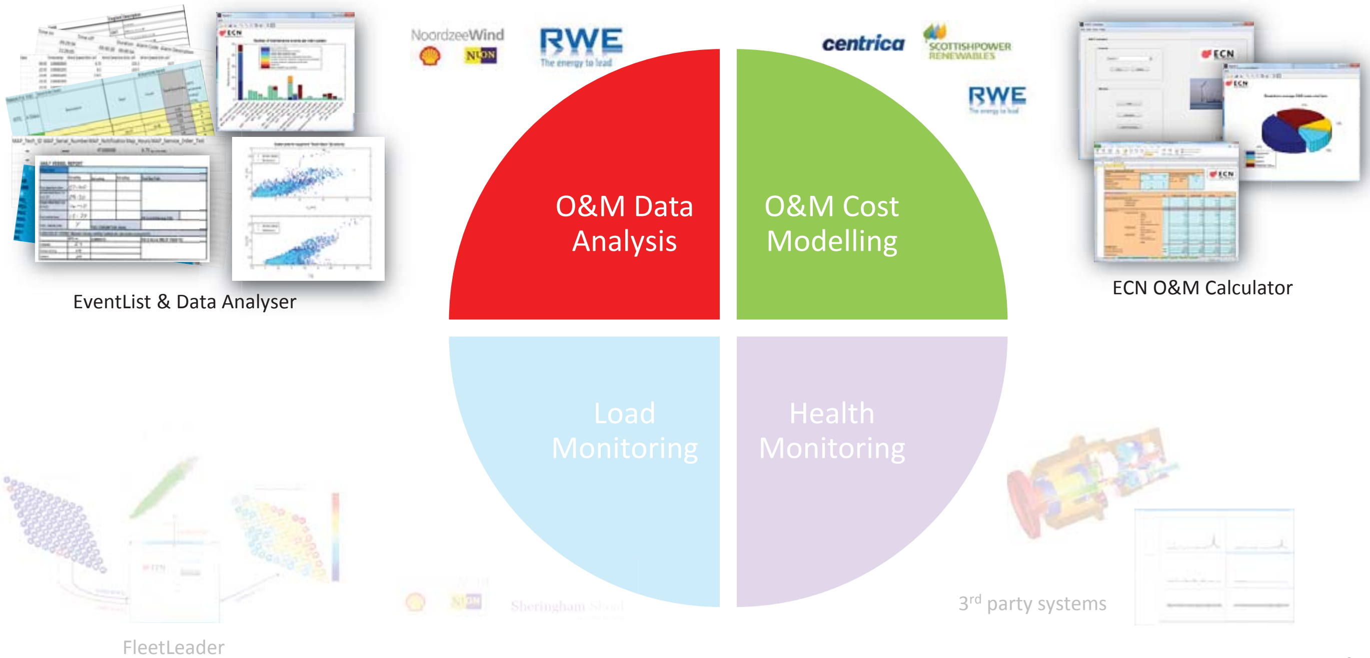
- **Wind & wave climate:** assess wind speed, wind rose, wave height, wave period, etc.
- **Weather limits equipment:** assess operational limits access equipment





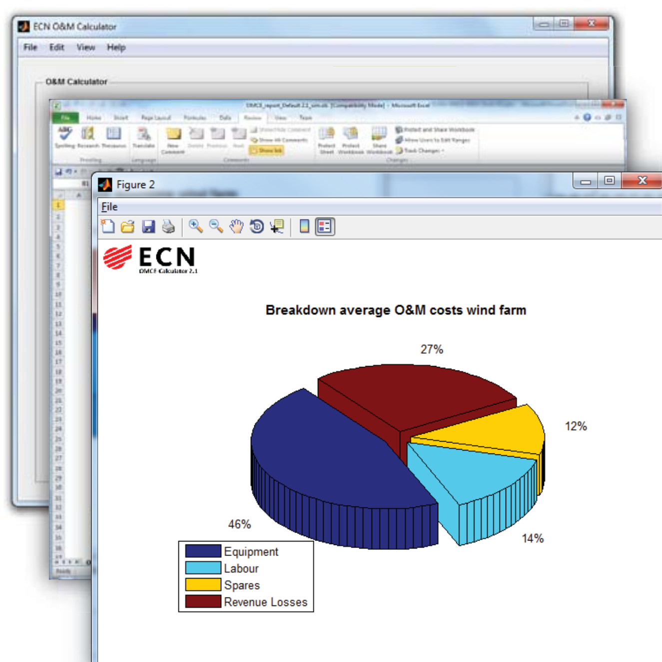


ECN O&M System Key elements



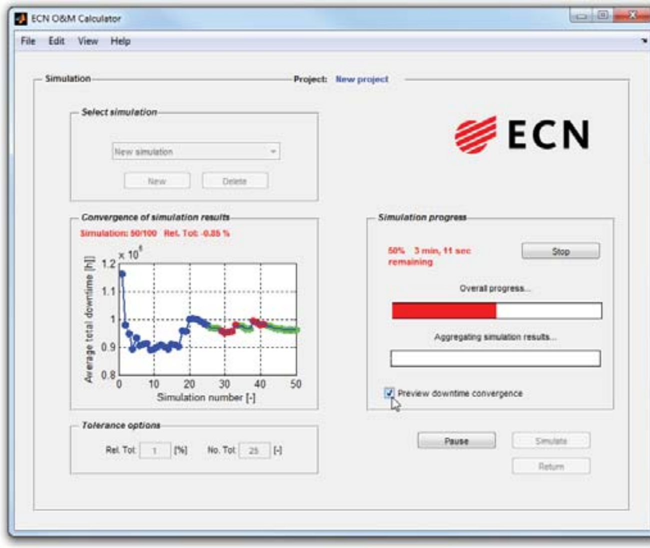
Decision making: O&M Calculator

- Based on the generated key info and input the current O&M concept should be re-evaluated.
- The O&M Calculator provides a platform to accurately predict the near-future O&M costs.
- Its results can be used to identify the most viable options for improving availability and reducing costs.



O&M Calculator

- MATLAB executable with GUI
  - User friendly interface
- Time-domain simulation
  - Variable step-size up to 1-minute
- Three types of maintenance
  - Unplanned corrective
  - Condition based
  - Calendar based
- Allows detailed modelling
  - Number of equipment and technicians
  - Stock control
  - Flexible maintenance model

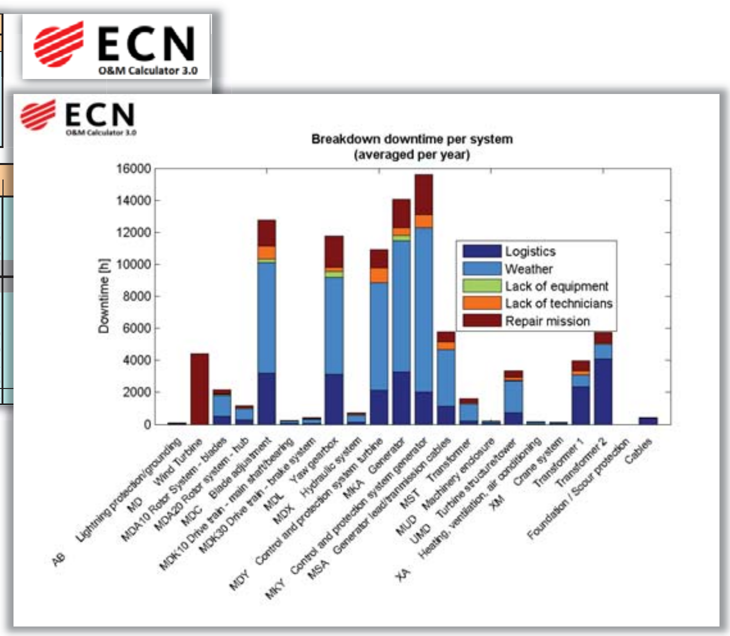


Modelling Results

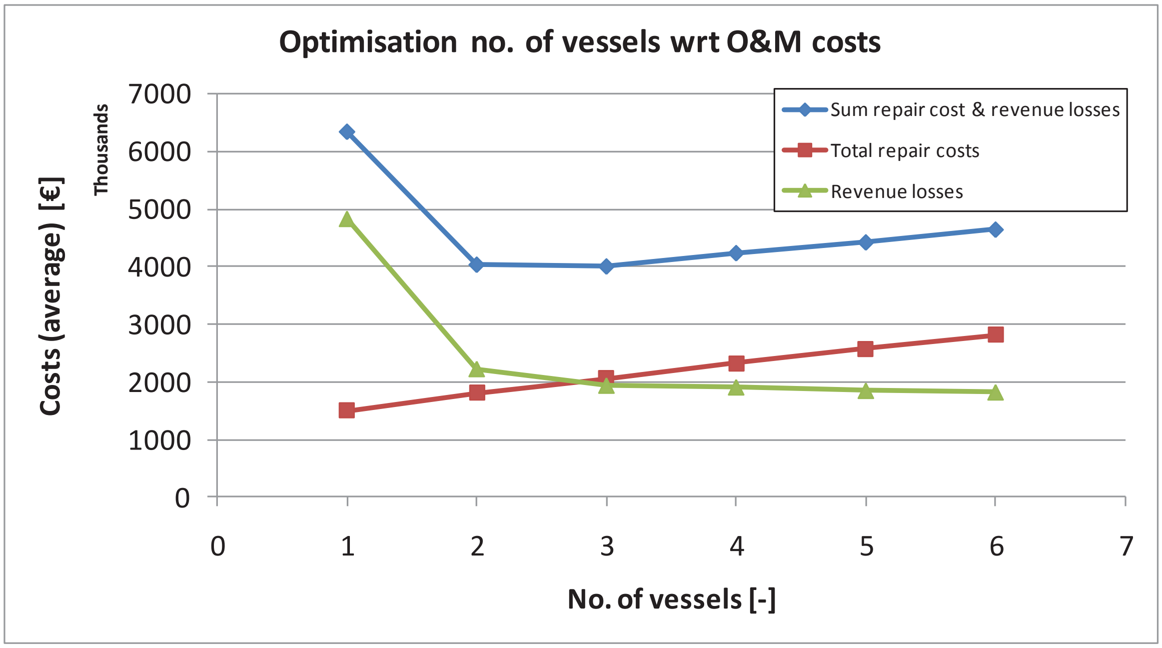
- Results presented in MS Excel report and in pre-defined graphs

Summary of downtime & costs				
Project	**New project**		**Key simulation results (average)**	
Installed wind farm capacity	520.0	MW	Availability [time/yield]	91.9 / 90.9%
Number of wind turbines in farm	130		Costs [¢€/kWh]	3.49
Simulation	**New simulation**		Repair costs [M€/yr]	64.48
Simulation period	1	yr	Rev. losses [M€/yr]	24.44
Start-up period	1	yr	Total effort [M€/yr]	88.92
Number of simulations	100			

Wind farm averaged per year			Unit	Average of simulations	Standard deviation
Number of maintenance events per year					
	Unplanned corrective		-	1,157.26	46.28
	Condition based		-	56.00	0.00
	Calendar based		-	130.00	0.00
Downtime per year					
	Unplanned corrective	Logistics	h	17,179	1,627
		Weather	h	43,283	13,587
		Lack of equipment	h	1,749	950
		Lack of technicians	h	0	0
		Repair	h	11,215	784
		Balance of plant	h	14,201	29,380
		TOTAL unplanned corrective	h	87,627	31,046

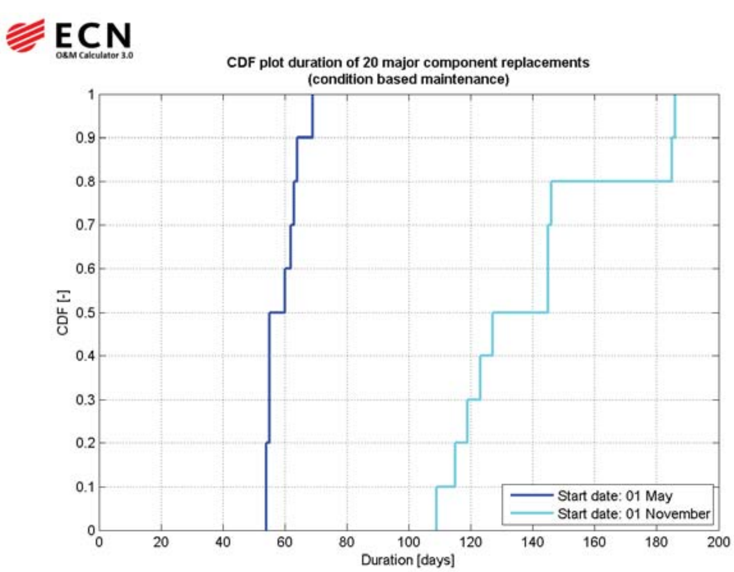


O&M Calculator examples



O&M Calculator examples

Replacement 20 major components: Expected duration campaign



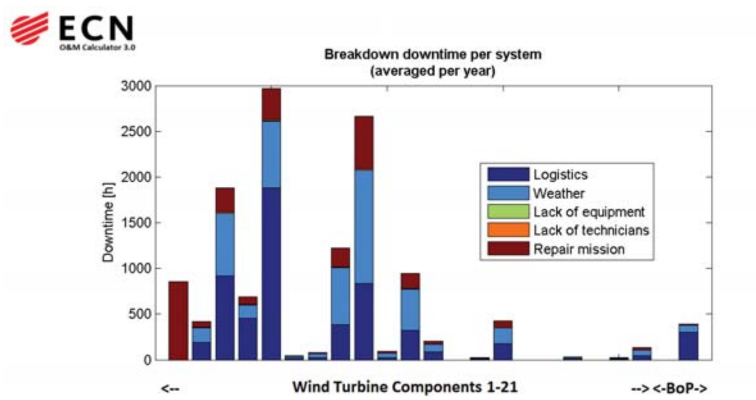
<u>Start in May:</u>
- Relatively short duration
- Low uncertainty

<u>Start in November:</u>
- Long duration!
- High uncertainty!

Case study: *Rhyl Flats wind farm*

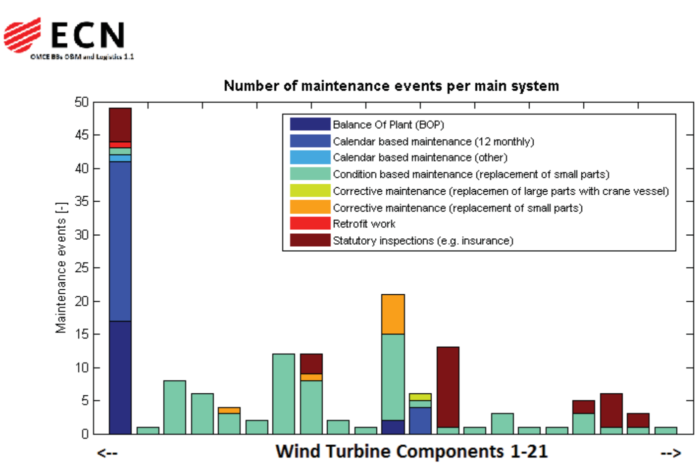
- Step 1: Reference calculation O&M costs
  - Based on historical data and assumptions

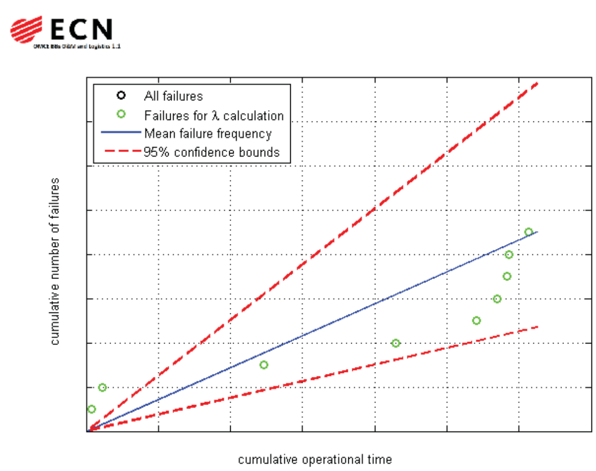
Summary of downtime & costs				
Project	**Rhyl Flats baseline**		***Key simulation results (average)***	
Installed wind farm capacity	90,0	MW	Availability [time/yield]	94 / 93.2%
Number of wind turbines in farm	25		Costs [c€/kWh]	4,52
Simulation	**sim**		Repair costs [M€/yr]	12,51
Simulation period	1	yr	Rev. losses [M€/yr]	2,63
Start-up period	1	yr	Total effort [M€/yr]	15,14
Number of simulations	1000			



Case study: *Rhyl Flats wind farm*

- Step 2: Analysis operational data
  - 3 months of operational data
  - Derived estimated failure rates of components





Case study: *Rhyl Flats wind farm*

- Step 3: Update calculation O&M costs
  - Based on updated input data (e.g. failure rates)

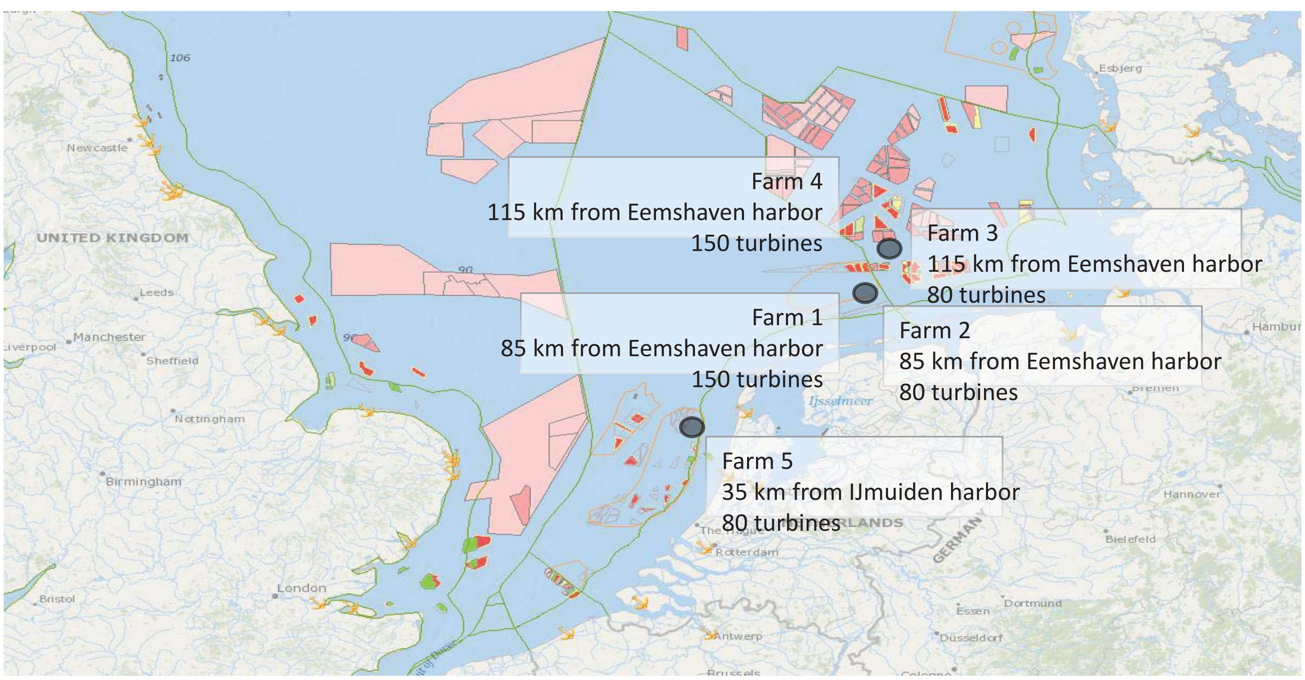
Summary of downtime & costs				
Project	**Rhyl Flats updated**		***Key simulation results (average)***	
Installed wind farm capacity	90,0	MW	Availability [time/yield]	96.2 / 95.8%
Number of wind turbines in farm	25		Costs [c€/kWh]	3,35
Simulation	**sim**		Repair costs [M€/yr]	9,52
Simulation period	1	yr	Rev. losses [M€/yr]	1,64
Start-up period	1	yr	Total effort [M€/yr]	11,16
Number of simulations	1000			

- Step 4: Implement O&M strategy improvements
  - Reduce number of available access vessels & technicians
  - Only perform preventive maintenance when wind speeds are below 4 m/s

Summary of downtime & costs				
Project	**Rhyl Flats optimised**		***Key simulation results (average)***	
Installed wind farm capacity	90,0	MW	Availability [time/yield]	96.2 / 96%
Number of wind turbines in farm	25		Costs [c€/kWh]	3,00
Simulation	**sim**		Repair costs [M€/yr]	8,53
Simulation period	1	yr	Rev. losses [M€/yr]	1,57
Start-up period	1	yr	Total effort [M€/yr]	10,10
Number of simulations	1000			

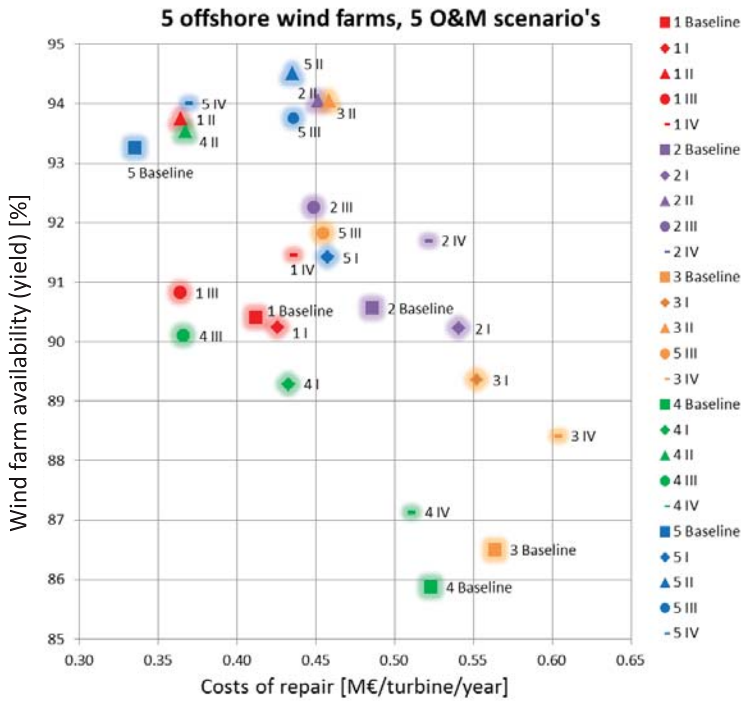
10% costs reduction in OPEX
~ 1.7% reduction in LCOE;
4% decrease in revenue losses

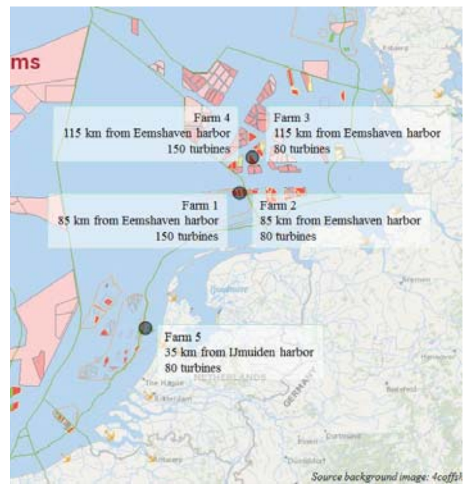
Case Study 2 : *Extensive analysis of North Sea WF*



Source background image: 4coffshore.com

Case Study 2: *North Sea*





Summary

- **Offshore wind**- a potential industry, besides its challenging economics
- Significant **influence on LCOE**- Identification & reduction of its cost components
- **Wind Farm optimization-** the focus for LCOE reduction
- Improvement in different **cost components** can influence LCOE by **2-9%**
- **OPEX reduction**- by structuring operational data & predicting O&M costs
- Reduction of **10% in OPEX** in a real wind farm led to **1.7% reduction in LCOE**

Thank you for your attention

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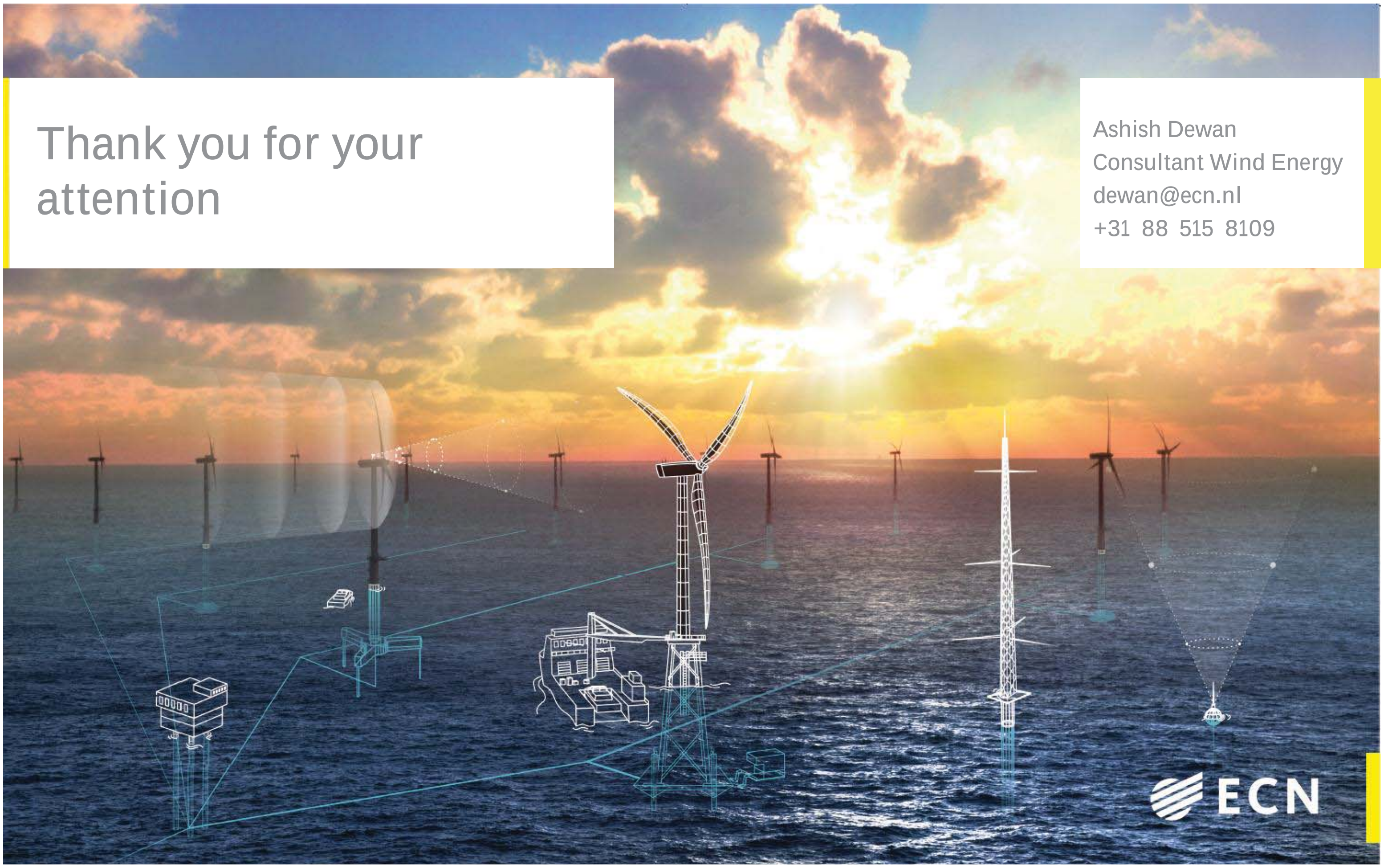

Offshore Wind Balance of System Cost Modeling

Tyler Stehly
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Golden, CO USA
Tyler.Stehly@nrel.gov

With Balance of System (BOS) costs contributing up to 70% of the installed capital costs, it is imperative to understand the BOS costs for offshore wind projects as well as potential cost trends for new technology. NREL has developed and recently updated a BOS techno-economic model using project cost estimates developed from wind energy industry sources. Aspects of BOS costs covered include engineering and permitting, ports and staging, transportation and installation, vessels, support structure and foundation, and electrical. The data introduce new and updated scaling relationships for each component to estimate costs as a function turbine and project parameters. Based on these updated and new relationships, an analysis to understand the non-turbine costs associated with fixed bottom and floating offshore wind projects has been conducted. The analysis establishes a more robust baseline cost estimate, identifies primary cost drivers, and explores the sensitivity of the levelized cost of energy (LCOE) to permutation in each BOS cost element.

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Assessing Levelized Cost of Energy for Offshore Wind

International Workshop on Life-Cycle Costing of Offshore Wind Turbines and Farms

Tyler Stehly

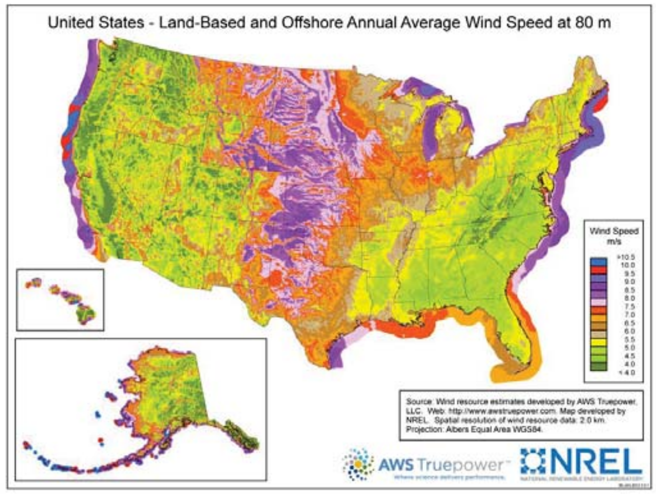
October 1, 2015

Introduction/Outline

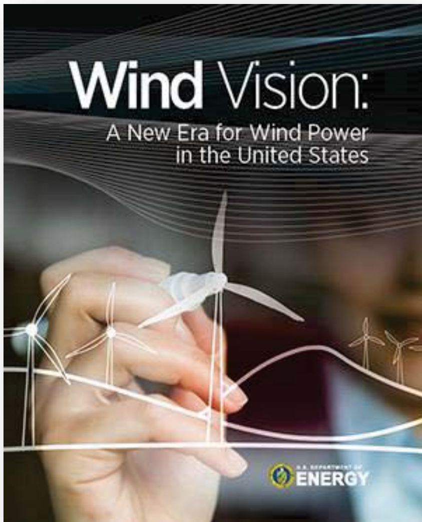
- **Provide background of offshore wind in the U.S.**
- **Review NREL Levelized Cost of Energy (LCOE) framework**
- **Present case studies for selected analysis tools**
  - Offshore Balance of System (BOS)
  - ECN O&M Tool

U.S. Offshore Wind Overview

- Estimates show shallow (0–30 m) and transitional depth (30–60 m) waters to have a net resource of 773 gigawatts (GW)
- If including deep waters that would require floating sub-structures, the total net U.S. offshore wind resource is estimated to be well over 2,000 GW



http://www.nrel.gov/wind/resource_assessment.html



http://www.energy.gov/windvision

- The U.S. Department of Energy has adopted "*Wind Vision"* to support the development of an offshore wind industry in the United States
- The strategy scenario calls for deployment of 3 GW by 2020, 22 GW by 2020, and 86 GW by 2030.

Levelized Cost of Energy (LCOE)

$$\text{LCOE} = \frac{(\text{CAPEX}*\text{FINANCE})+\text{OPEX}}{\text{OPEX}}$$

Systems Engineering

http://www.nrel.gov/wind/systems_engineering/

Contact: Katherine.Dykes@nrel.gov

LCOE

Turbine Capital Costs (CAPEX)

NREL Wind Turbine Cost and Scaling Model
- Model based on empirical relationships and simple scaling equations

~~~~~~~~~~~~~~~~~~~~

Detailed Design Tools
- Physics-based models for individual wind turbine components (e.g., blades, drivetrains)

Balance of System Capital Cost (CAPEX)

NREL Offshore Wind BOS Model
- Model based on offshore wind industry experience in Europe

~~~~~~~~~~~~~~~~~~~~

Detailed Design Tools
- Physics-based models for BOS components (e.g., foundations, substructures)

Operation and Maintenance (OPEX)

ECN Offshore Wind O&M Tool
- Industry-standard Excel-based planning tool
- Estimates expected long-term average O&M costs and wind plant annual availability based on historical weather data and user defined repair strategies
- Ability to provide instantaneous results/feedback and modeling of unconventional scenarios

Finance (FINANCE)

System Advisor Model (SAM)
- Detailed cash flow modeling
- Several options for project finance structure (e.g., tax equity, non recourse debt)
- Integrated analysis capabilities (e.g., Monte Carlo simulation)

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Simplified Representation
- Weighted Average Cost of Capital (WACC)
- Capital Recovery Factor
- Term to represent impact of taxes and depreciation

Annual Energy Production (AEP)

Openwind
- Industry-standard wind plant layout optimization and energy assessment tool
- Estimation of energy losses due to wake effects utilizing 6-7 different approaches to wake propagation

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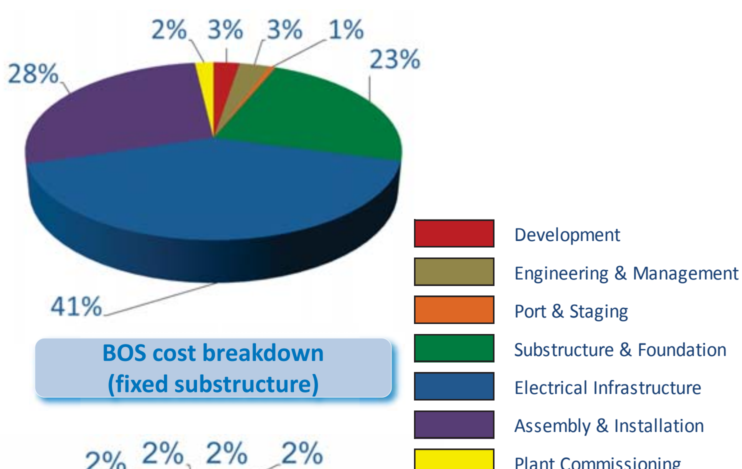
Electrical modeling
- Modeling to capture wind system electrical losses (e.g., array-cable and export-cable losses)

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

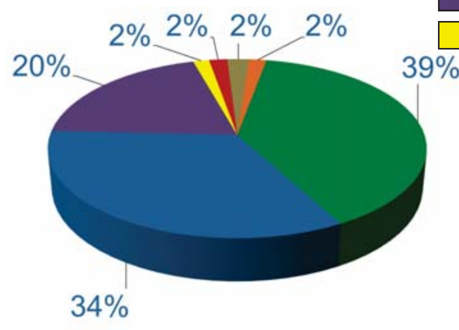
Case Study 1: Parametric Analysis using NREL's Offshore BOS Model

Case Study 1: Parametric Sensitivity Analysis

Baseline Parameters (Fixed/Floating)	
Project Size (megawatts [MW])	600
Turbine Rating (MW)	6
Rotor Diameter (meters [m])	155
Hub Height (m)	90
Distance to Shore (kilometers [km])	40
Distance to Installation Port (km)	60
Water Depth (m)	25/250
Array Spacing (rotor diameters)	9x9



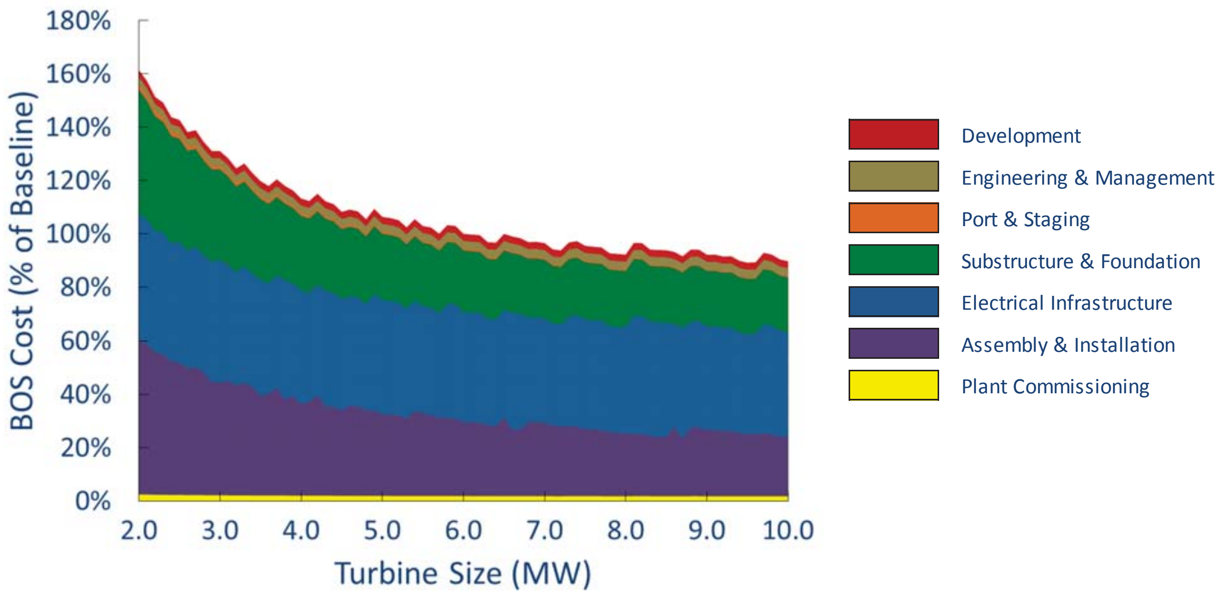
BOS cost breakdown (fixed substructure)



BOS cost breakdown (floating substructure)

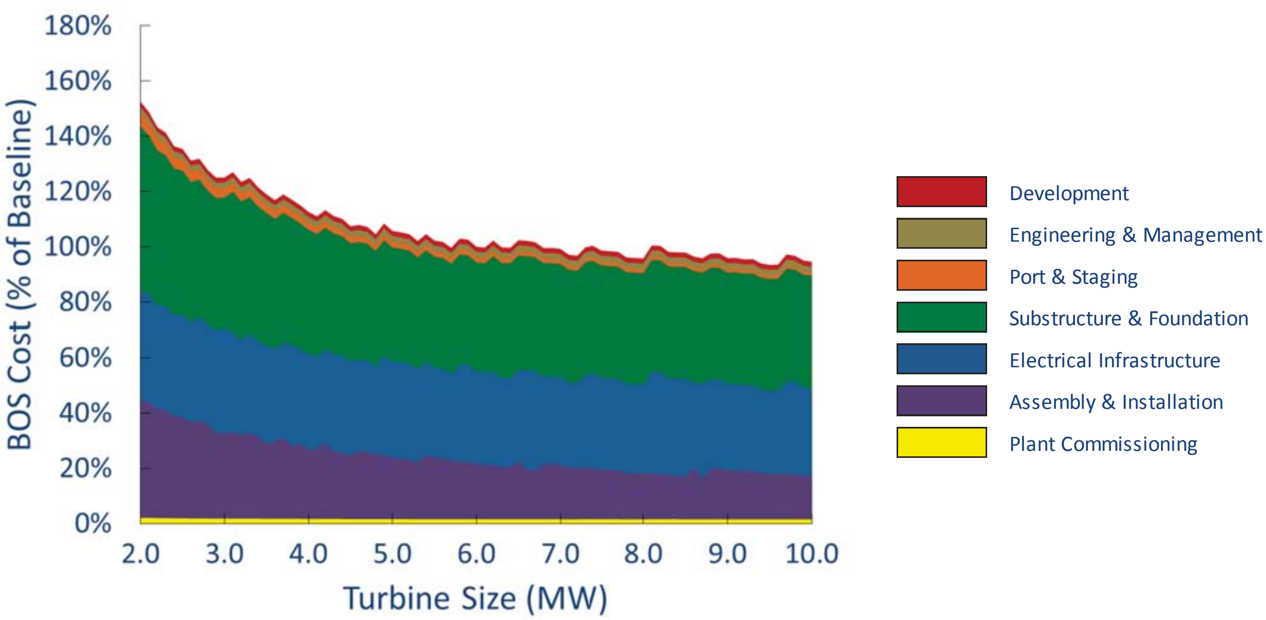
- Baseline parameters were chosen to reflect a representative offshore wind project in the mid-Atlantic
- To represent the impact of altering a single variable, all analyses use common baseline project parameters while the variable under investigation is changed.

Case Study 1: Sensitivity to Turbine Size (Fixed)



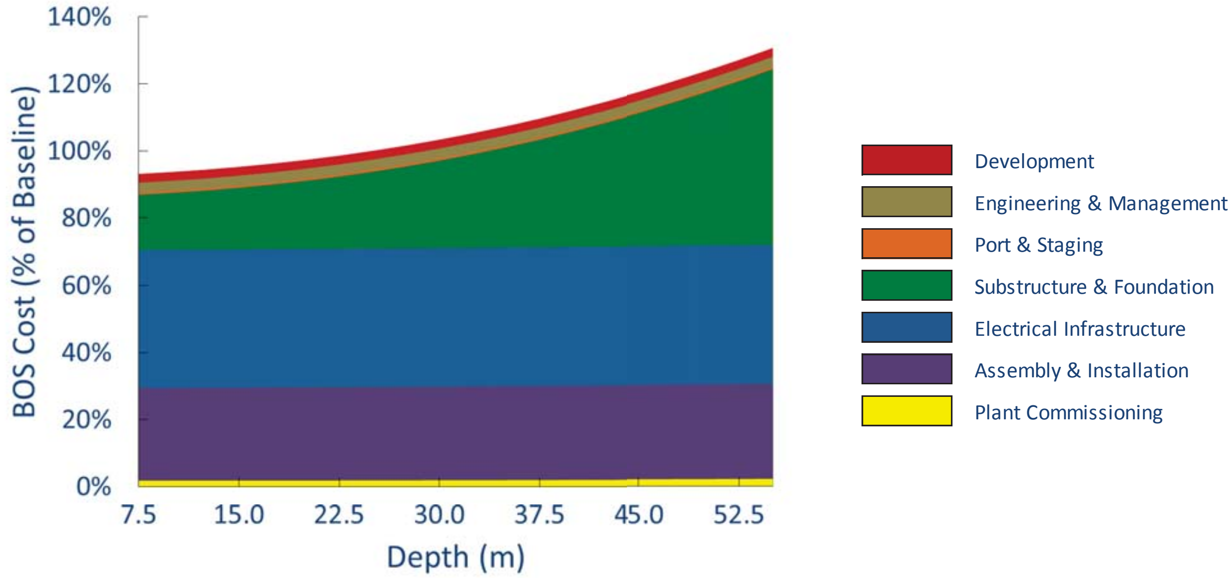
- Offshore BOS cost decreases with increased turbine size because fewer turbines are needed to maintain a given plant size, in this case 600 megawatts.
- Cost fluctuations introduced as the number of turbines are changed

Case Study 1: Sensitivity to Turbine Size (Floating)



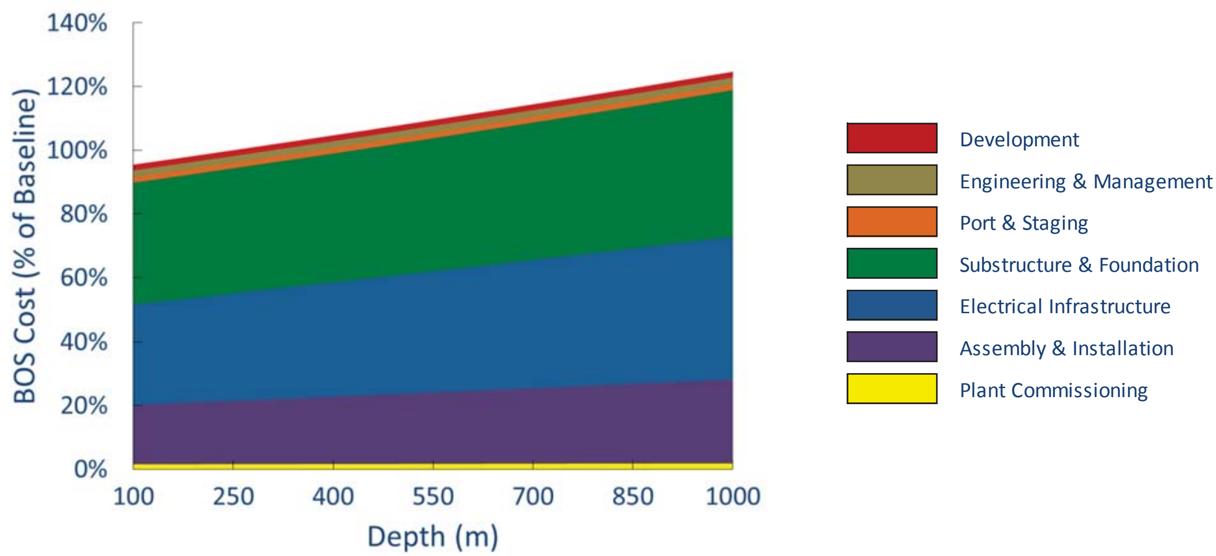
- Offshore BOS cost decreases with increased turbine size because fewer turbines are needed to maintain a given plant size, in this case 600 megawatts.
- Cost fluctuations introduced as the number of turbines are changed

Case Study 1: Sensitivity to Water Depth (Fixed)



- Costs increase with deeper water primarily from the need for larger, more expensive substructures and foundations in deeper waters.
- Fixed bottom water depth ranges from 0 meters to 60 meters resulting in BOS cost varying approximately 35%.

Case Study 1: Sensitivity to Water Depth (Floating)



- Substructure and foundation costs increase because mooring lines become longer in deeper water.
- Electrical infrastructure costs are higher since longer cabling is needed to reach the seafloor in deeper waters.
- Installation of mooring systems increase cost in deeper water.
- Floating water depth ranges from 100 meters to 1,000 meters resulting in BOS cost varying approximately 30%.

Case Study 1: Conclusions

- Increase in turbine size for both fixed and floating substructures tend to reduce BOS cost.

- Increase in water depth increases BOS cost for both fixed and floating substructures
  - Fixed is primarily driven by a larger more expensive substructure and foundation
  - Floating is driven by increased mooring line, cable, and installation costs

- Fixed bottom technology has a higher impact on BOS cost over a smaller range of water depth (0 – 60 meters) vs. floating technology with a lower impact on BOS cost over a large range of water depth (100 – 1,000 meters)

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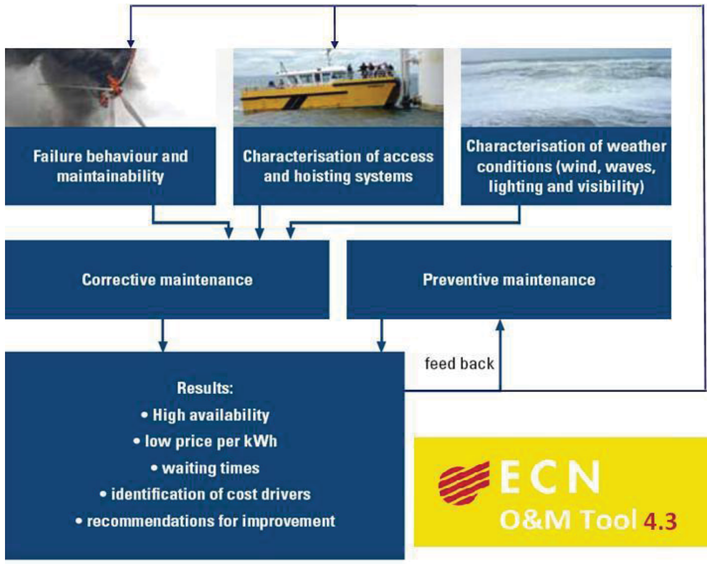
Case Study 2: Parametric Analysis using ECN's O&M Tool

ECN O&M Tool



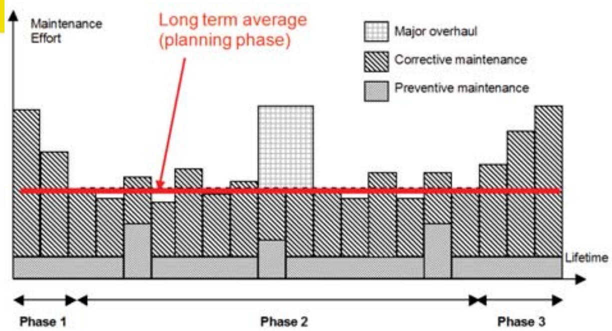
Input parameters

Outputs:

- **Long-term annual average costs**
- **Downtime**
- **Revenue losses due to corrective and preventative maintenance**

Allows ability to identify:

- **Cost drivers**
- **Areas of improvement (e.g., increase component reliability, lower cost vessels)**
- **Uncertainties of inputs and outputs of the model using the probabilistic function (@Risk)**



Figures from: User Guide and Model Description of ECN O&M Tool Version 4
Obdam, T.S.; Braam, H.; Radmakers, L.W.M.M. 2011

Case Study 2: OPEX Parameter Study

O&M costs for each technology driven by **distance from project to port** and **metocean conditions**

3 representative sites selected to represent metocean conditions across the US Offshore Wind Resource (10 yrs. of correlated Wind and Wave data)

- Mild, Moderate, Severe
- ECN Model set up for each site

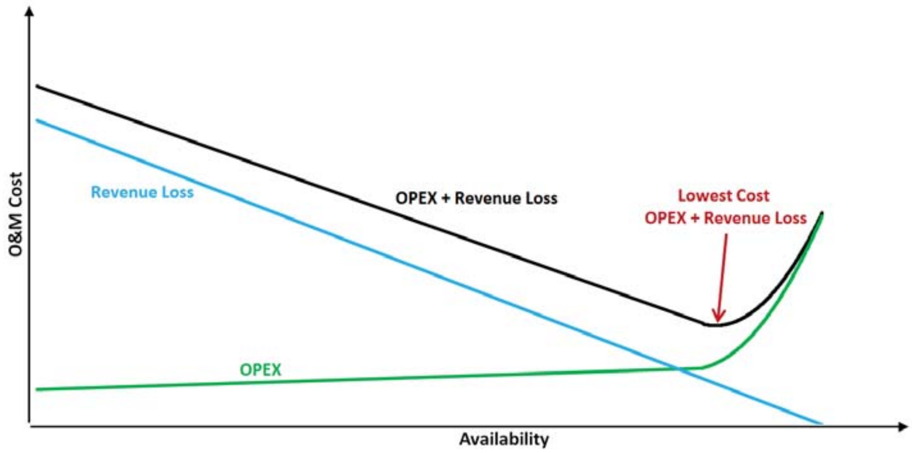
For each site, parameter study is conducted in the ECN O&M Tool for a range different access strategies, ranging from basic to innovative

Difference between Fixed-Bottom scenarios and Floating Scenarios is in approach to correcting major failures:

- Fixed-bottom: in-situ repairs using identical jack-up vessel as for installation
- Floating: tow-to-shore repairs using a spread consisting of AHTS vessels and assist tugs

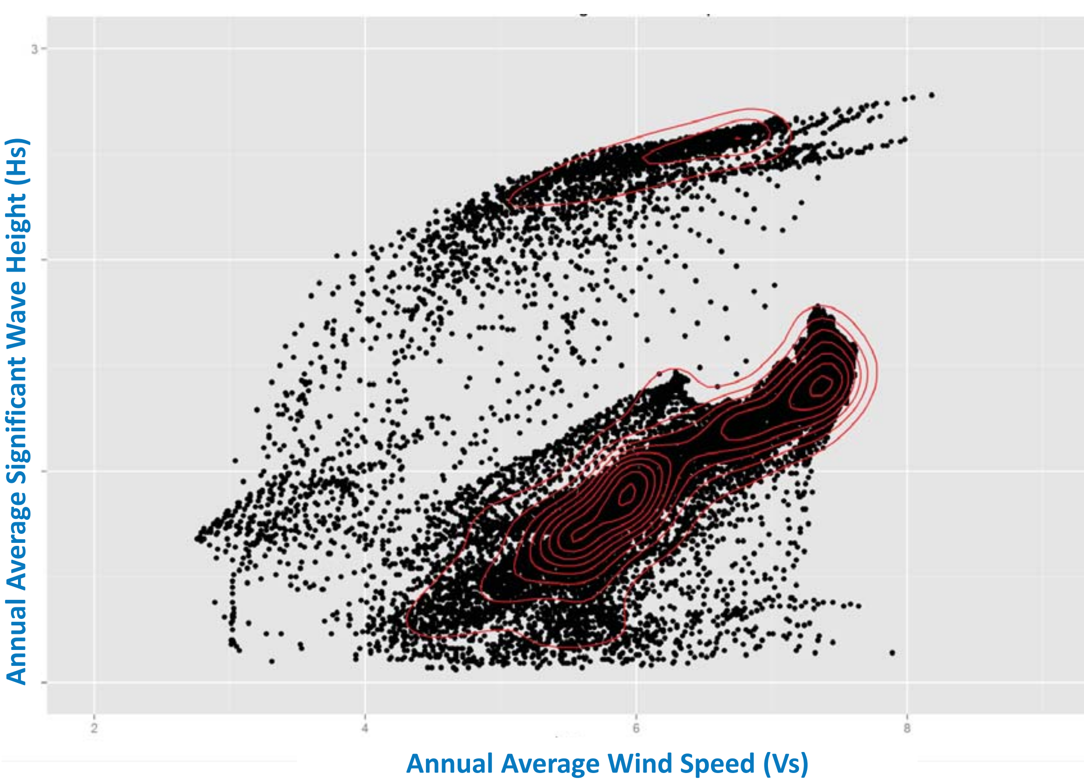
Case Study 2: Analysis Approach

- **Compare results:**
  - ECN Tool outputs are OPEX, availability, and total O&M cost (OPEX + Revenue Loss).
  - Analysts identified economic breakpoints between O&M strategies for each of the three representative sites.
- **Develop OPEX and availability equations for each technology:**
  - Analysts then disaggregated results into their constituent parts in order to determine how OPEX and availability might realistically change with distance to port, assuming adoption of the optimal O&M strategy at each distance.
  - Analysts then fit curves to the OPEX and availability result data to describe the relationship between OPEX, availability, and other parameters



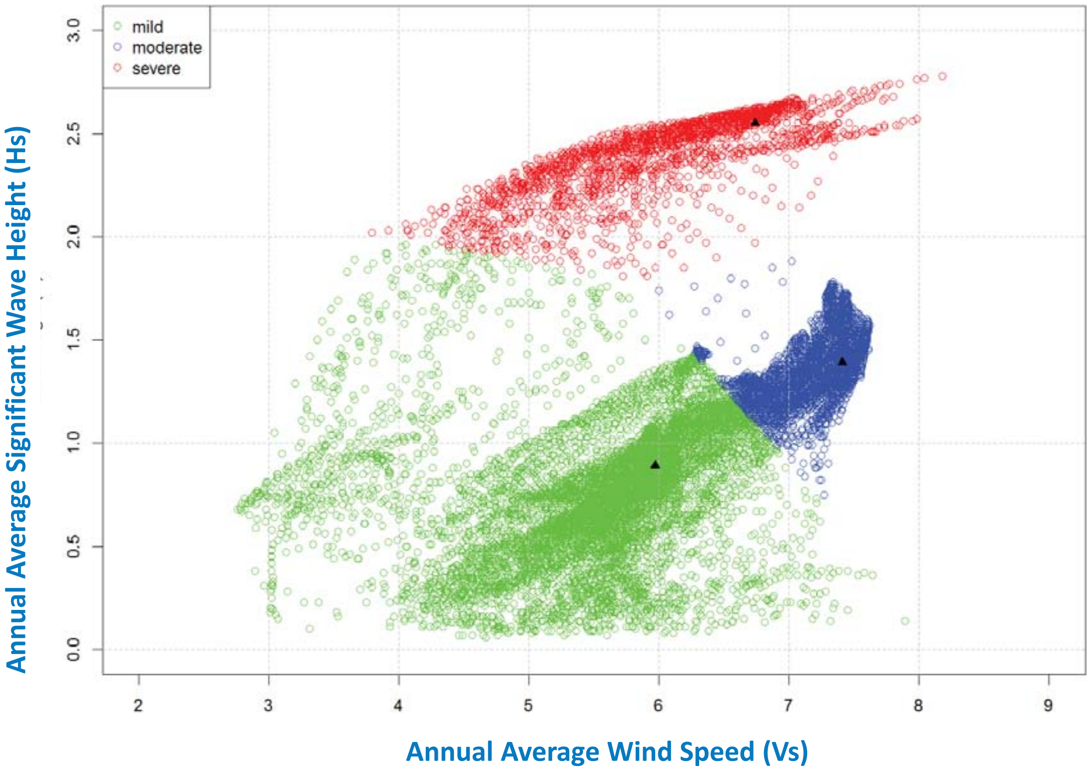
Case Study 2: Weather Categorization

Joint distribution of Annual Average Significant Wave Heights (Hs) and Wind Speed (Vs) @ 10 m above MSL

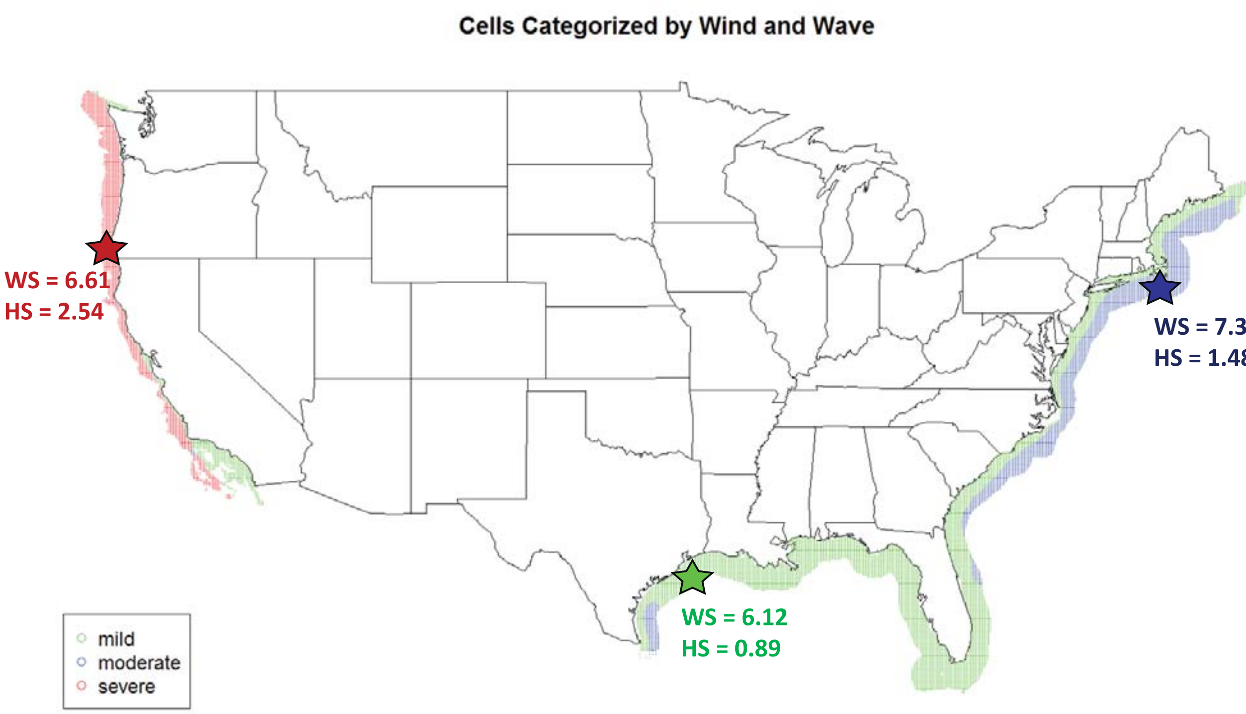


Case Study 2: Weather Categorization

Each site is associated with one of three sites using weighted least squared method (0.5 m Hs = 1 m/s Vs)



Case Study 2: Weather Categorization



WIS stations (stars) with closest match to local maxima selected to represent each metocean category. Hourly data gathered from each station and used in ECN O&M Tool

Case Study 2: Matrix of Access Cases

Matrix of Site Conditions:

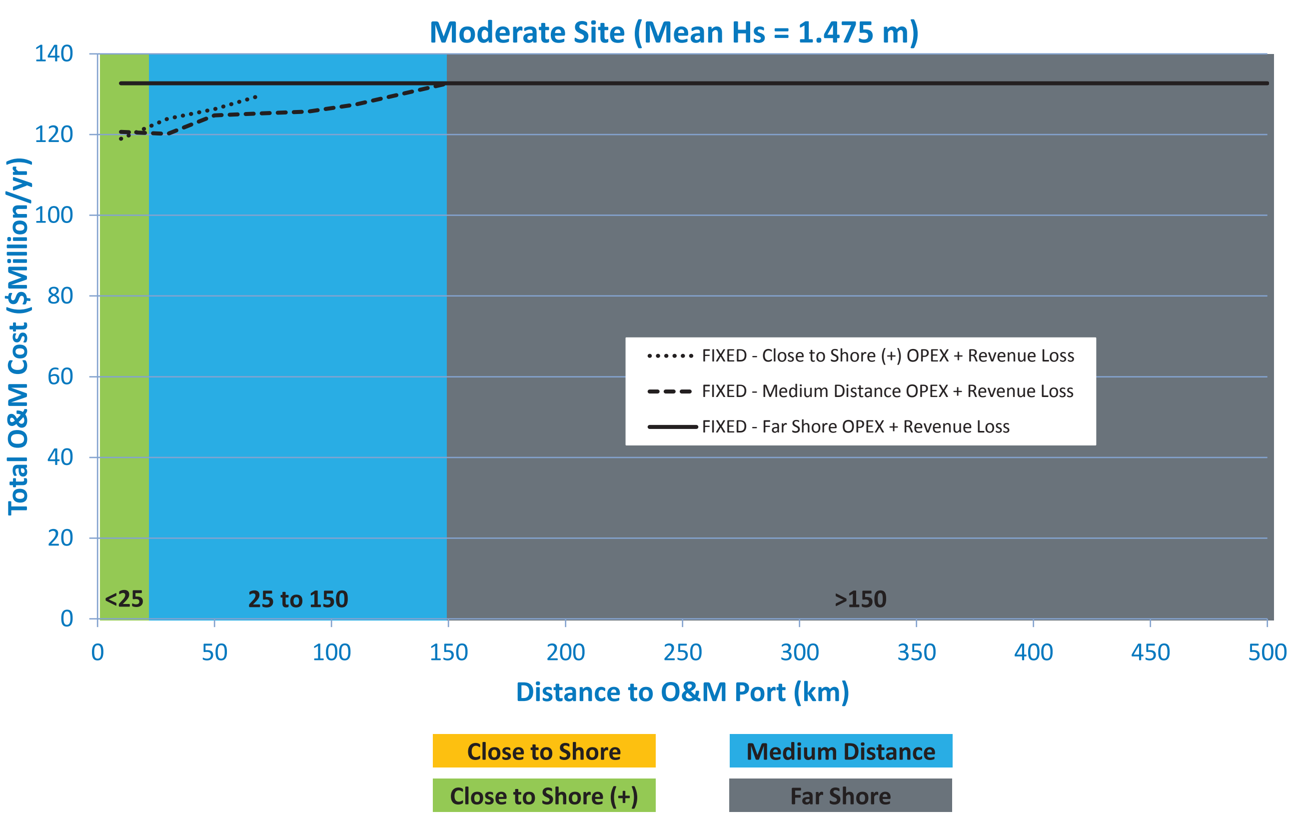
Distance to O&M Port	Metocean Conditions								
	Mild ($Hs_{Average}$ < 1) (m)			Moderate (1 < $Hs_{Average}$ < 2) (m)			Severe (2 < $Hs_{Average}$) (m)		
	Mean Hs = 0.885	Mean Hs = 0.885	Mean Hs = 0.885	Mean Hs = 1.475	Mean Hs = 1.475	Mean Hs = 1.475	Mean Hs = 2.54	Mean Hs = 2.54	Mean Hs = 2.54
10 km	Close to Shore	Medium Distance	Far Shore	Close to Shore (+)	Medium Distance	Far Shore	Close to Shore (+)	Medium Distance	Far Shore
30 km	Close to Shore	Medium Distance	Far Shore	Close to Shore (+)	Medium Distance	Far Shore	Close to Shore (+)	Medium Distance	Far Shore
50 km	Close to Shore	Medium Distance	Far Shore	Close to Shore (+)	Medium Distance	Far Shore	Close to Shore (+)	Medium Distance	Far Shore
70 km	Close to Shore	Medium Distance	Far Shore	Close to Shore (+)	Medium Distance	Far Shore	Close to Shore (+)	Medium Distance	Far Shore
90 km	***	Medium Distance	Far Shore	***	Medium Distance	Far Shore	***	Medium Distance	Far Shore
110 km	***	Medium Distance	Far Shore	***	Medium Distance	Far Shore	***	Medium Distance	Far Shore
150 km	***	Medium Distance	Far Shore	***	Medium Distance	Far Shore	***	Medium Distance	Far Shore
200 km	***	***	Far Shore	***	***	Far Shore	***	***	Far Shore
300 km	***	***	Far Shore	***	***	Far Shore	***	***	Far Shore
400 km	***	***	Far Shore	***	***	Far Shore	***	***	Far Shore
500 km	***	***	Far Shore	***	***	Far Shore	***	***	Far Shore

***Distance exceeds an assumed 2 hour limit for transport time technicians from the O&M port to the project

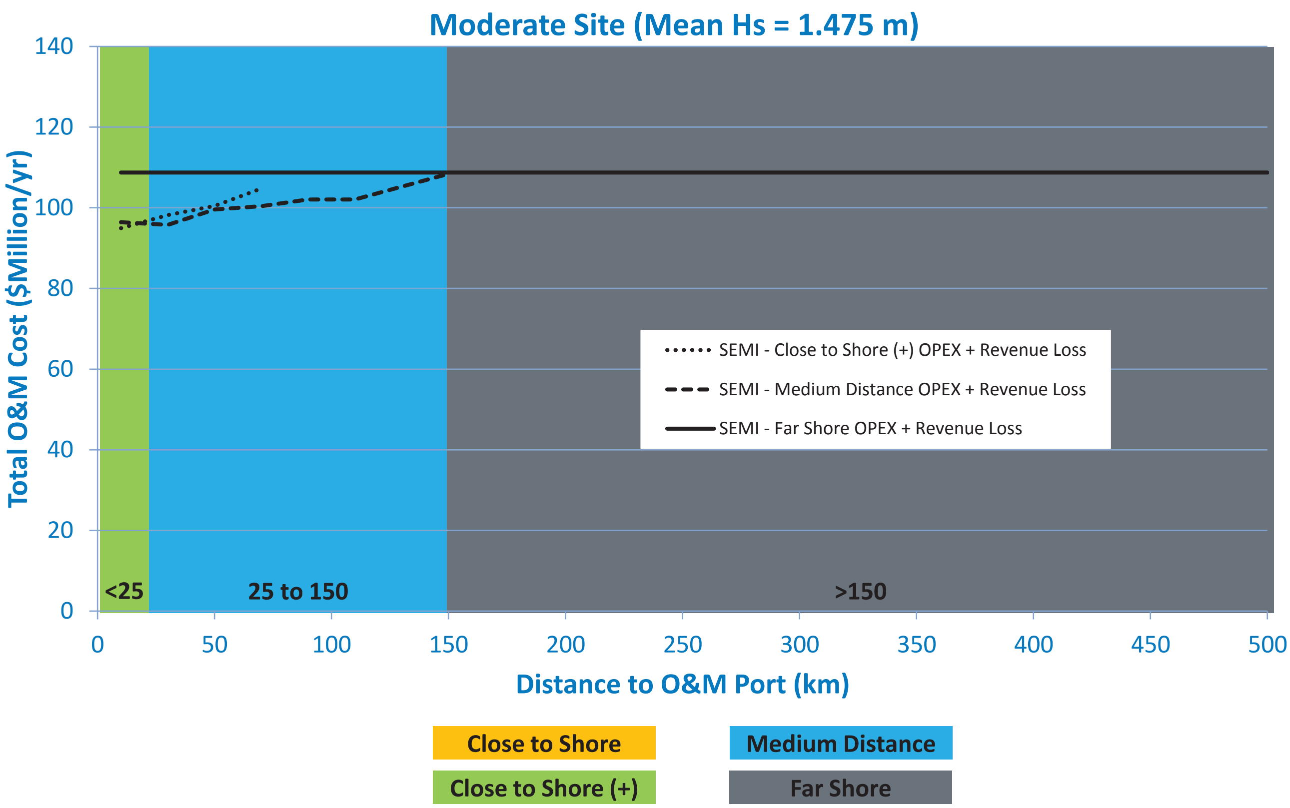
Matrix of O&M Strategies:

	O&M Strategy			
	Close to Shore	Close to Shore (+)	Medium Distance	Far Shore
Description	Standard Port-Based O&M Strategy	Standard Port-Based O&M Strategy	Enhanced Port-Based O&M Strategy	Mothership-Based O&M Strategy
Principle Access Vessel	Crew Transfer Vessel	More Expensive Crew Transfer Vessel with Higher Wave Limitation (e.g., Fjellstrand and FOB SWATH)	Advanced Crew Transfer Vessel (i.e., Surface Effect Ship)	Crew Transfer Vessel And Mothership

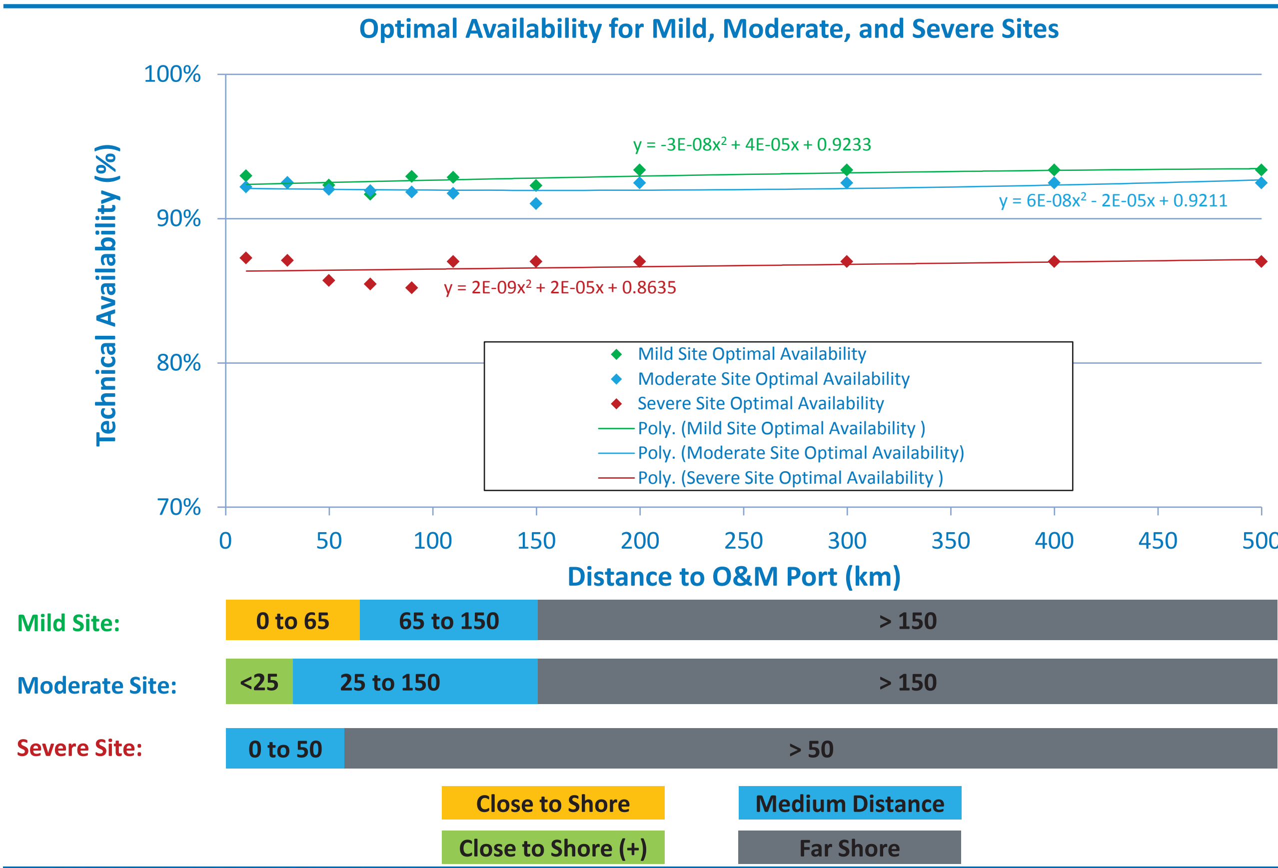
Case Study 2: Fixed-Bottom Results – Moderate Site



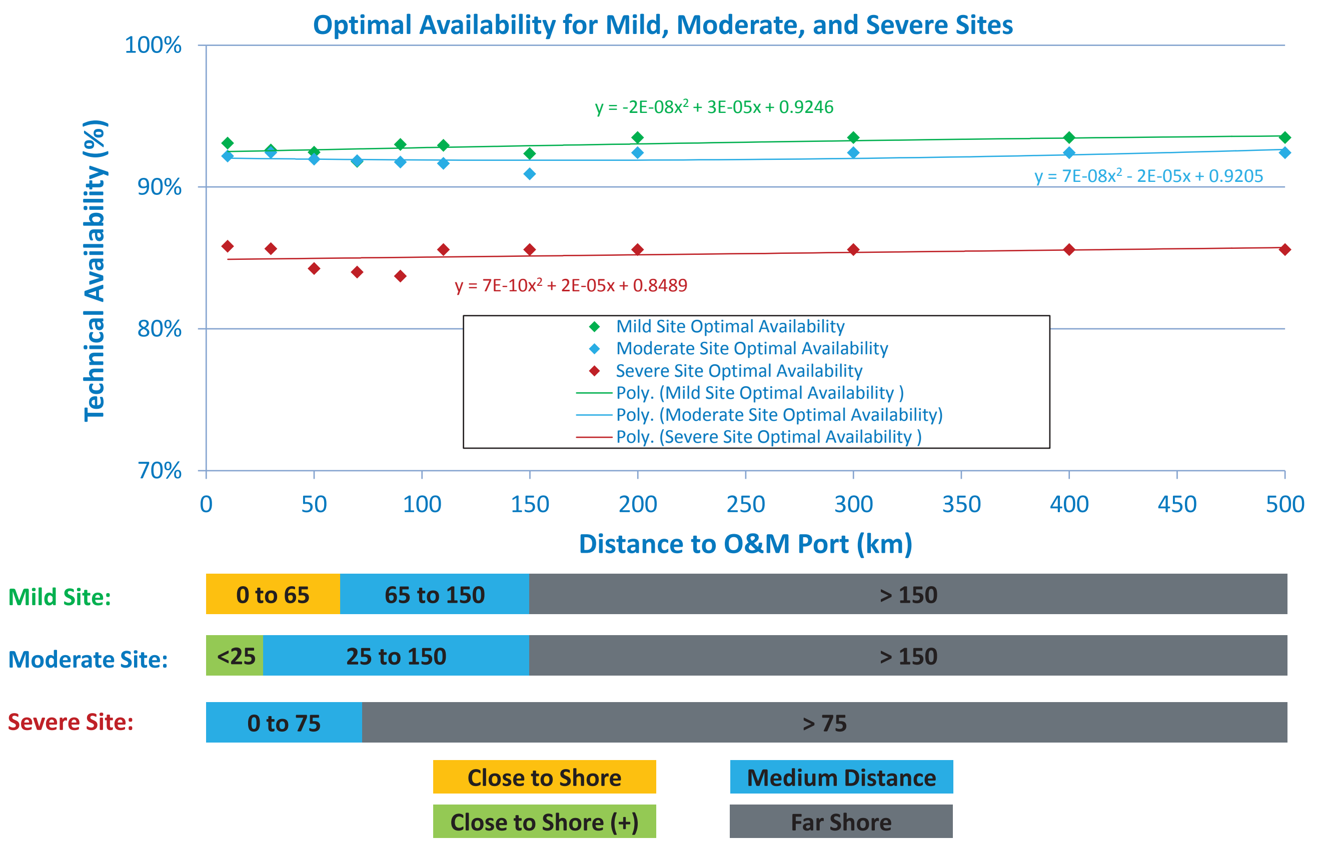
Case Study 2: Floating - Semi Results – Moderate Site



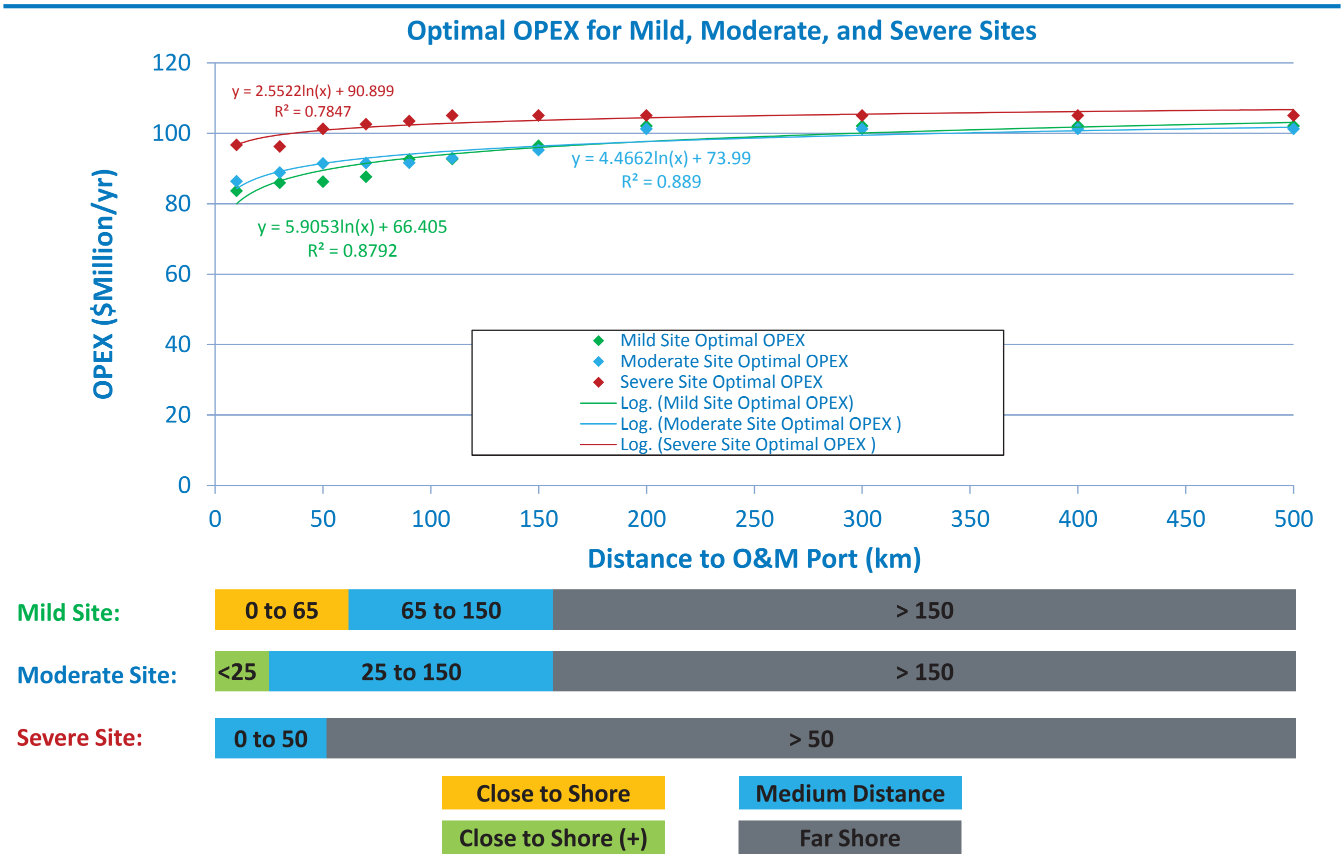
Case Study 2: Fixed-Bottom Results – Availability



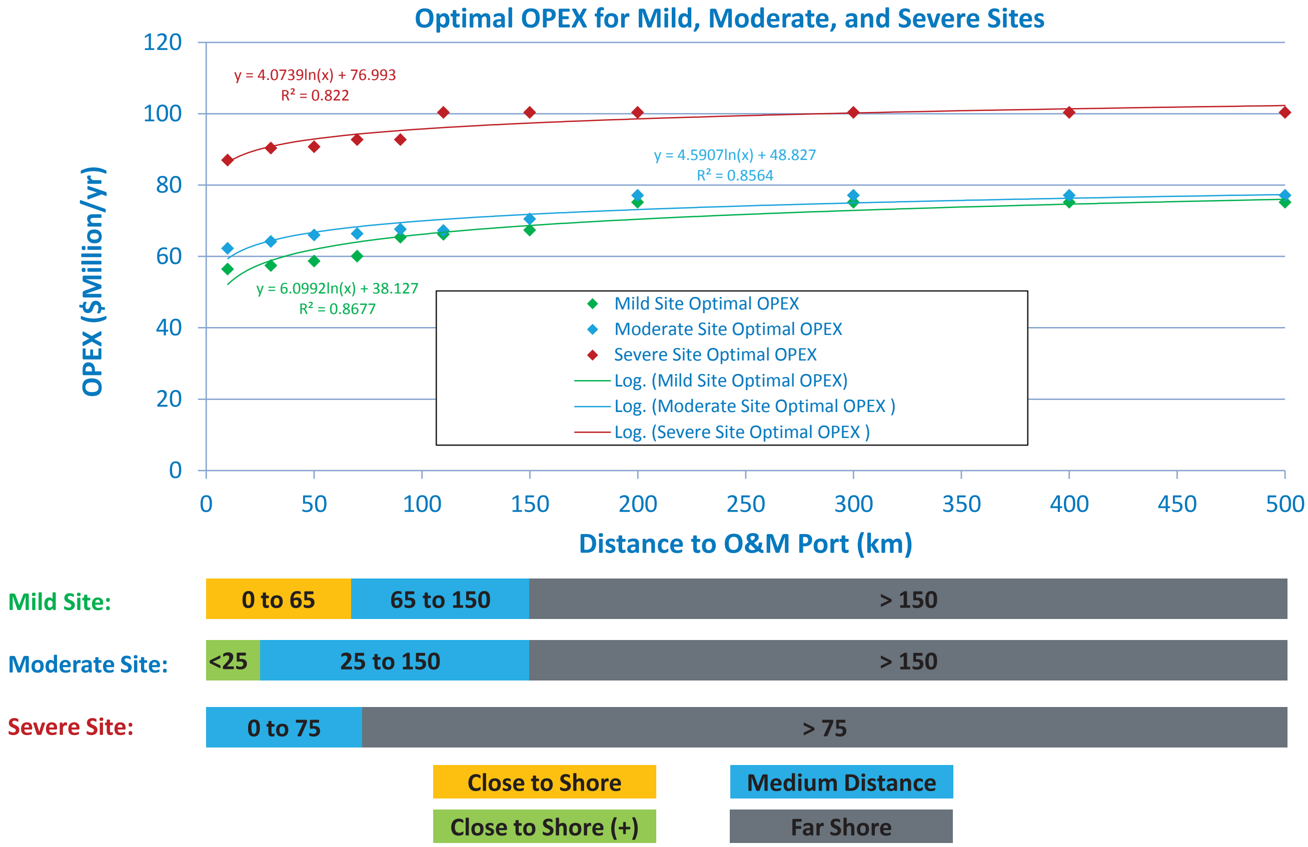
Case Study 2: Floating- Semi Results – Availability



Case Study 2: Fixed-Bottom Results – OPEX Curves



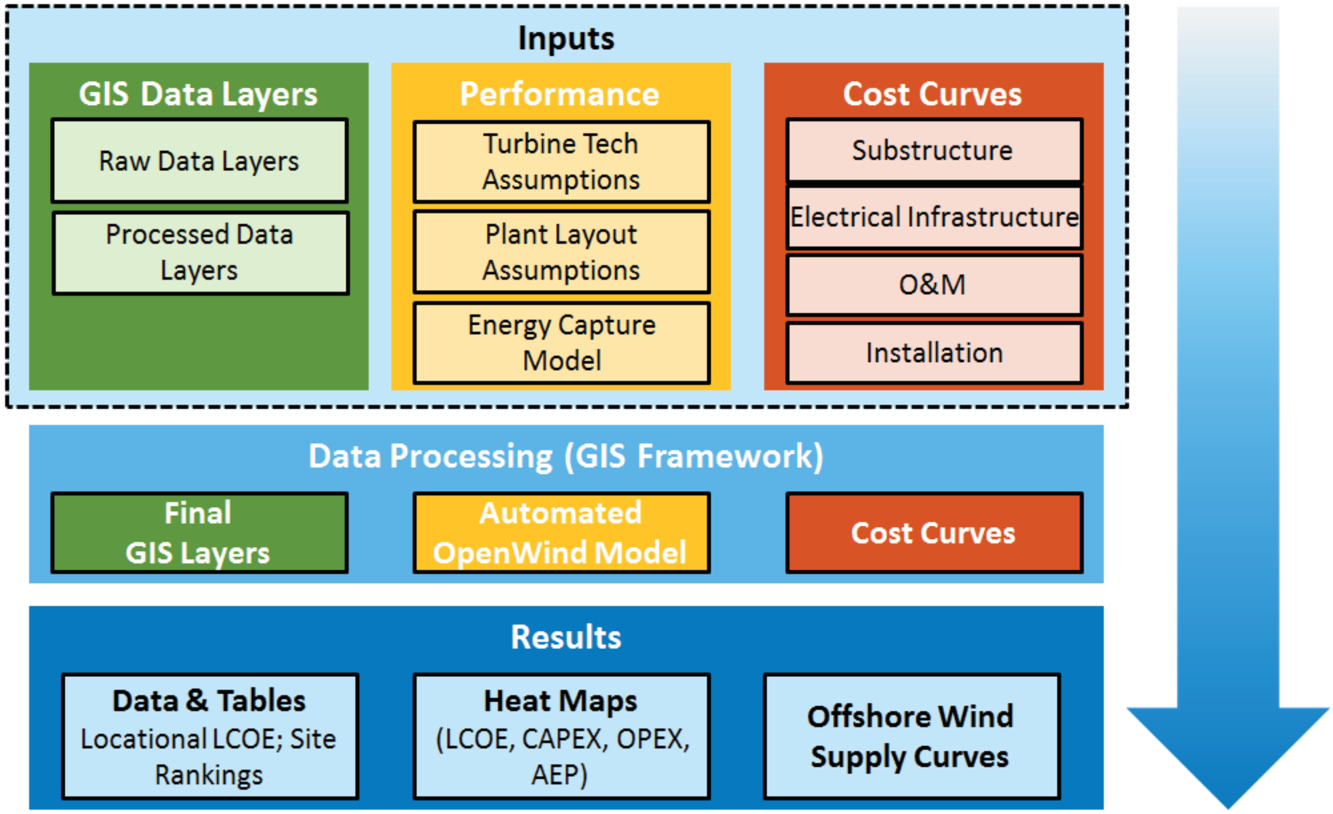
Case Study 2: Floating-Semi Results – OPEX Curves



Case Study 2: Key Insights

- **Metocean characteristics and distance to shore are key drivers for O&M cost and availability**
  - The industry is developing technology solutions and O&M strategies to mitigate the influence of these variables on availability; however, this generally increases the cost of the O&M strategy
- **Floating substructures can be repaired at port are generally expected to cost less compared to fixed bottom technologies in mild and moderate sites**
  - Potential to reduce costs 18-20% compared to fixed substructures in moderate metocean conditions using a medium distance O&M strategy
  - In severe sites this may reduce costs by 2-3%
- **Floating technology tend to be have a higher variance in O&M cost in severe metocean conditions compared to fixed substructures**
- **Wind plant availability nearly identical between fixed and floating technologies**
  - Severe metocean conditions reduce wind plant availability about 6-8% when comparing moderate and severe sites for both fixed and floating technologies using a medium distance O&M strategy

Next Steps



Thank You

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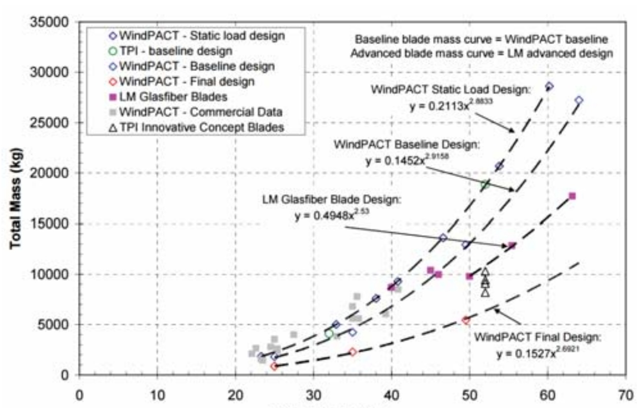
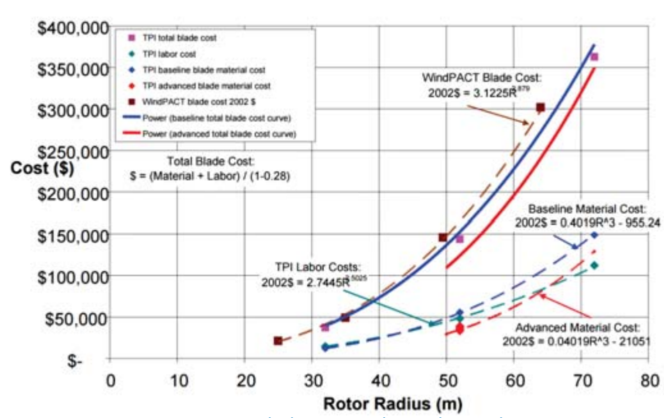
Back-up Slides

NREL Cost and Scaling Model

- **Built from work done by University of Sutherland and the Wind Partnerships for Advanced Component Technology (WindPACT)**
- **Projects costs based on different scales of turbines**
  - Not intended to predict turbine "pricing" (which is a function of volatile market factors)
- **Cost and scaling functions were developed for major components and subsystems**
- **Cost and scaling model is expected to be updated and integrated into SAM**



Blade mass scaling relationship



Blade cost scaling relationship

http://www.nrel.gov/wind/pdfs/40566.pdf

NREL Offshore Balance of System (BOS) Model

- The NREL Offshore BOS model is based on data provided by wind industry stakeholders
  - Draws from offshore wind projects in Europe and experience in the onshore wind industry in the United States
- NREL has been implementing recent improvements to the model that give users the capability to analyze costs for both fixed and floating technologies
- Parameter studies

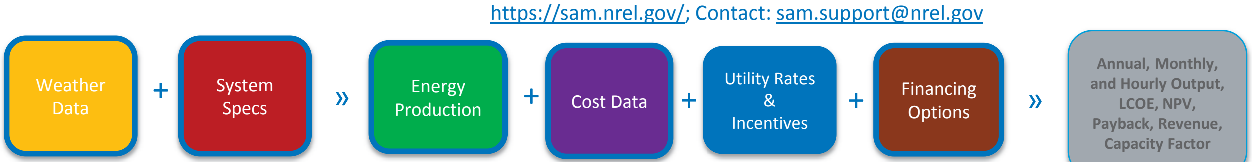
System Advisor Model (SAM)

The System Advisor Model (SAM) is a free user-friendly computer program that **calculates a renewable energy system's hourly energy output** and **calculates the cost of energy** for a renewable energy project over the life of the project.

SAM includes a variety of technologies and financial market options:

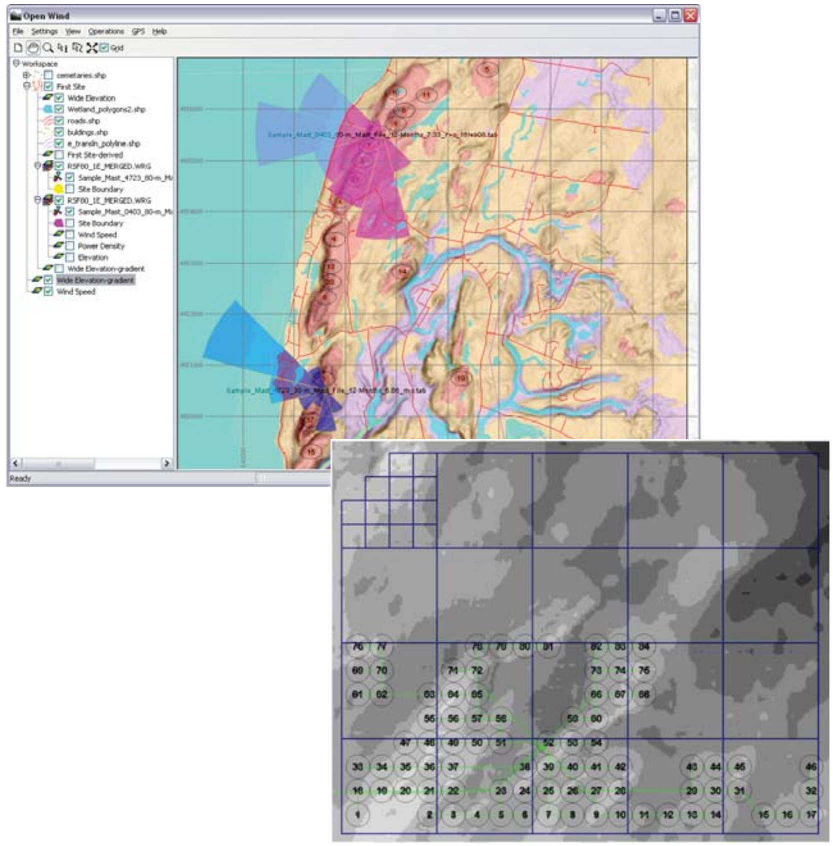
- PV
- Wind
- Solar Water Heating
- Concentrating Solar Power
- Geothermal
- Biomass Power
- Detailed cash flows or simple LCOE calculations
- Utility-scale or distributed systems

https://sam.nrel.gov/; Contact: sam.support@nrel.gov



Openwind (AWS Truepower)

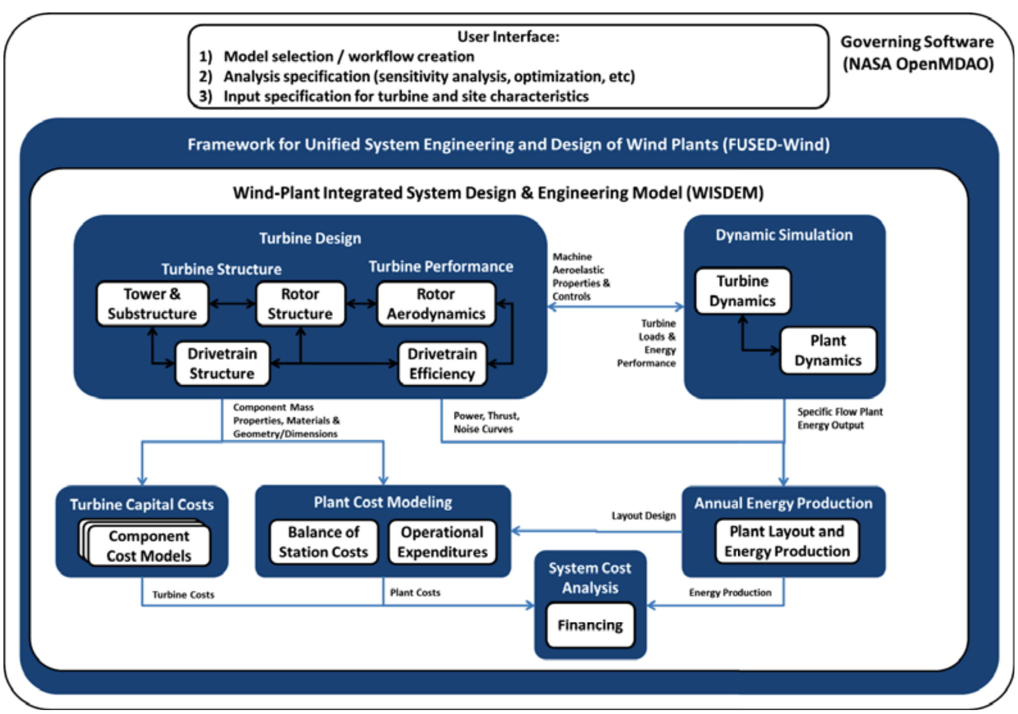
- Wind energy capture utilizing manual of optimized turbine locations
- Estimation of energy losses due to wake effects utilizing 6-7 different approaches to wake propagation:
  - Park Wake
  - Modified Park Wake
  - Eddie Viscosity Wake
  - Fast-Eddie Viscosity Wake
  - Deep Array Eddie Viscosity Wake
  - Etc…



NREL Wind Energy System Engineering

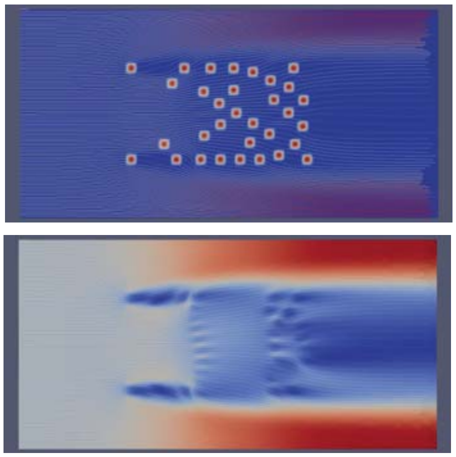
Project to develop, maintain, and apply a software platform to:

1. Integrate wind plant engineering and cost software.
2. Apply advanced analysis methods in multidisciplinary design, analysis and optimization.
3. Develop a common platform and toolset to promote collaborative research.

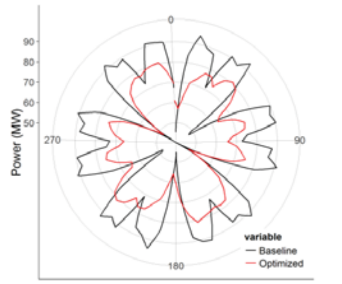


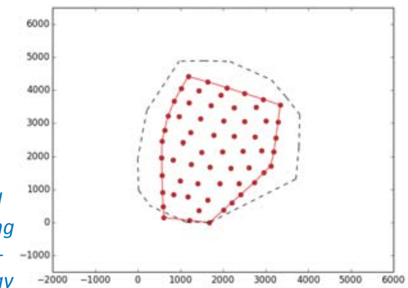
NREL Wind Energy Systems Engineering

- **High performance computing capabilities applied in several project activities for wind plant optimization and analysis:**
  - Integrated optimization of wind plant controls and layout design
  - Integrated optimization of wind plant layout with computational fluid dynamic (CFD) models using adjoint methods
  - Integrated optimization of turbine selection and plant layout using standard industry tools



Optimization of plant layout on Peregrine using adjoints in FEniCS





Optimization of plant layout and controls with FLORISSE (extending now to full coupling with FUSED-Wind and CCBlade) for full energy production optimization on Peregrine

http://www.nrel.gov/wind/systems_engineering/

Contact: Katherine.Dykes@nrel.gov

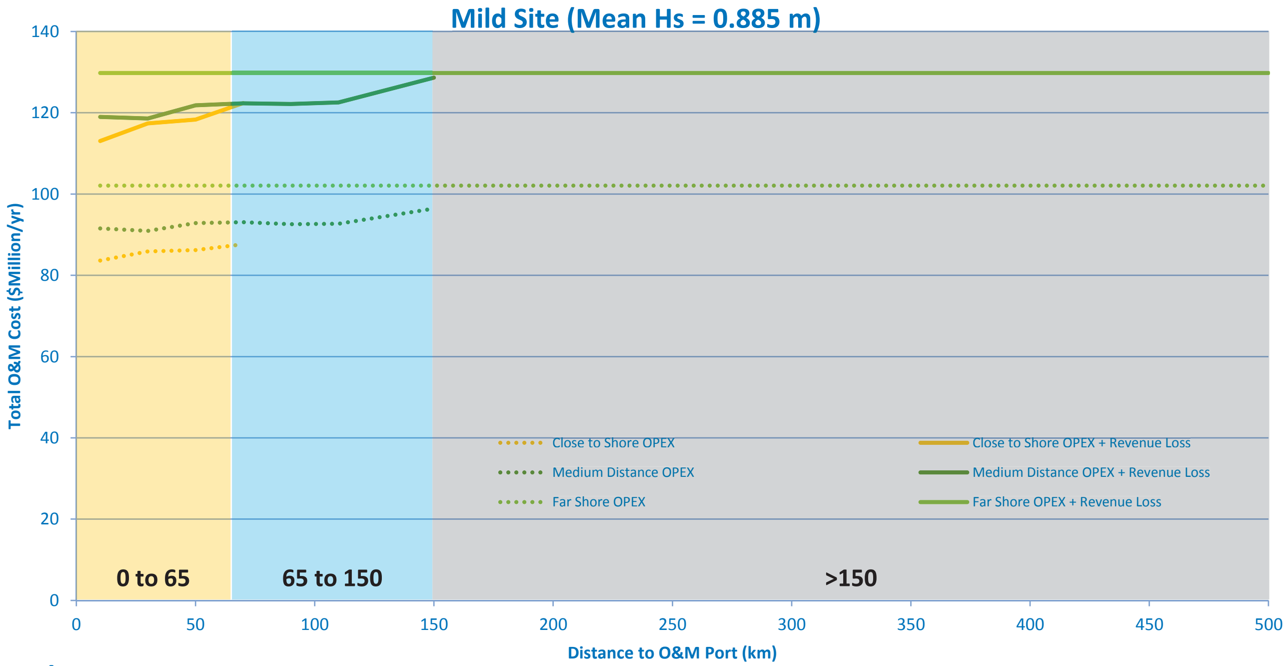
OPEX Modeling – Modeling Parameters

	Close to Shore	Close to Shore+	Medium Distance	Far Shore
Alias	CS	CS+	MD	FS
Description	Standard Port-Based O&M Strategy	Standard Port-Based O&M Strategy	Enhanced Port-Based O&M Strategy	Mothership-Based O&M Strategy
Principle Access Vessel	Basic CTV	Advanced CTV	SES	CTV with Mothership support
Wind Limit (m/s)	20	20	20	20
Hs Limit (m)	1.5	2.3	2.5	2.5*
Vessel Speed (kn)	20	20	35	20
Access Vessel Dayrate	$2,800†	$6,500‡	$9,000‡	$2,800†
Passengers (#)	12	12	12	12
Shift Length (hr.)	12	12	12	12
Docking and Transfer Time (hr.)	0.5	0.5	0.5	1.0
Fuel consumption rate (gal./hr):	25	25	20	25
Fixed Annual Maintenance Costs	n/a	n/a	n/a	$18,000,000‡
Capital Investment	n/a	n/a	n/a	n/a

†ECN User Guide
‡Communications with industry
Note: All other O&M equipment was assumed to remain the same as in the BP1 O&M analysis

*Crew Transfer Vessels (CTVs) were assumed to have relaxed weather limitations, reduced transport speed, and longer access time for modeling the far shore O&M strategy. CTV limitations were assumed to be the same as the mothership to simulate the ability of the mothership to directly transport technicians for repair.

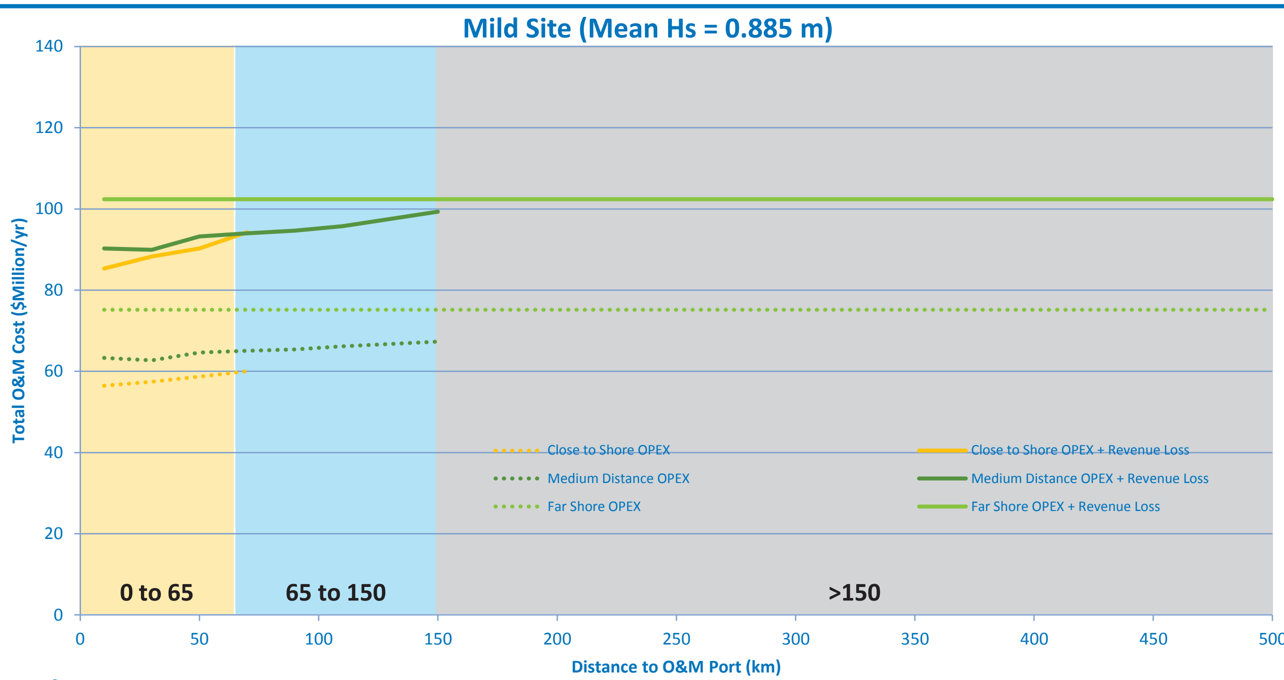
OPEX Parameter Study Fixed-Bottom Results – Mild Site



Results:

- **Transportation time restriction (2 hr.) drives breakpoints between strategies at the mild site**

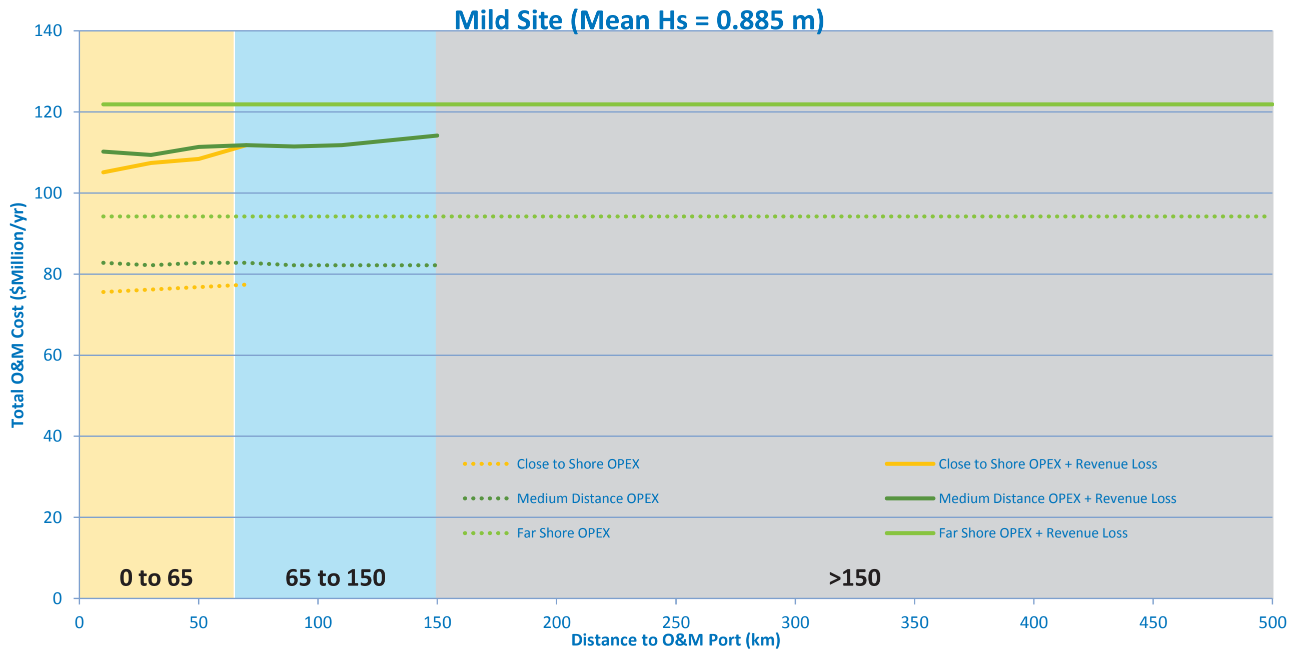
OPEX Parameter Study Floating-Semi Results – Mild Site



Results:

- **Transportation time restriction (2 hr.) drives breakpoints between strategies at the mild site**

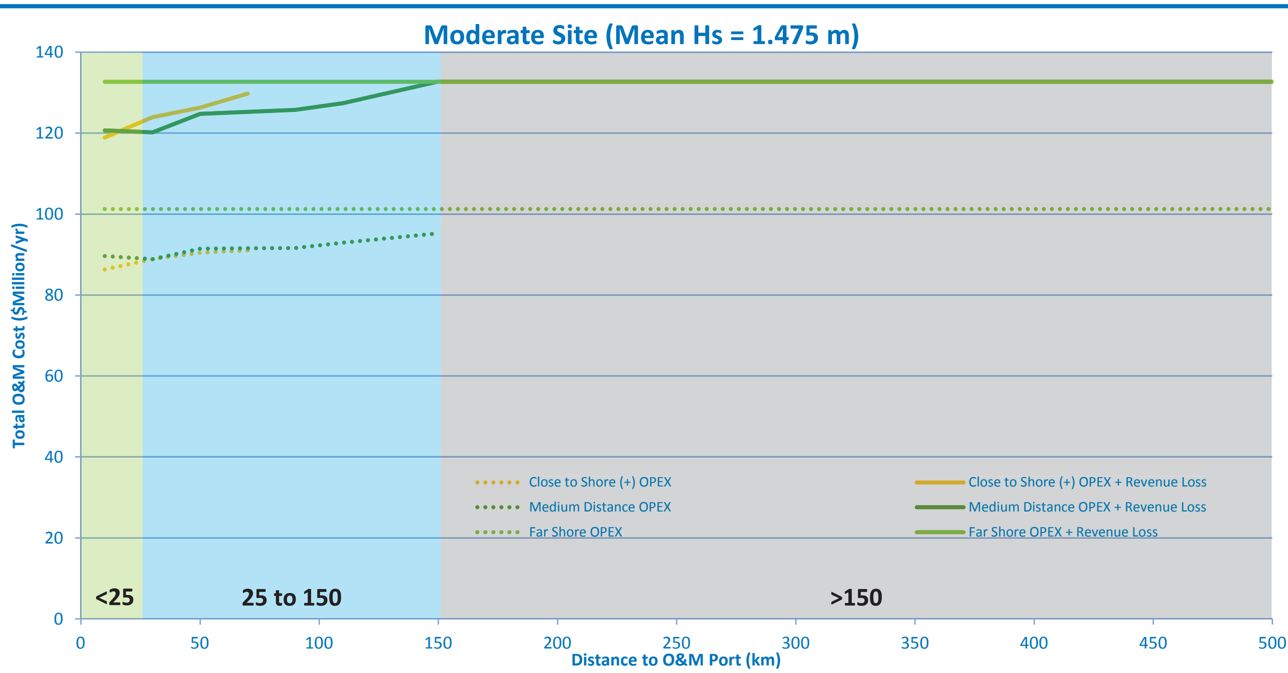
OPEX Parameter Study Floating-Spar Results – Mild Site



Results:

- **Transportation time restriction (2 hr.) drives breakpoints between strategies at the mild site**

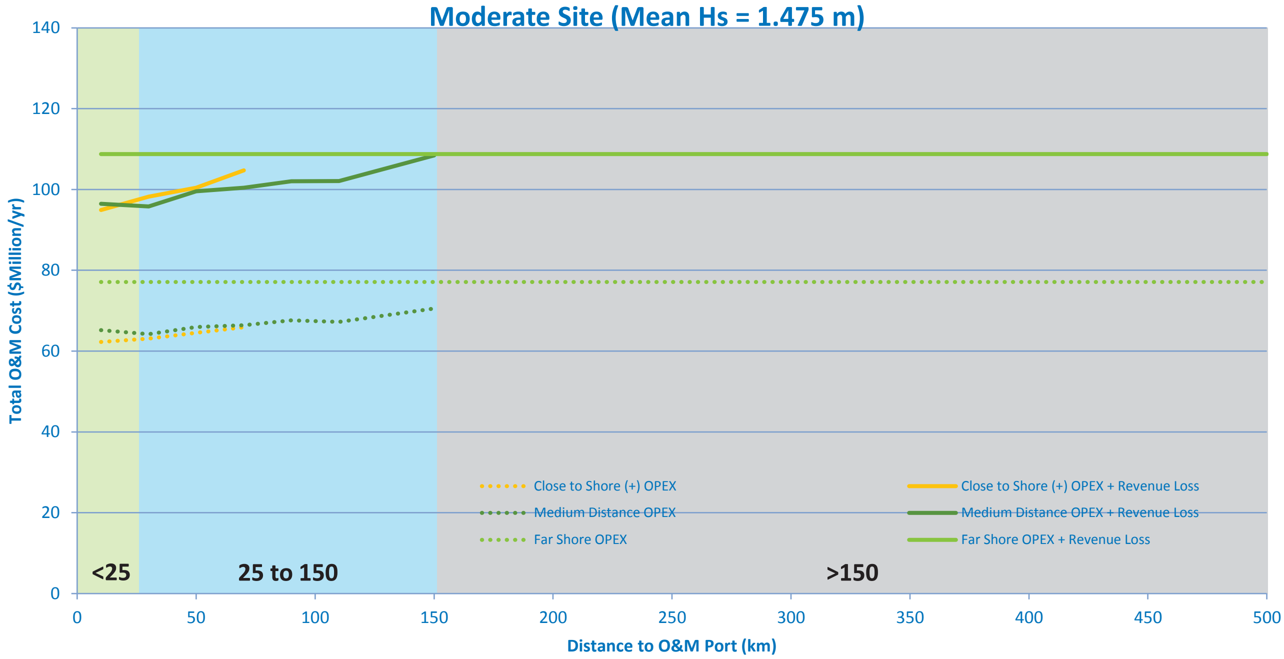
OPEX Parameter Study Fixed-Bottom Results – Moderate Site



Strategy:

- **Cost drives the breakpoint between Close to Shore (+) and Medium Distance Strategies**
- **Transportation time restriction (2 hr.) drives breakpoint between Medium Distance and Far Shore Strategies**

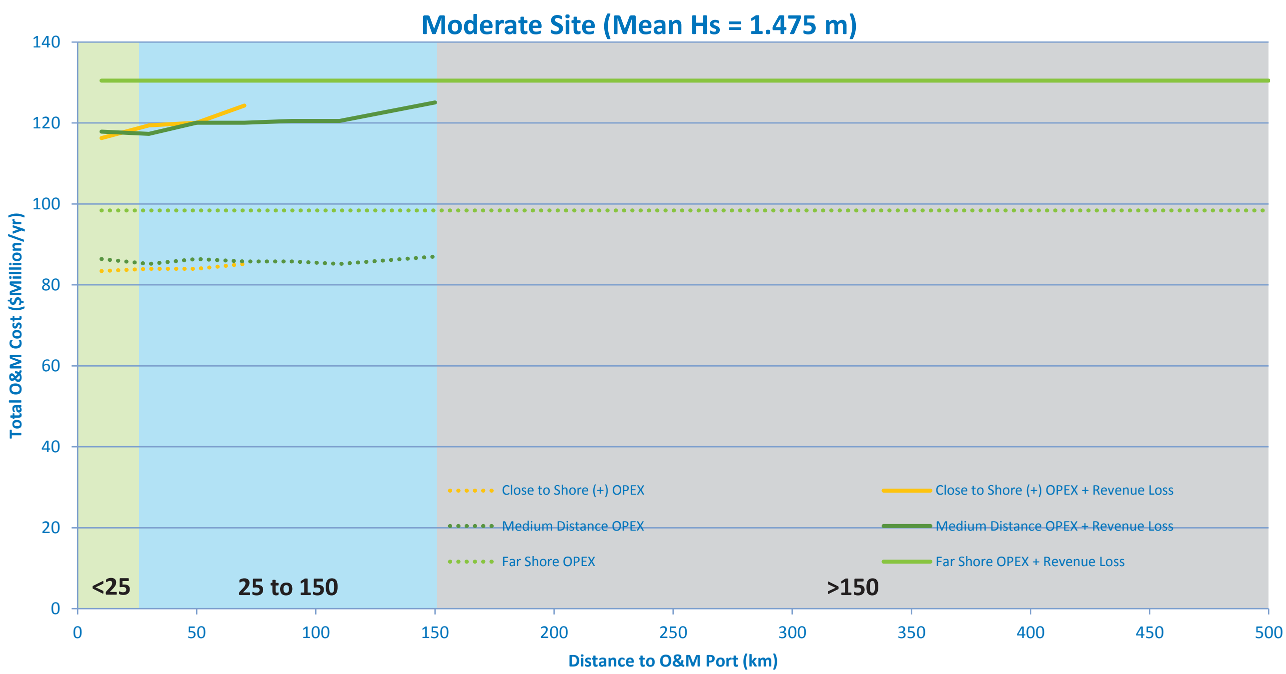
OPEX Parameter Study Semi Results – Moderate Site



Strategy:

- Cost drives the breakpoint between Close to Shore (+) and Medium Distance Strategies
- Transportation time restriction (2 hr.) drives breakpoint between Medium Distance and Far Shore Strategies

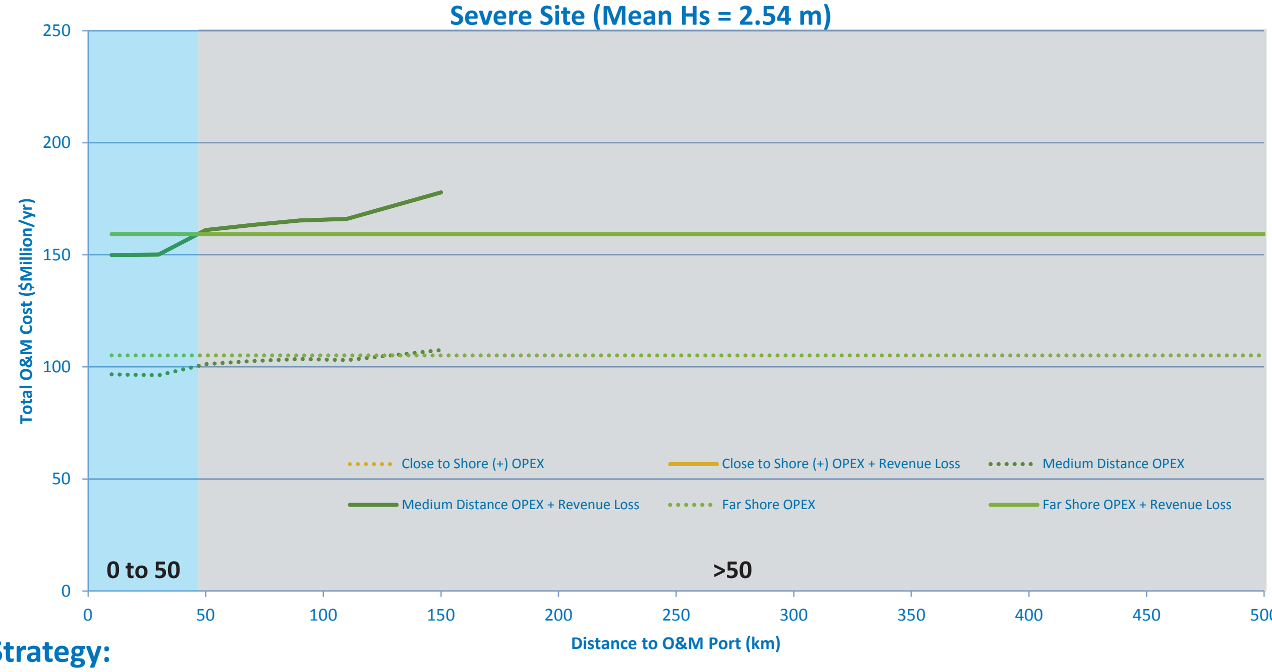
OPEX Parameter Study Spar Results – Moderate Site



Strategy:

- Cost drives the breakpoint between Close to Shore (+) and Medium Distance Strategies
- Transportation time restriction (2 hr.) drives breakpoint between Medium Distance and Far Shore Strategies

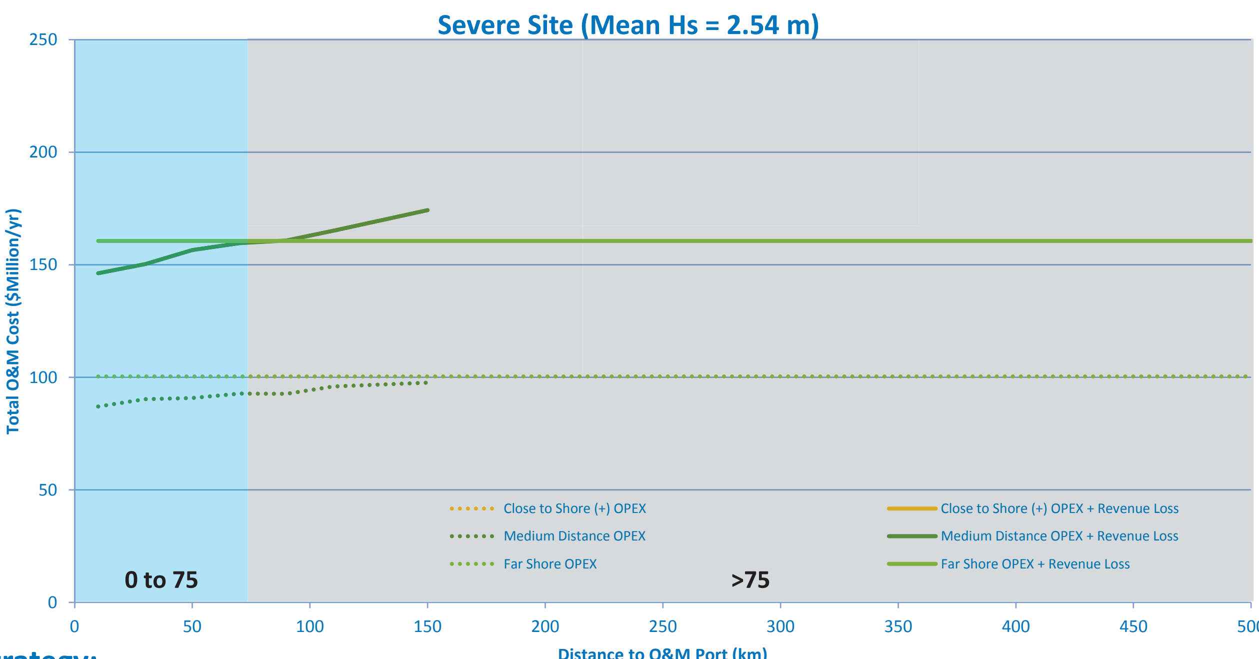
OPEX Parameter Study Fixed-Bottom Results – Severe Site



Strategy:

- **Close to Shore (+) strategy never cost effective at the severe site**
- **Economics drives the breakpoint between the Medium Distance and Far Shore Strategies**

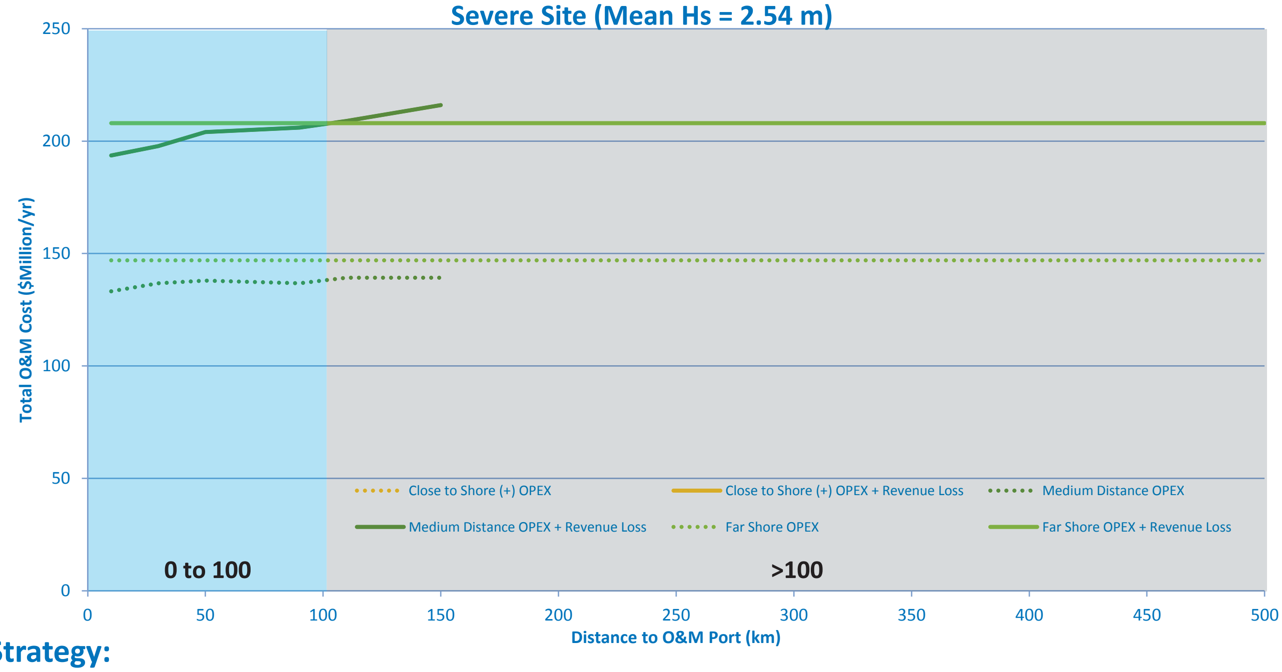
OPEX Parameter Study Floating-Semi Results – Severe Site



Strategy:

- **Close to Shore (+) strategy never cost effective at the severe site**
- **Economics drives the breakpoint between the Medium Distance and Far Shore Strategies**

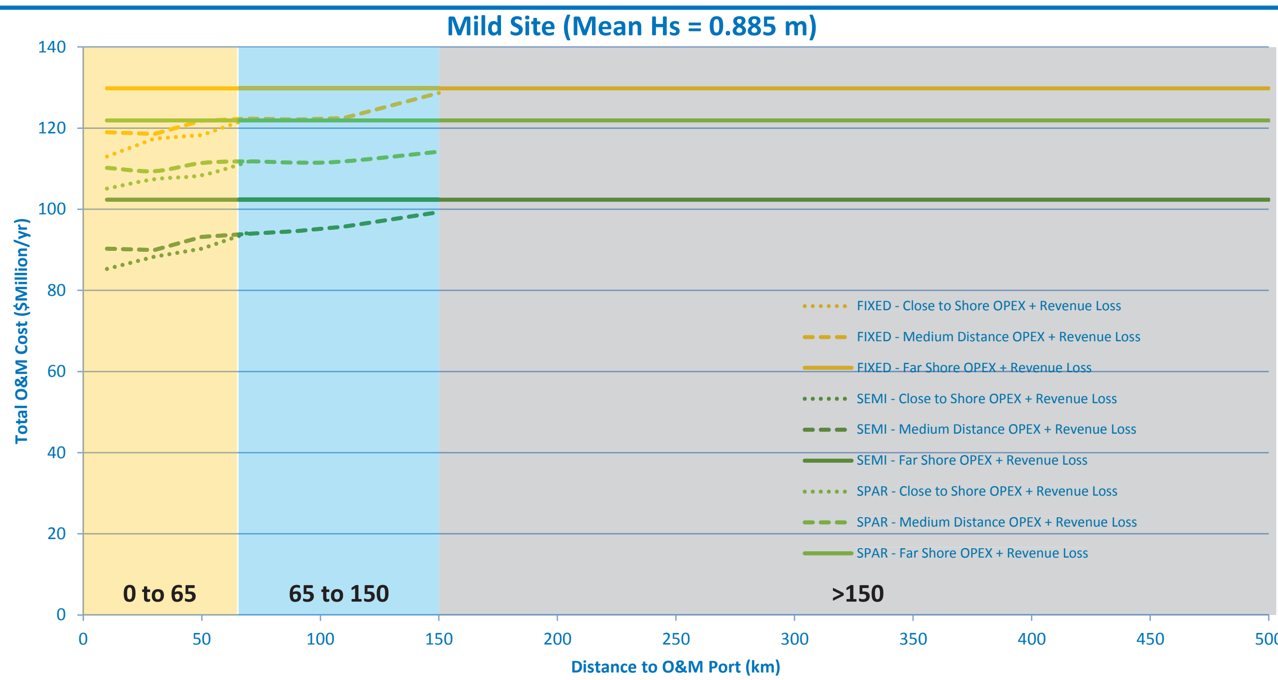
OPEX Parameter Study Floating-Spar Results – Severe Site



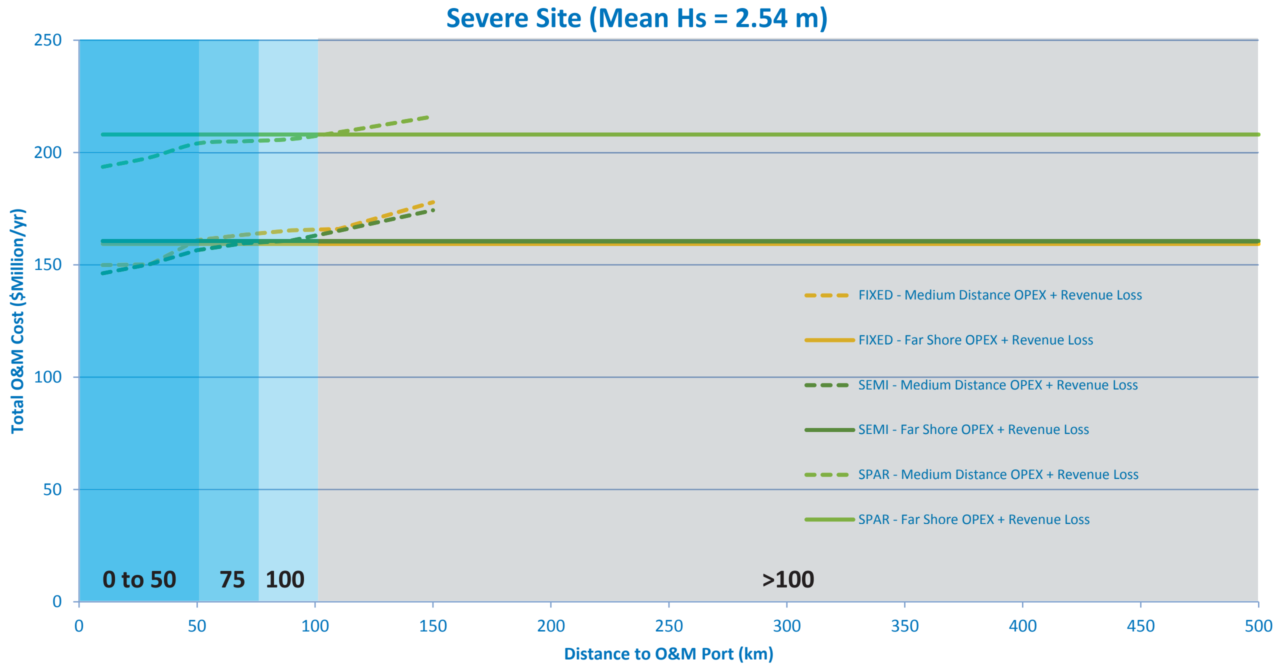
Strategy:

- **Close to Shore (+) strategy never cost effective at the severe site**
- **Economics drives the breakpoint between the Medium Distance and Far Shore Strategies**

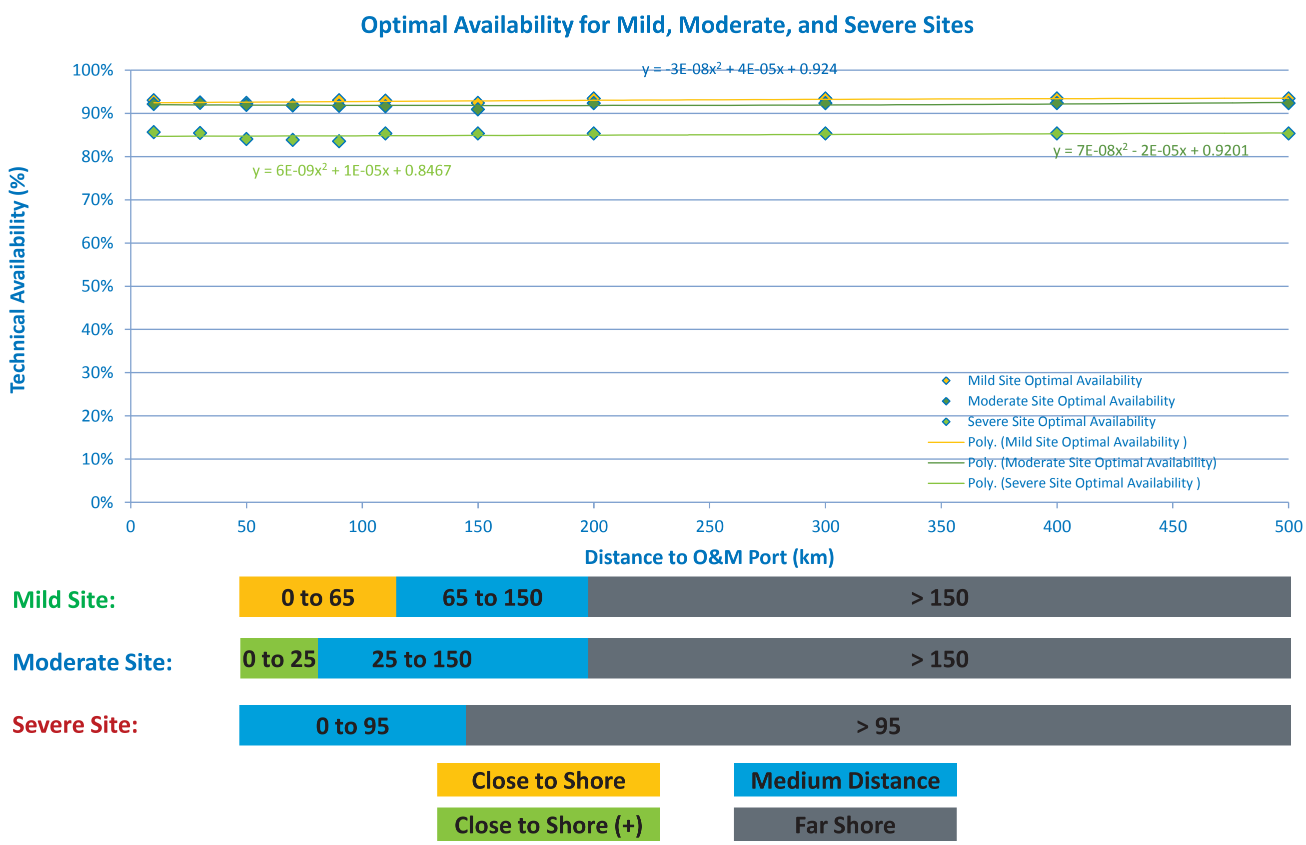
OPEX Comparison – Mild Site



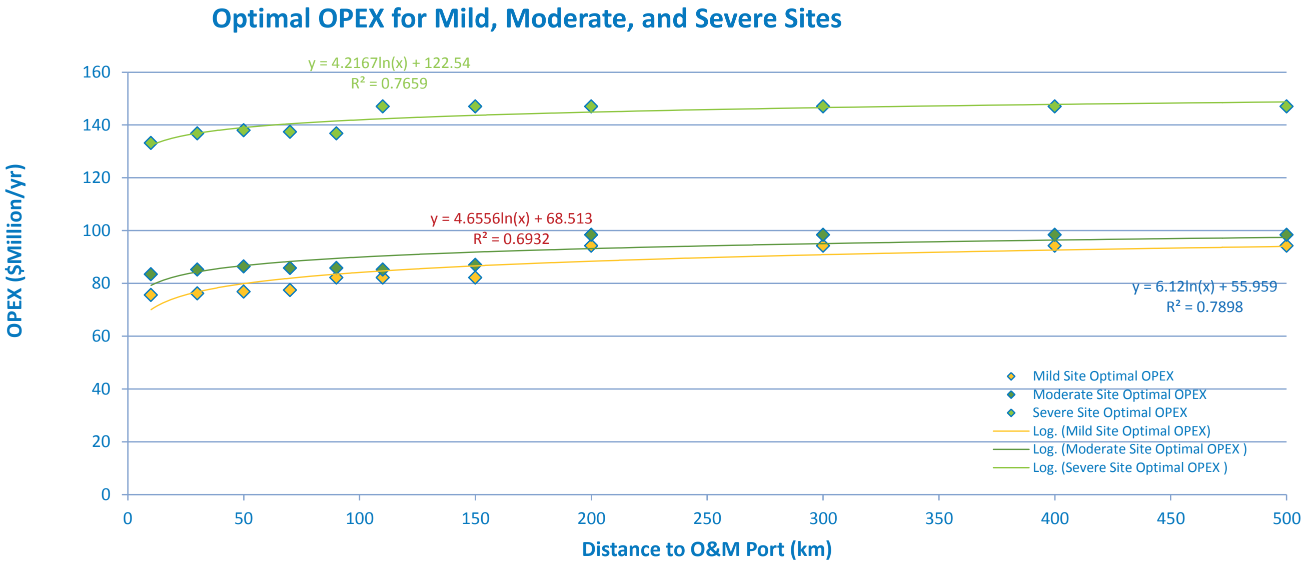
OPEX Comparison – Severe Site

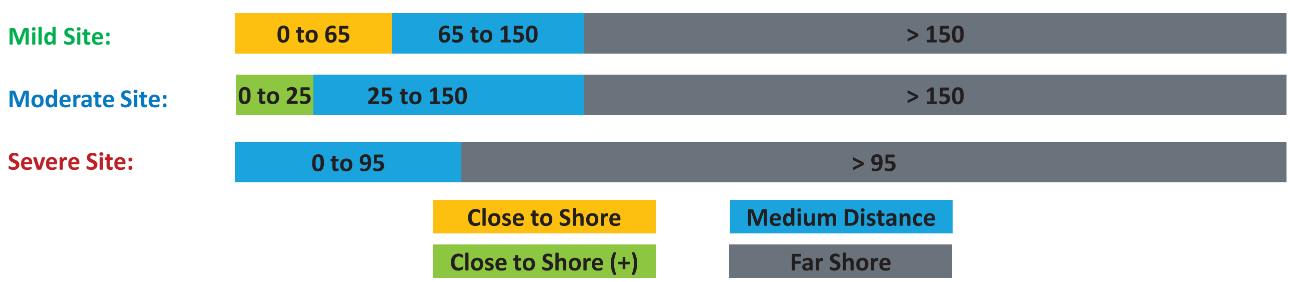


OPEX Parameter Study Floating-Spar Results – Availability



OPEX Parameter Study Floating-Spar Results – OPEX curves





Power Purchase Agreement (PPA): Performance-Based Levlized Cost of Energy

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Before establishing the federal Public Utilities Regulatory Policies Act (PURPA) in 1978 on producing electricity specifically from renewable resources, US power plants were built, owned, and operated by utilities to serve their own load. Levelized cost of energy (LCOE) was used as a metric for comparing energy prices; it was calculated by the total life cycle for the total lifetime energy production constant capacity factor (CF). The wind power plants CF degradation or downtimes (DTs) due to variable wind speed should be considered in calculating LCOE. Though the LCOE model considers the cost of turbine maintenance, it does not consider the loss of profit from not producing energy or over-producing energy outlined in contract terms within power purchase agreements (PPAs).

A PPA, also known as energy performance contracting (EPC) is defined as a long-term contract to buy electricity from a power plant. PPAs secure the payment stream for a power producer and satisfy the purchaser's (often federal and state) regulations/requirements for long-term electricity generation. A PPA defines a price schedule at which electricity is sold with optional annual escalation and a variety of time-of-delivery factors. Outlined minimum and maximum annual energy delivery quantities in PPAs reduces the risk that the energy buyer will be paying for energy that exceeds consumer needs while at the same time providing for enough energy to be supplied for consumer needs. The important parameters that are addressed in PPAs include: the levelized cost of energy (with/without state and federal incentives), length of the agreement, and delivery of energy. While the traditional cost of energy represents an expected investment to bring a plant to commercialize operation, a PPA reflects long-term prices for electricity after counting for incentives, such as the production tax credit received from Environmental Attributes.

Using PPAs over a traditional energy contract allows for more flexibility in future energy production and ensure a fair pricing schedule that improves on the delivery of energy to the buyer. PPAs can play a critical role in the success of a wind project. The length of agreement, commissioning process, sale and purchase, curtailment, transmission, project financing, wind resource and turbine performance characteristics at a studied site, and environmental attributes (credits) all affect a wind PPA. There was a total of 29,632 MW in 337 signed PPAs for farms in January 2014. PPAs owned by states/governments have considerable contractual security (they adjust the lack of expected results with additional credits); however, they do not always deliver the expected results due to either over/under estimation of performance parameters such as not-accurate wind assessment analysis and technology improvements or contractual terms such as intermittency of PTC. Hence, securing a good PPA is not simple, and instead, it is often one of the most challenging elements of wind project development. Hence, in this work contractual terms concurrent with designing system parameters to meet customer and contractor requirements for a wind plant PPA have been studied in which, more realistic numbers in wind PPAs would be defined through addressing existing uncertainties.

Power Purchase Agreements (PPA): Comparisons of Performance-Based Levelized Cost of Energy

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International Workshop on Life-cycle Costing of Offshore Wind Turbines and Farms
University of Maryland, College Park, Maryland, USA
October 01, 2015

Motivation

- Power Purchase Agreements (PPAs) were created as a “fair” method to both the utility and the power generating company.
- A review of the LCOE through PPA contract terms to help define a “fair” cost for each unit of energy.

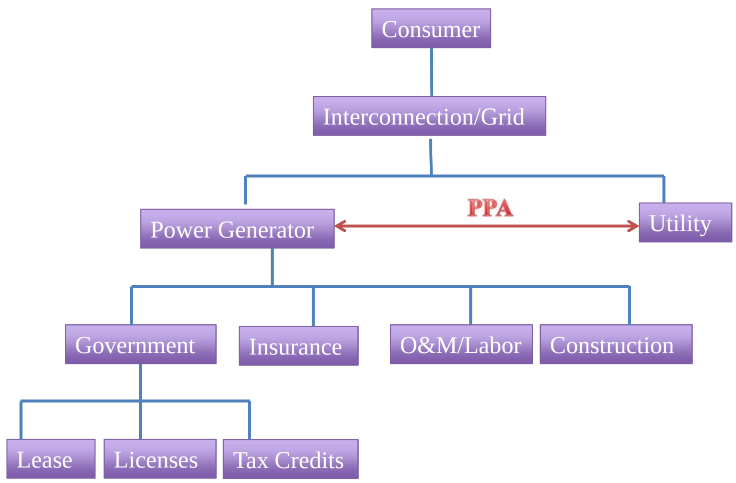
Objective

- To optimize PPAs and cost of energy (COE) through contract terms.
- To study the impact of annual energy delivery thresholds (maximum and minimum) on the Levelized Cost of Energy (LCOE).

Background

- US power plants were built, owned, and operated by utilities to serve their own load until 1978 when the federal Public Utilities Regulatory Policies Act (PURPA) established producing electricity specifically from renewable resources.
- There was a total of 29,632 MW in 337 signed PPAs for farms in January 2014.
- Despite the increasing trends to use PPAs, there is no criteria to compare different PPAs.
- Without a comparison, there is no method to fully meet the goal of a “fair” contract to both the Seller and the Buyer.

Business Structure



PPA Structure

<u>PPA content and focus of this work:</u>

- Delivery of energy
  - Maximum and minimum annual energy production
- Obligations
  - Obligation to buy generated power
- Purchase prices and price schedule
  - Requirements for the Seller to obtain grants and loans to help reduce Cost of Energy (COE)
  - Includes the acquirement of renewable energy credits
- Billings and Payments
  - All kWh production to be paid for every month by the Buyer
  - Fiscal year calculations to adjust invoices according to annual penalties

Other PPA Parts

- Term
- Operations and Control
- Limitations
- Milestones
- Metering
- Credit
- Interconnection and Grid
- Force Majeure
- Decommissioning
- Indemnification, Liability and Insurance

All of these are important attributes of PPAs, however they will not be considered in this study.

Different PPA Types: For Energy Delivery

- No penalties in energy delivery quantity
- Just a minimum delivery quantity
  - Set at ***52%*** of the first year's expected production
- Just a maximum delivery quantity
  - Set at ***75%*** of the first year's expected production
- Both a maximum and minimum delivery quantity

Model

Parameters	Equations
Penalty cost for not reaching annual minimum energy delivery	$PN = \sum_{i=1}^{n} \frac{(0.52P_{\exp1} - P_i) \cdot C_i}{(1+r)^i}$
Production loss from incurring maximum annual energy to be bought	$PL = \sum_{i=1}^{n} \frac{(P_i - 0.75P_{\exp1}) \cdot C_i}{(1+r)^i}$
Levelized Cost of Energy (LCOE)	$LCOE = \frac{\sum_{i=0}^{n} \left(\frac{I_i + OM_i + F_i - TC_i + Pen_i}{(1+r)^i}\right)}{\sum_{i=0}^{n} \left(\frac{E_i}{(1+r)^i}\right)}$ $Pen = PN + PL$ $E_i = 8760 \cdot P_i \cdot CF_i$ $TC_i = IBI_i + PBI_i + CBI_i + ITC_i + PTC_i + D_i$

Levelized Cost Of Energy

$$\frac{\text{Sum of costs over lifetime}}{\text{Sum of electricity produced over lifetime}}$$

- **Other LCOE models:**

1. $$\frac{CRF}{8760 P_R C_f}(C_I + C_{om(esc)})$$

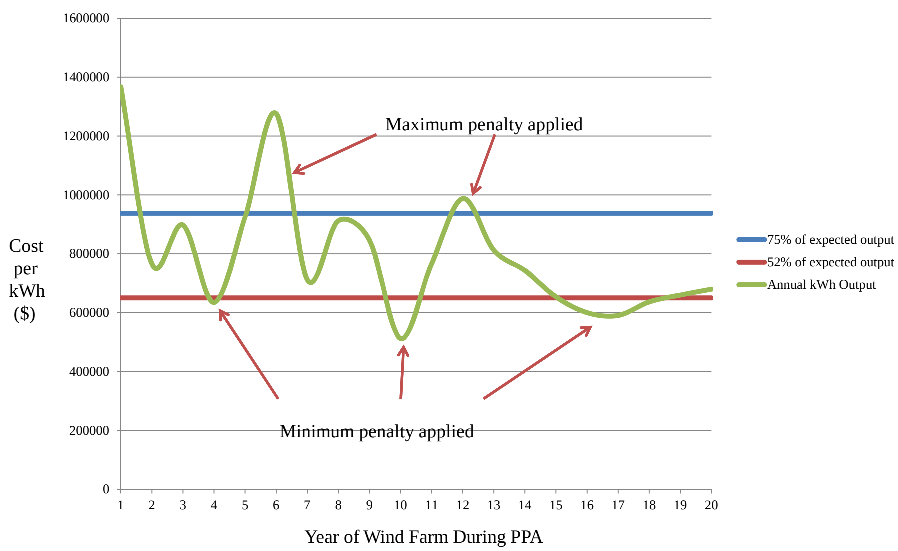
2. $$\frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Variable Values

- Tax Credit of $0.05 for all farms
- Down Time is included in the Capacity Factor calculation
- Investments are used only in year 1 as a one time initial cost
- Constant cost of money independent of PPA types
- WACC of 8.9% as calculated by NREL report in 2015[1]
- *t* begins at year 0 because WACC does not apply in the initial year
- O&M cost: $0.01 per produced kWh[2]
- Investment cost: $1500 per kW[2]
- Fuel cost: $0 (wind as a free and abundant energy source)[2]

[1]Sullivan Patrick, et al. (2015) "2015 Standard Scenarios Annual Report: U.S. Electric Sector Scenario Exploration," National Renewable Energy Laboratory. Available on : http://www.nrel.gov/analysis/data_tech_baseline.html
[2] Soren Kohn, et al. (2009) " The Economics of Wind Energy" European Wind Energy Association. Available on: http://www.ewea.org/fileadmin/files/library/publications/reports/Economics_of_Wind_Energy.pdf

Application of Penalties



Wind Farms Used

Wind farm dataset	Wind turbine manufacturer	Year Built	Rated power (kW)	Number of Turbines	Location
1	Vestas	2002	2000	17	Germany
2	Enercon	2005	2000	24	Germany
3	Siemens	2010	2300	11	Denmark
4	Enercon	2010	2000	10	Germany
5	Vestas	2010	3000	18	Denmark
6	Vestas	2007	3000	5	Germany
7	Siemens	2006	3600	7	Germany

* Wind data from WindStats

Set 2 LCOEs

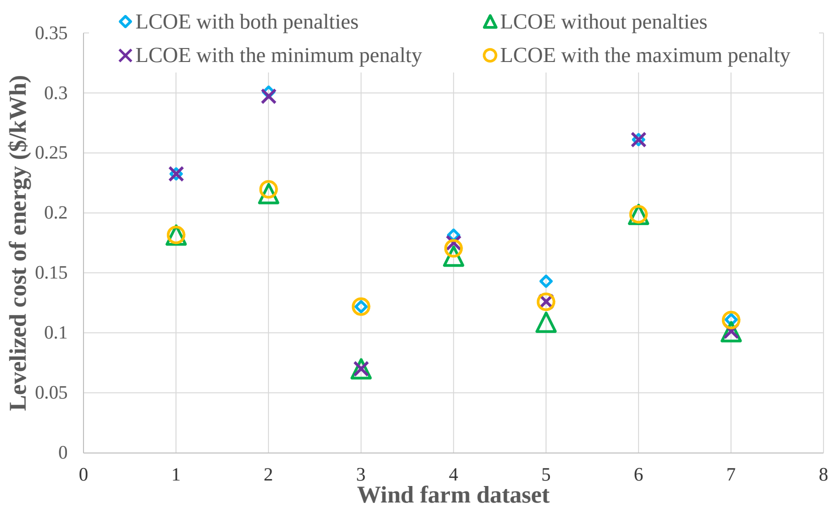
- There were only 5 years of data from WindStats, so the LCOEs reflect a short-term contract.
- The final LCOE calculated from the discounted sum of the 5 years.

Wind farm dataset	Wind turbine manufacturer	Year Built	Rated power (kW)	Number of Turbines	Location
2	Enercon	2005	2000	24	Germany

	2011	2012	2013	2014	2015
No Penalty	1.010	0.542	0.393	0.299	0.216
Both Penalties	1.064	0.625	0.502	0.411	0.301
Maximum Penalty	1.016	0.547	0.397	0.304	0.220
Minimum Penalty	1.058	0.620	0.497	0.407	0.297

LCOE is decreasing over the years →

Results



Summary

- A PPA with just a maximum annual energy delivery is the best option for a contract with penalties
- The reason for the differences in the LCOE clusters in different wind farms is unknown
- Results show that it is best to reduce risk for the Buyer and Seller in entering a contract either without penalties or with just the defined maximum

Future research

- Research into the optimum LCOE based on PPA terms for the Buyer
  - Looks into the cost models to sell energy for the Buyer
- Research into optimizing the percentage of expected annual delivery for penalties
- More research into the reasons why each PPA contract produces different LCOEs
  - Needs more data on wind farms and actual costs, including money spent or lost on penalties

Maintenance and Operation Management Strategy to Reduce the Cost of Offshore Wind Power Generation

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The current state of offshore wind energy presents economic challenges that call for concerted efforts to seek solutions and chart out future paths of technology and research that will reduce the overall cost of production of offshore wind power. Among the several things needed in order to bring down the cost and make offshore wind power more viable are: Economic modeling and optimization of costs of the overall wind farm system, including installation, operations, and maintenance and service methodologies, remote monitoring, and diagnostics. Key parts to these are the collection of pertinent data on all components and related systems of the offshore wind farm and developing a robust health monitoring system for the operation of the turbines that will seek to reduce the cost of operations and maintenance.

Failures in offshore wind turbines are mostly common in the mechanical and electrical systems. Failures in both of these systems combined account for majority share in annual downtime. While replacing/servicing electrical systems are relatively easy, mechanical (gear box) systems are much more laborious, which account up to typically 25% of total annual down time. There are many off the shelf systems to improve the prediction and prevention of such failures, most of them are proprietary. Data is collected based on different Supervisory Control and Data Acquisition (SCADA)/ Condition Monitoring (CM) systems and is analyzed at a centralized location and decisions are made.

Considering wind turbine gearbox failures are leading reasons for higher maintenance in offshore wind farms, we decided to study gearbox data by comparing healthy and damaged gearbox sensor data collected from the National Renewable Energy Laboratories (NREL).

In this presentation we show signal data analyzed using Discrete Fourier Transform (DFT) and Discrete Cosine Transform (DCT) characterization techniques and comparing the results to find the better performing method in failure events classification and prediction. The identified signal patterns were then fed to a classifier for classifying (decision making) as normal or faulty. Our goal is to find characterization and classification techniques which are effective and efficient in identifying and predicting anomalies in the system through signal processing techniques.

Our preliminary investigation included applying a Fast Fourier Transform (FFT) and DCT on the raw signal data after signal segmentation to generate a space vector of both characterization techniques. The two space vectors were then tested with two vector similarity measures of Pearson correlation coefficient and Euclidean distance. The results of these experiments revealed that the Euclidean distance measure was superior to the correlation-based method in separating the healthy from damaged signal vectors with an average ratio of 10% to 50% respectively.

For classification, we trained a neural network model using a synthesized signals by embedding a faulty signal at randomly selected locations in a healthy signal and testing the classifier using random samples. The results were very promising with 99% true positive and 9% false positive. This has the potential of predicting catastrophic events and triggering alarms that could be used to provide information for appropriate timely corrective measures.

Maintenance and Operation Management Strategy to Reduce the Cost of Offshore Wind Power Generation

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UNIVERSITY OF MARYLAND EASTERN SHORE

Introduction

The current state of offshore wind energy presents economic challenges that call for concerted efforts to seek solutions and chart out future paths of technology and research that will reduce the overall cost of production of offshore wind power.

Introduction

Factors include:

Economic modeling and optimization of costs of the overall wind farm system, including installation, operations and maintenance and service methodologies, remote monitoring, and diagnostics.

Intelligent Health Monitoring Software System (IHMSS)

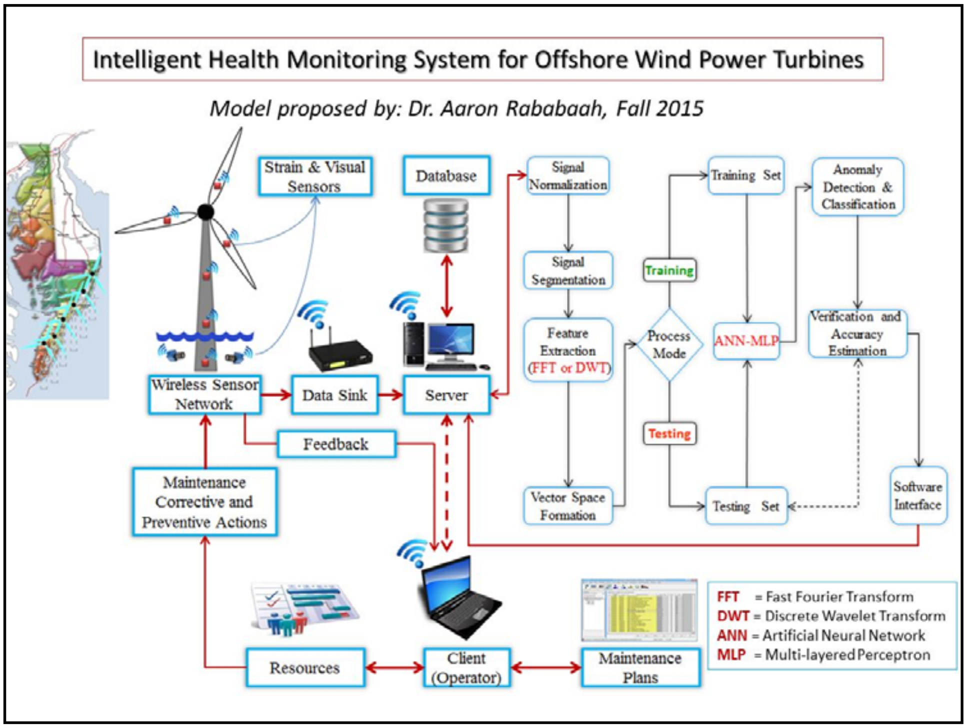
- The aim of developing the IHMSS is to reduce the cost of maintenance and operation of offshore wind power generation. This development is in five phases.

IHMS Model

- The concept of the proposed IHMS-WPT system is based on the model illustrated in Figure 1
- The model consists of five main components including:
- The sensor network attached (or embedded in) to the structure of the wind turbine
- The server that manages the data collection and database maintenance

IHMS Model

- The intelligent anomaly detection and classification software, the client (operator) that interacts with the server, resources and maintenance plans to issue needed corrective and preventive actions, and
- The resources available to the entire system to be used upon request by the client.



Wireless Sensor Network

- A network of sensors is deployed on the structure of the turbine to monitor the current structural health of the wind turbine.
- The sensors collect **data** periodically and wirelessly transmit it to a **data sink** which temporarily buffers all data collected from all sensors and wirelessly transmit them to the **server** which in turn permanently archives streams of collected sensor readings in a **database** to be used in the analysis phase of the intelligent software system.

The Server

- The server is a computer node that coordinates and maintains the sensor readings in a database. This database can be remotely queried by the client operator. The database is used by the intelligent software system for data analysis and inferences needed for further decision making and actions based on anomaly detections.

The Client Operator

- The client is a computer node that enables an operator to access the server and database remotely in teal time and query the current and archived status of the sensor readings.
- Further, the client can manage the operation of the intelligent system and collect results and issue reports to schedule maintenance plans for the wind turbine structure.
- The client operator has access to the available resources of the system to task them to do the recommended maintenance plans.

The Intelligent Software System

- The software system integrates two techniques to achieve reliable anomaly pattern detection and classification.
- These techniques are Digital Signal Processing (DSP) and Artificial Neural Networks (ANN).
- For the DSP, the Fast Fourier Transform (FFT) and the Discrete Wavelet Transform are used to denoise and characterize the sensor signals.
- For the ANN, the Multi-Layered Perceptron (MLP) is used as classification network for the characterized signals of the sensors.

Advantages of IHMS

- Reducing the frequency of offshore trips and transporting/ transferring equipment to the site
- Save time
- Reducing the frequency of exposure of maintenance crew to potential hazardous activities and environment

Advantages of IHMS

- Remove and/or minimize critical decision making away from Maintenance Crew facing the emergencies on site and transfer it to high level trained and expert personnel
- Provide several Central Monitoring locations that can share inputs , expertise, scheduling and managing emergencies
- Improve the methodology of operation and maintenance and reduce conflicts, interferences and redundancies

Development Phases

- Phase 1 System Modeling
- Phase 2 System Training
- Phase 3 System Simulation
- Phase 4 Small-Scale Real World System Deployment
- Phase 5 Large-Scale Real World System Deployment

Phase 1 System Modeling

- Based on the proposed model (Figure 1), the software is designed to accept inputs and implement different real world system components including sensors, data sink, server, and clients.
- These components are integrated so that they function seamlessly as the intended system.

Phase 2 System Training

- The training and the intelligence of machine learning component of the system are accomplished through building signal samples that are statistically significant, establish training sample set and testing sample space to train the system and evaluate its preliminary reliability in detecting and classifying structural anomalies

Phase 3 System Simulation

- Virtual scenarios of normal and abnormal/anomalous structural states are simulated and fed into the system to investigate the system capability of recognizing and reporting properly the registered events.
- The successful and satisfactory completion of this stage forms the basis for the next phases.

Phase 4 Small-Scale Real World Deployment

In this phase we aim to develop IHMSS that is suited for a single wind turbine system. Due to the lack of real data, we propose to accomplish this phase through the following stages:

- We will utilize NREL data sets and other possible sources as our baseline for training and testing the proposed model.

Phase 4 Small-Scale Real World Deployment

- Since characterization phase has been accomplished, we will proceed to study potential intelligent classifiers including Neural Networks, Fuzzy Logic, Clustering techniques and select one to be used as our classifier to classify the detected fault.

Phase 4 Small-Scale Real World Deployment

- Completing the IHMSS model as proposed and implementing our unique event-based characterization vs. traditional characterization methods and comparing the two approaches for potential efficiency gains.
- Testing the completed IHMSS model on data sets collected from different sources to validate its effectiveness and efficiency.

Phase 5 Large-Scale Real World Deployment

The goal of this phase is to scale-up the previous phase to a wind farm consisting of possibly of fifty turbines rather than considering a single turbine. We propose to accomplish this phase through following the stages

Phase 5 Large-Scale Real World Deployment

- Establishing a real data set for one turbine to be ran for certain period of time which is expected to be within 10 minutes. This data set will have healthy data and data of faulty components (gears, bearings, etc.).
- The data established in stage 1 above will be modified by adding, removing, amplifying, attenuating, etc. the existing failure events to simulate 50 turbines with different failures.

Phase 5 Large-Scale Real World Deployment

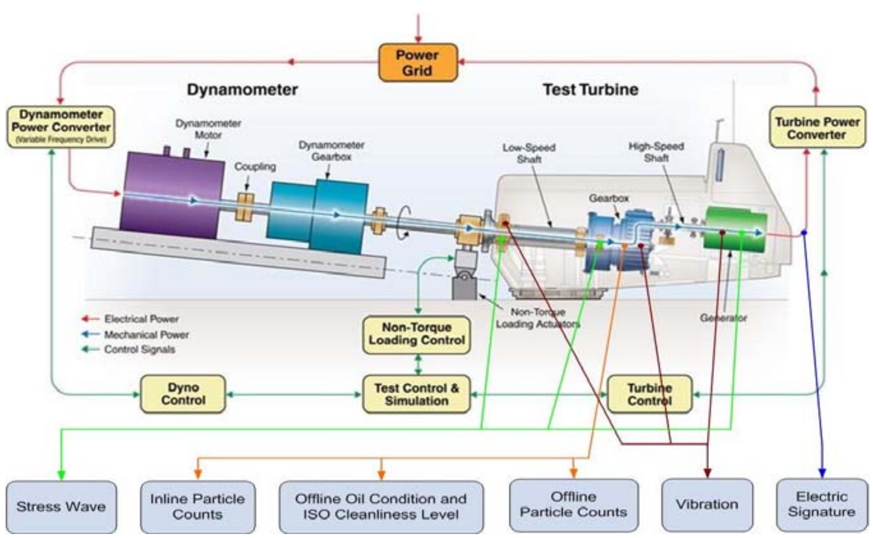
- Scenarios will be designed and ran on this simulated wind farm and one agent of IHMSS will be monitoring a single turbine.
- One central database/server will be simulated to collect, maintain and manage all the events detected by the individual IHSS systems.

Phase 5 Large-Scale Real World Deployment

- A user interface will be developed to facilitate the user interaction/queries with the server to generate reports about the health states of the simulated wind farm
- Testing of the developed wind farm health monitoring system will be conducted using the simulated turbines to verify its operational effectiveness and efficiency.

Analysis of Wind Turbine Gearbox Sensor Data

NREL Condition Monitoring Overview

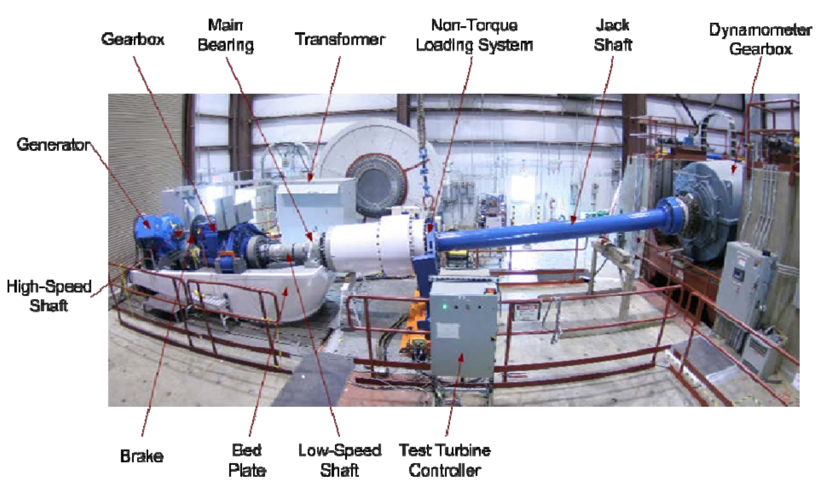


Gearbox Details

- Gearboxes used in 750kW wind turbines
- Both damaged and healthy gearboxes are the same model
- Same vibration sensors on both gearboxes
- In most of the literature, the "damaged" gearbox is referred to as "gearbox 1"
- In most of the literature, the "healthy" gearbox is referred to as "gearbox 2"

The Healthy Gearbox

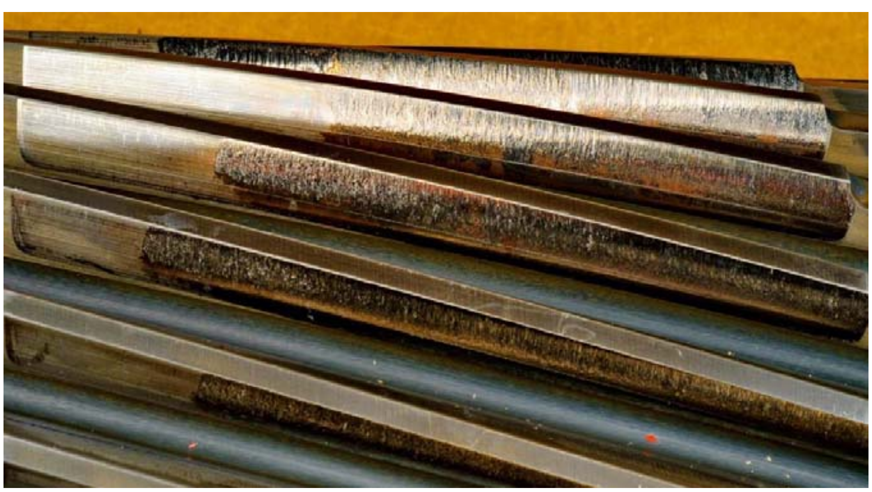
- A working gearbox tested in a dynamometer



The Damaged Gearbox

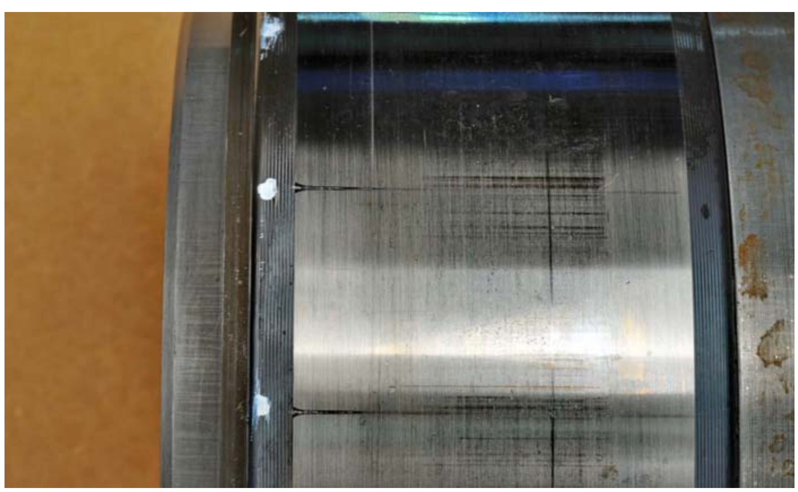
- Run in test performed on a dynamometer and the sent into the field for data collection
- Experienced many faults of > 90C bearing temperature
- Two significant oil loss events
- Unit shipped back to NREL labs where sensor data was collected
- Unit sent to engineering company for detailed failure analysis

Scuffing: High-speed pinion

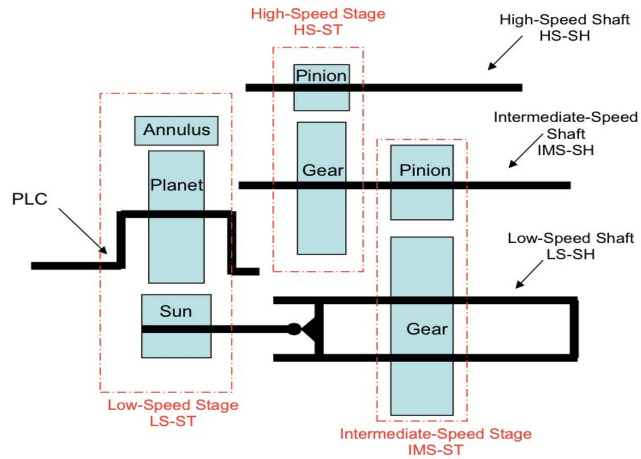


Scuffing: “O”-ring seal plate

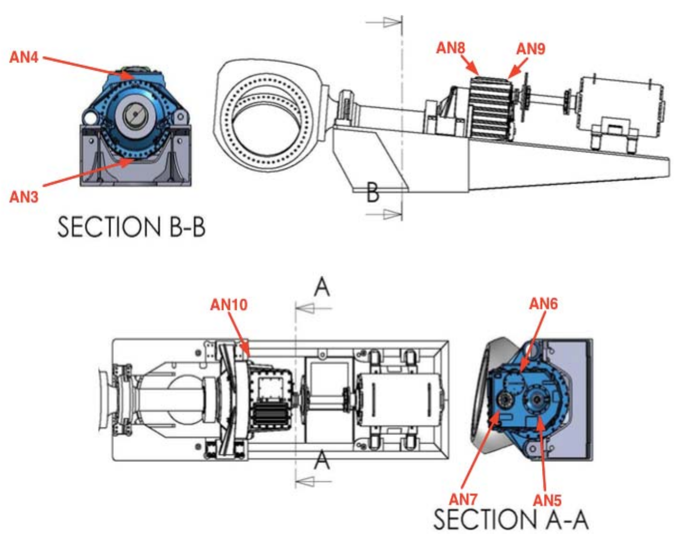
Assembly Damage: Bearing D IR



Gearbox Physical Layout



Sensor Locations



Sensor Descriptions

(b) AN7 to AN10 (Left to Right)

Sensor Label/Signal Name (see Figure 5)	**Description**	**Sensor Model**	**Units in Data File**
AN3	Ring gear radial 6 o'clock	IMI 626B02	m/s^2
AN4	Ring gear radial 12 o'clock	IMI 626B02	m/s^2
AN5	LS-SH radial	IMI 622B01	m/s^2
AN6	IMS-SH radial	IMI 622B01	m/s^2
AN7	HS-SH radial	IMI 622B01	m/s^2
AN8	HS-SH upwind bearing radial	IMI 622B01	m/s^2
AN9	HS-SH downwind bearing radial	IMI 622B01	m/s^2
AN10	Carrier downwind radial	IMI 626B02	m/s^2
Speed*	HS-SH		rpm

*Format is not the same for data collect from the "healthy" test gearbox.

Data Acquisition

- 40KHz sampling per channel using National Instruments PXI-4472B DAQ module
- 8 sensors are industrial accelerometers with model numbers IMI 626B02 and IMI 622B01
- 1 sensor is an RPM sensor measuring the high speed shaft
- Sensors rated for 0.2Hz-6KHz(626B02) and 0.2Hz-10KHz(626B01)

The Data

- Conveniently stored in Matlab format
- Two sets of data, one for the healthy gearbox and one for the damaged gearbox.
- Each set consists of ten, one minute samples from every sensor.
- All the data is under the conditions below

Table 4: Test Condition

Main Shaft Speed (rpm)	**Nominal HSS Speed** (rpm)	**Electric Power** (% of rated)	**Duration** (min)
22.09	1800	50%	10

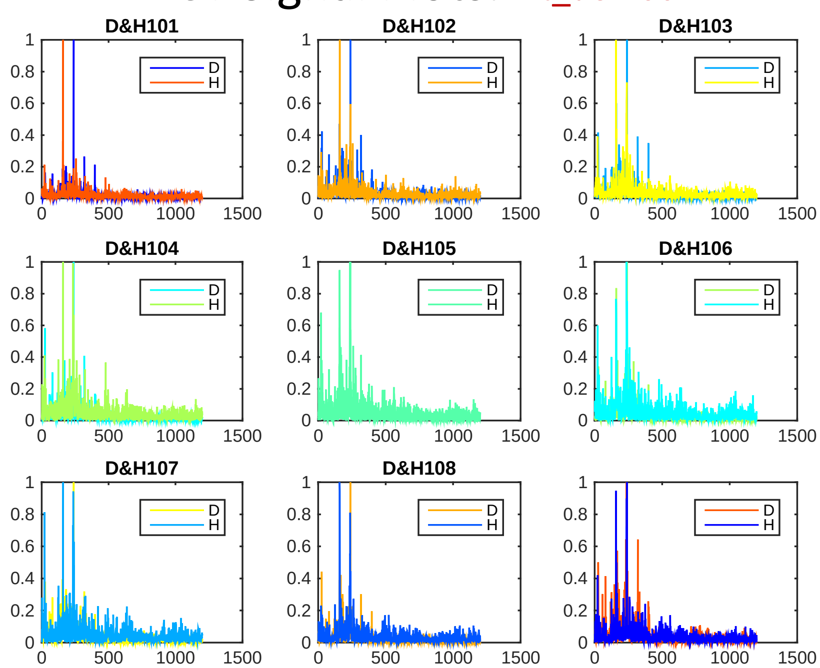
NREL's Data License Agreement

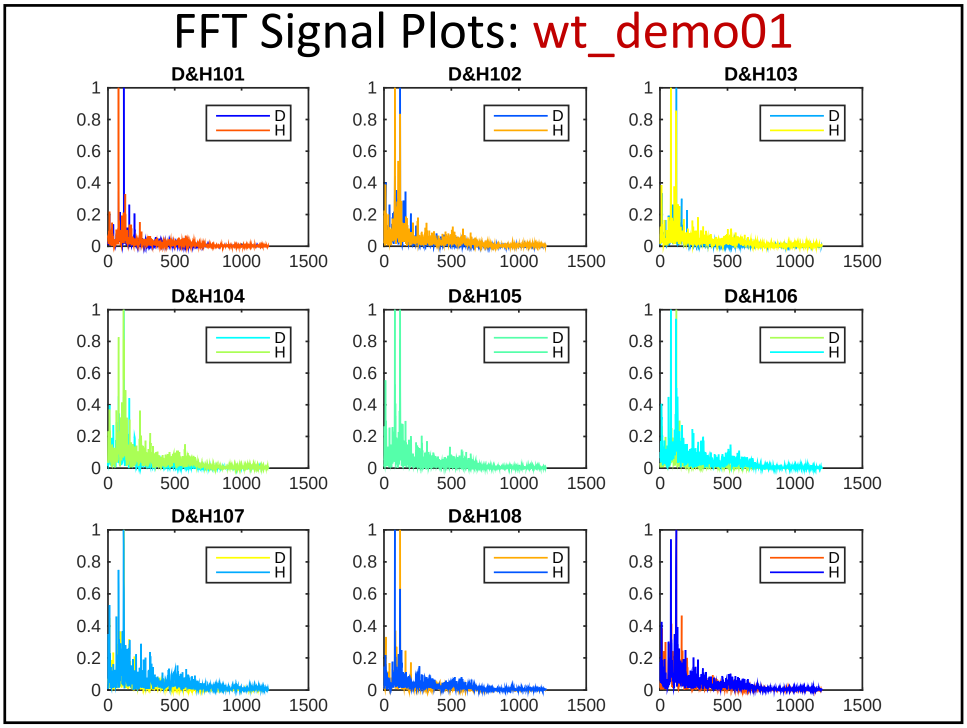
1. In any use of the datasets, you need to acknowledge the US Department of Energy (DOE)/National Renewable Energy Laboratory (NREL) for providing the datasets to support your work.
2. Except the acknowledgements as listed in 1, any other discussions of DOE/NREL in your planned publications (electronic or print format) need to be reviewed and approved by DOE/NREL.
3. You cannot share the datasets directly with others but are encouraged to direct them to contact NREL for information on downloading the datasets.

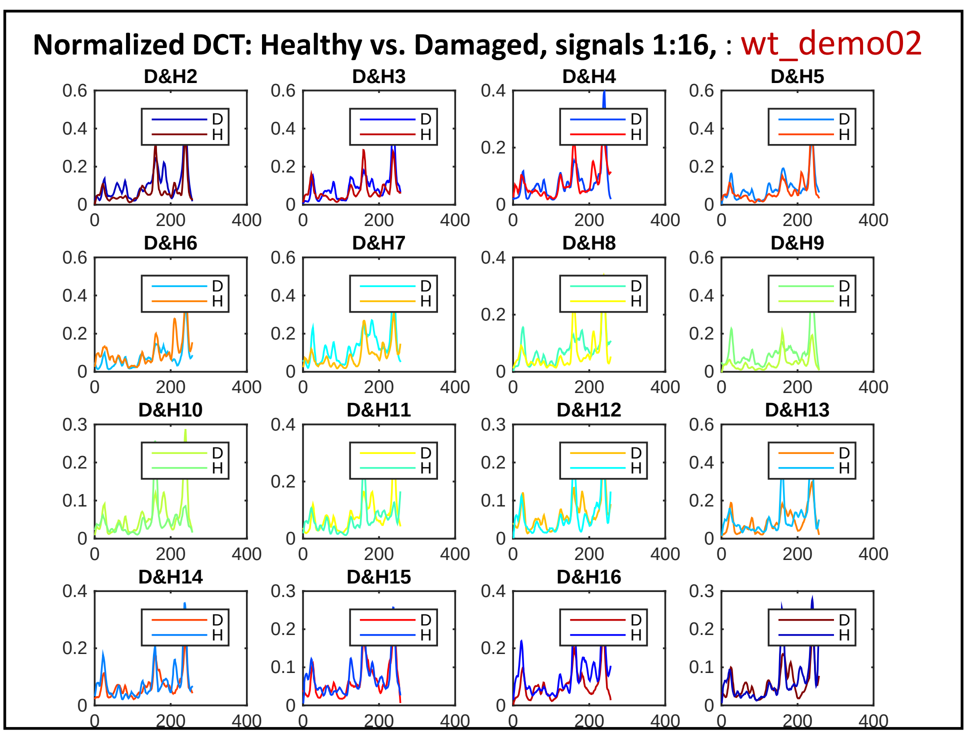
Primary Contact for This Data

- Shawn Sheng
  - shuangwen.sheng@nrel.gov

DCT Signal Plots: wt_demo01




FFT Signal Plots: wt_demo01
D&H101
D&H102
D&H103
D&H104
D&H105
D&H106
D&H107
D&H108
D
H


Normalized DCT: Healthy vs. Damaged, signals 1:16, : wt_demo02
D&H2
D&H3
D&H4
D&H5
D&H6
D&H7
D&H8
D&H9
D&H10
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D&H12
D&H13
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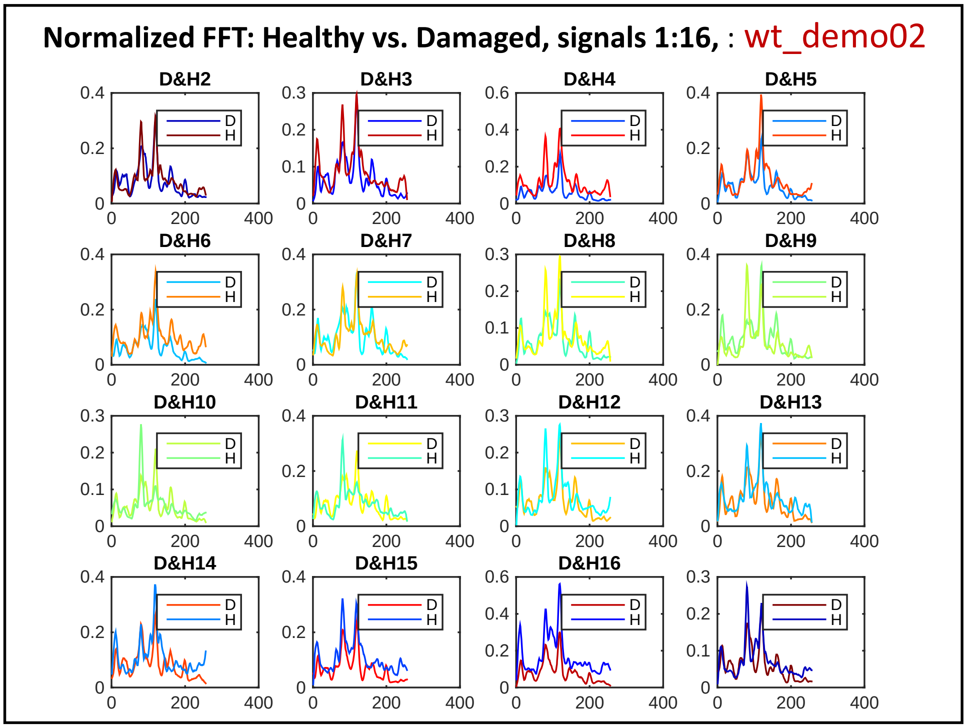
D&H16
D
H



Normalized FFT: Healthy vs. Damaged, signals 1:16, : wt_demo02
D&H2
D&H3
D&H4
D&H5
D&H6
D&H7
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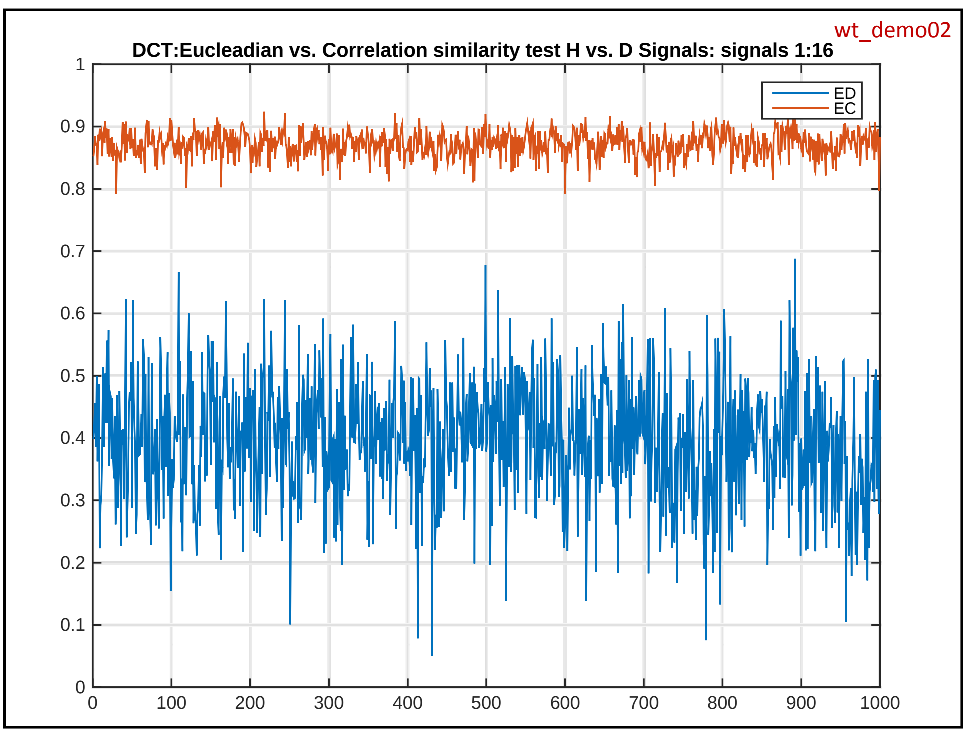
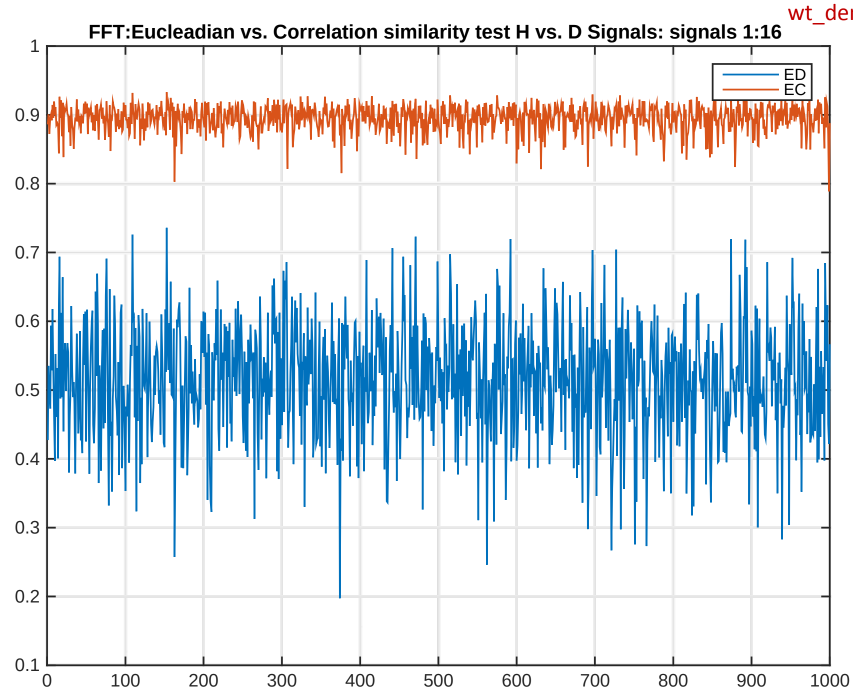
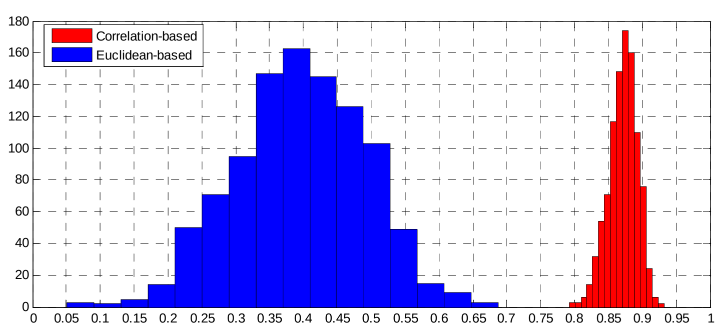


wt_demo02
DCT:Eucleadian vs. Correlation similarity test H vs. D Signals: signals 1:16
ED
EC

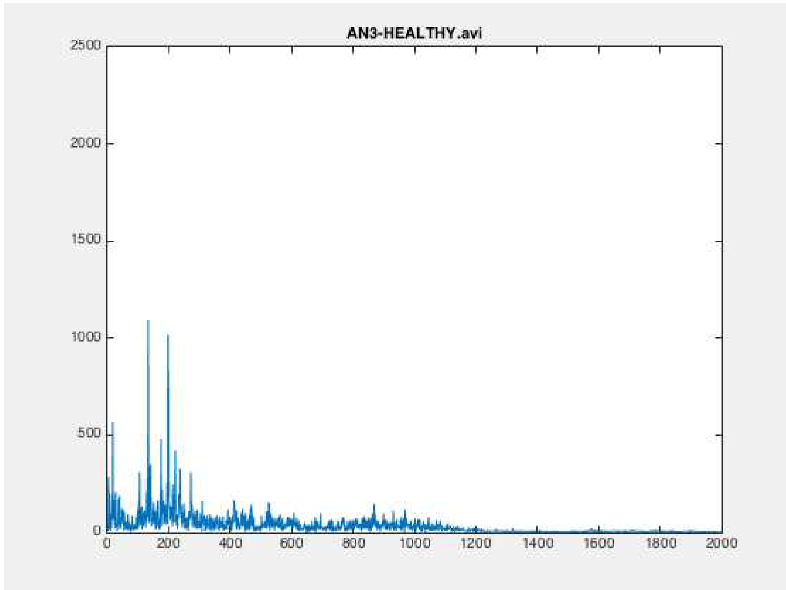
wt_demo02



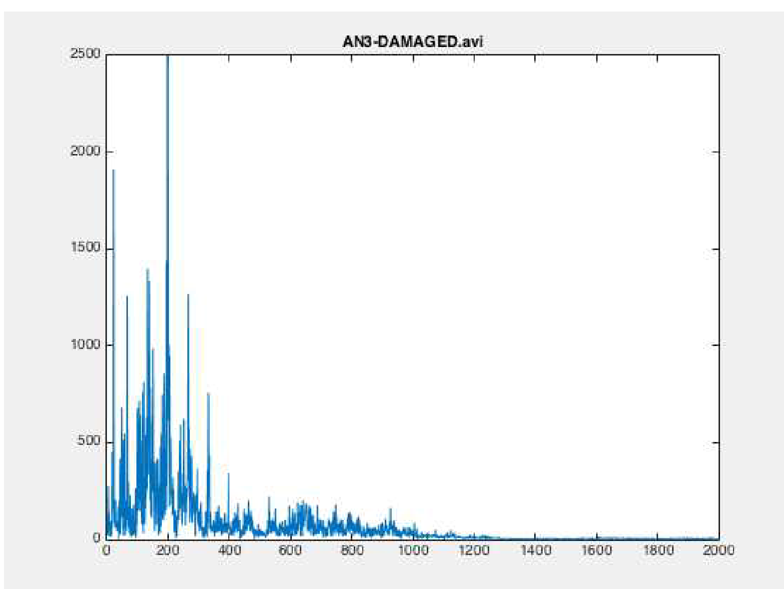
Similarity test FFT/DCT Represented as Histograms: wt_demo02



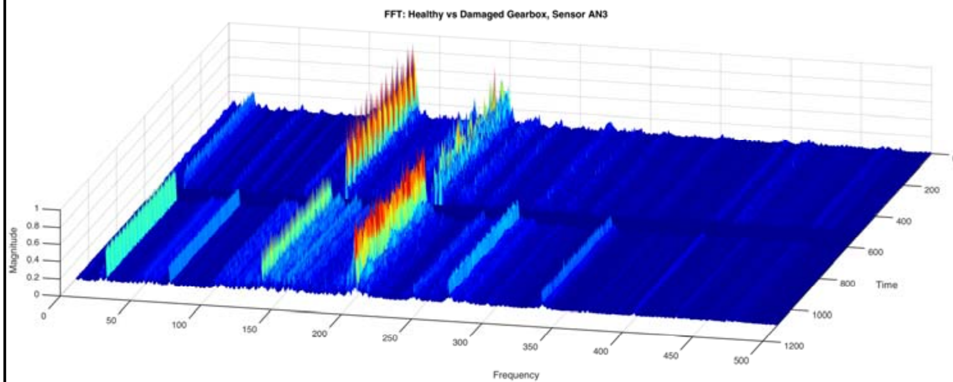
Real-time FFT Playback From Healthy Gearbox



Real-time FFT Playback From Damaged Gearbox



Visual Comparison of Sensor Data from Healthy Gearbox vs. Damaged Gearbox

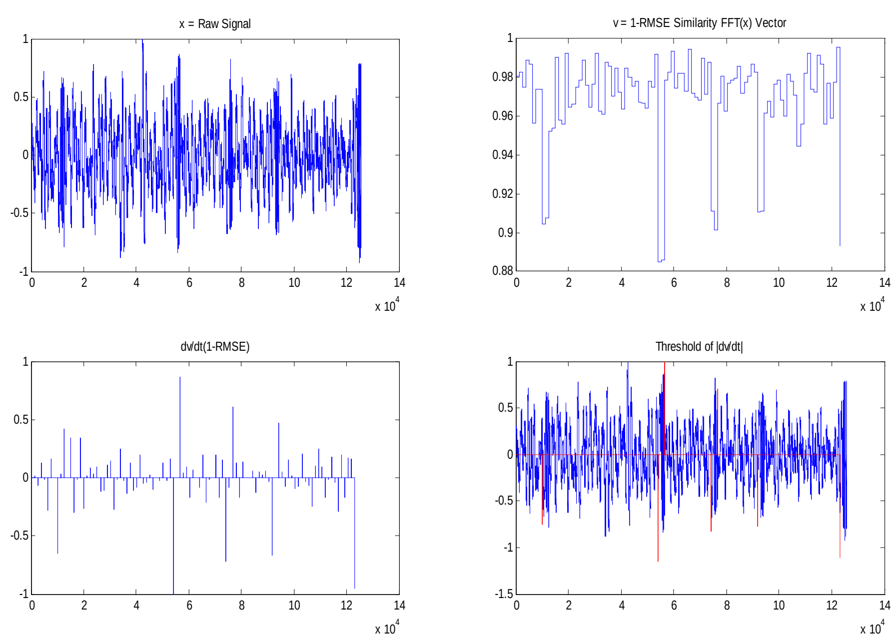


Damaged gearbox sensor data is in the forefront

Damaged Gearbox Sensor Data Reveals:

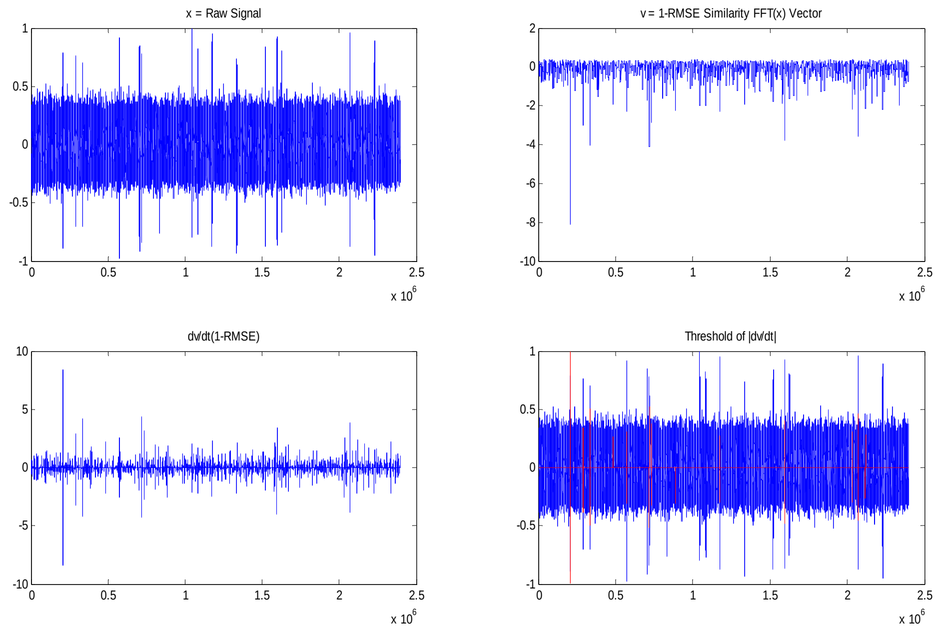
- Increased noise
- Additional peaks
- Existing peaks present in healthy state either attenuated or strengthened

Simulated Healthy signal with Embedded Damaged Segments: wt_demo03



Simulated Healthy signal with Embedded **Simulated** Damaged Segments (No Intelligence): wt_demo04

True Positive (TP) = 53.33% False Positive (FP) = 33.33%



Real Healthy/Damaged Data (ANN Training): wt_demo05

Training Classification Accuracy = 99%, MSE = 1%

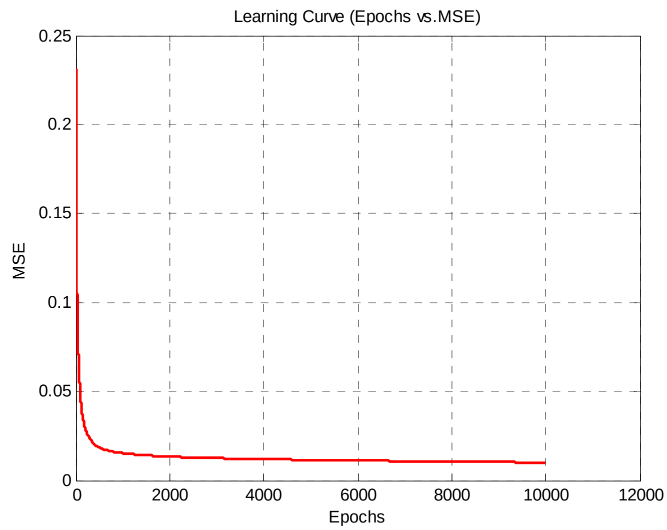
Target MSE = $1x10^{-6}$

```
>> [net g lbl] = wt_demo05(hsg, dsg);
Forming training vector space ...
TRAINGD, Epoch 0/10000, MSE 0.231196/1e-006, Gradient 0.839512/1e-030
TRAINGD, Epoch 1000/10000, MSE 0.0153333/1e-006, Gradient 0.00824165/1e-030
TRAINGD, Epoch 2000/10000, MSE 0.0134147/1e-006, Gradient 0.00481436/1e-030
TRAINGD, Epoch 3000/10000, MSE 0.0125389/1e-006, Gradient 0.00368013/1e-030
TRAINGD, Epoch 4000/10000, MSE 0.0119696/1e-006, Gradient 0.00311681/1e-030
TRAINGD, Epoch 5000/10000, MSE 0.0115367/1e-006, Gradient 0.00279109/1e-030
TRAINGD, Epoch 6000/10000, MSE 0.0111777/1e-006, Gradient 0.00258063/1e-030
TRAINGD, Epoch 7000/10000, MSE 0.0108644/1e-006, Gradient 0.00243263/1e-030
TRAINGD, Epoch 8000/10000, MSE 0.0105823/1e-006, Gradient 0.00232212/1e-030
TRAINGD, Epoch 9000/10000, MSE 0.0103229/1e-006, Gradient 0.00223617/1e-030
TRAINGD, Epoch 10000/10000, MSE 0.0100808/1e-006, Gradient 0.0021675/1e-030
TRAINGD, Maximum epoch reached, performance goal was not met.
```

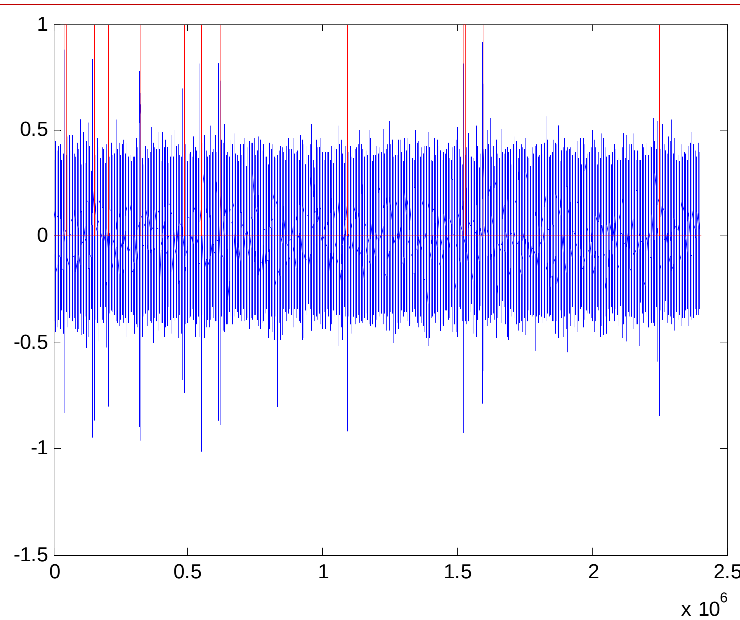
Final MSE measured = .01 = 1% ➔ Training Classification Accuracy = 99%

Target Gradient of the Error surface = 10^{-30} (Virtually 0)

Real Healthy/Damaged Data (ANN Training): wt_demo05
Training Classification Accuracy = 99%, MSE = 1%



Real Healthy signal with Embedded **Real** Damaged Segments (ANN Classifier): wt_demo06
True Positive (TP) = 100%　　False Positive (FP) = 9%



Next Stage for the ANN Classifier Optimization

1) Conducting significant number of experiments with current configuration of the ANN classifier and measure TP/FP rates for each trial:

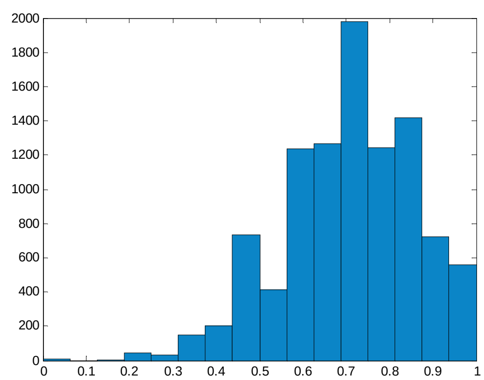
Experiment#	TP	FP
1	0.93	0.27
2	0.97	0.31
3	0.92	0.16
.		
.		
.		
100	0.87	0.07

2) Analyzing the PDF of TP and FP through their respective histograms and computing their μ and σ.
3) Heuristically, if $TP_{\mu} > 90\%$, $FP_{\mu} < 5\%$ ➔ it is satisfactory and presentable.
4) Otherwise, there are number of optimization techniques that need to be investigated including:
   a) ANN parameters configuration: number of hidden layers, number of neurons per layer, learning coefficient, momentum factor, etc.
   b) Randomizing training/testing sets
   c) Applying the same ANN to other sensor signals since we only tried on "AN3"
   d) More … brainstorming

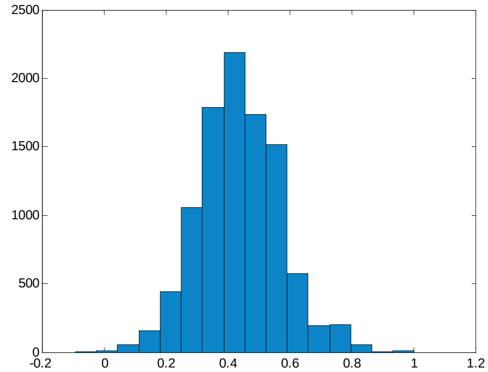
Basic Classification Technique – No Intelligence

TP Histogram

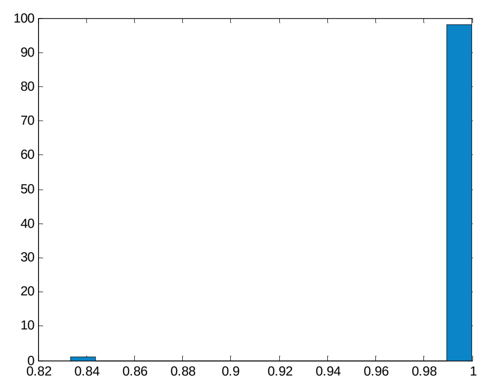
μ = 0.7133, σ = 0.1529



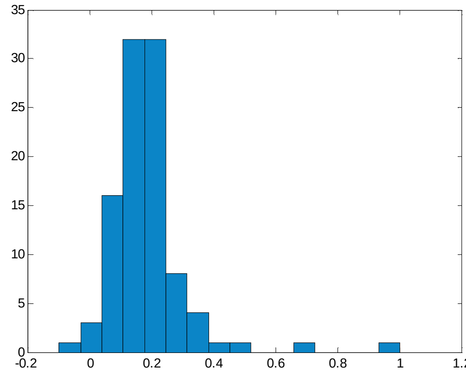
Basic Classification Technique – No Intelligence
FP Histogram
μ = 0.4342, σ = 0.1325



ANN Classification
TP Histogram
μ = 0.9983, σ = 0.0167



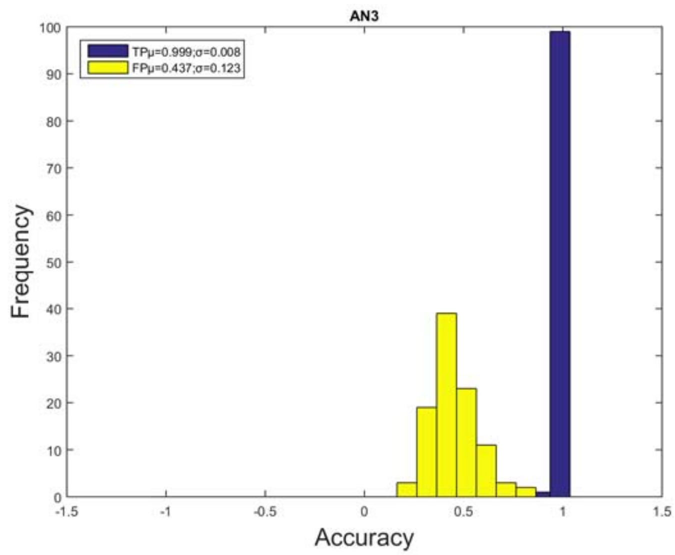
ANN Classification
FP Histogram
μ = 0.1825, σ = 0.1275



Further Analysis

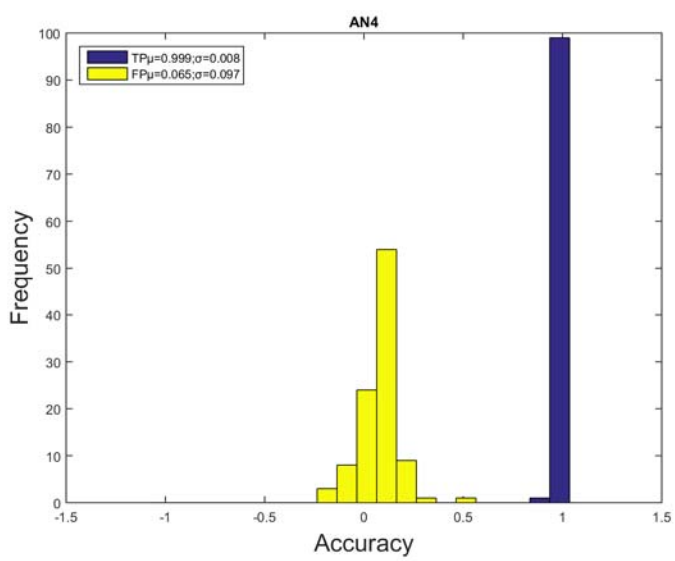
- Following slides contain histogram plots of True and False positive accuracies observed when Artificial Neural Network classifier is applied on NREL Gear box sensor data and statistical values are included in legend.
- Training data is fed in two different ways. Randomized and non randomized training data resulted in two sets of results and are tabulated for analysis.
- Classifier is tested for 100 cases on each sensor data except torque whose results doesn't match with other sensors' pattern.

AN3



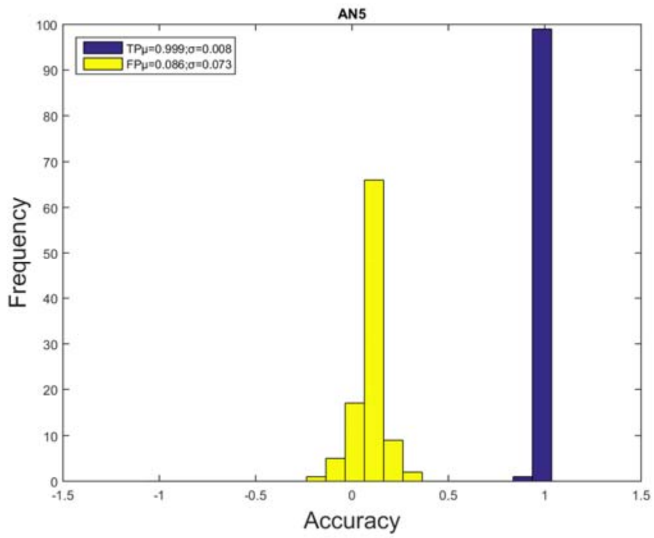
AN3
TPμ=0.999;σ=0.008
FPμ=0.437;σ=0.123
Frequency
Accuracy

AN4

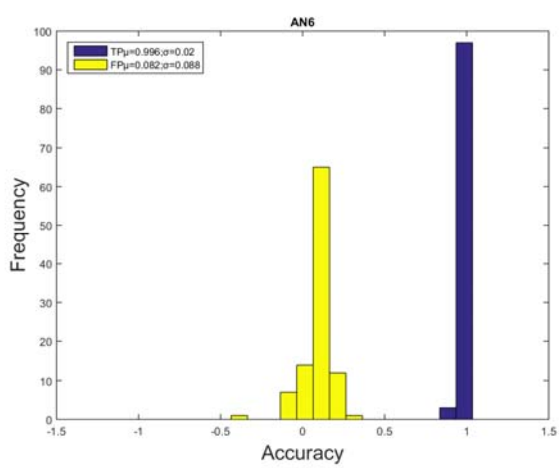


AN4
TPμ=0.999;σ=0.008
FPμ=0.065;σ=0.097
Frequency
Accuracy

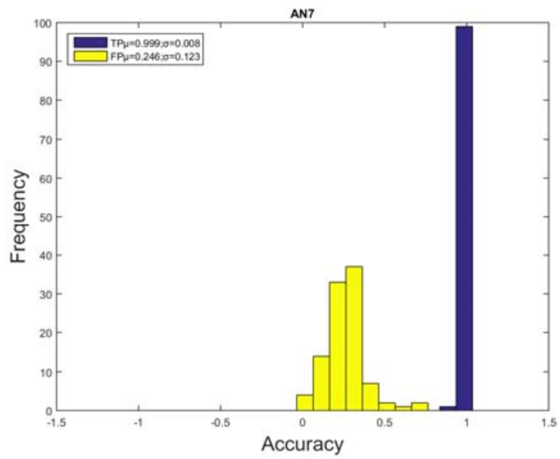
AN5


AN5
TPμ=0.999;σ=0.008
FPμ=0.086;σ=0.073
Frequency
Accuracy
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
1.5

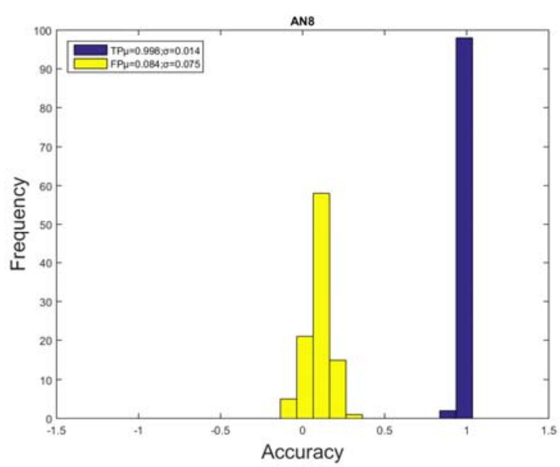
AN6


AN6
TPμ=0.996;σ=0.02
FPμ=0.082;σ=0.088
Frequency
Accuracy
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
1.5

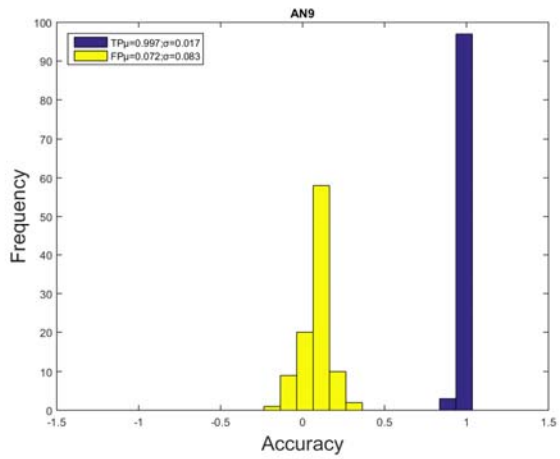
AN7


AN7
TPμ=0.999;σ=0.008
FPμ=0.246;σ=0.123
Frequency
Accuracy
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
1.5

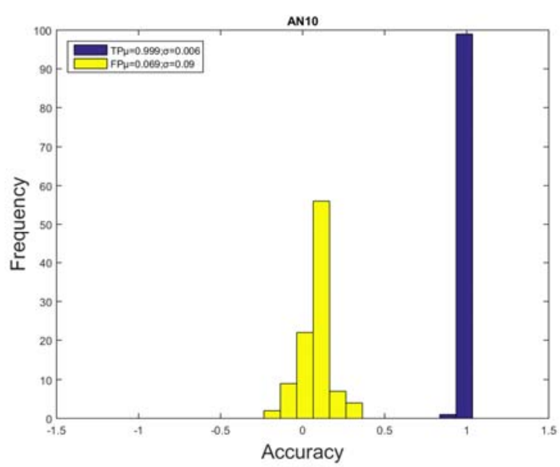
AN8


AN8
TPμ=0.998;σ=0.014
FPμ=0.084;σ=0.075
Frequency
Accuracy
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
1.5

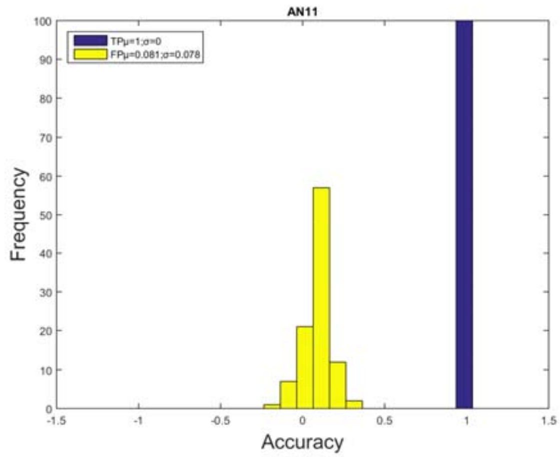
AN9


AN9
TPμ=0.997;σ=0.017
FPμ=0.072;σ=0.083
Frequency
Accuracy
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
1.5

AN10


AN10
TPμ=0.999;σ=0.006
FPμ=0.069;σ=0.09
Frequency
Accuracy
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
1.5

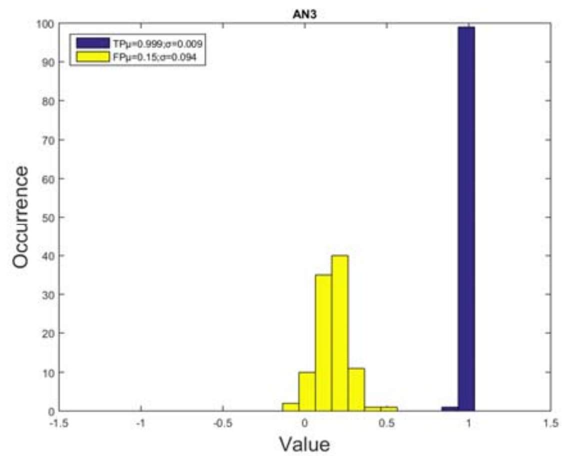
SPEED SENSOR



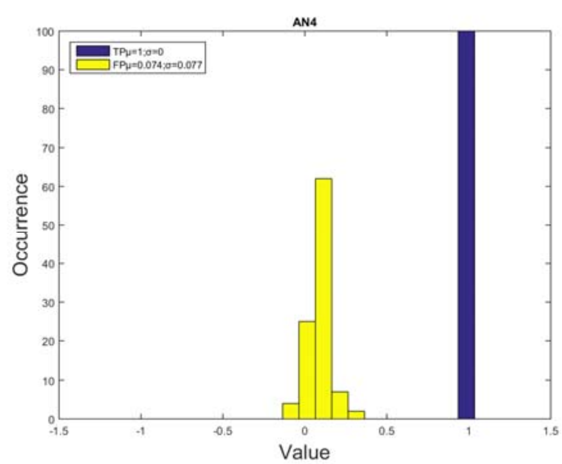
Mean and Std deviation results for Non randomized training data

Sensor	TP Mean	TP Std Dev	FP Mean	FP Std Dev
AN3	0.999231	0.007692308	0.43724	0.122600942
AN4	0.999167	0.008333333	0.064676	0.096637756
AN5	0.999231	0.007692308	0.08579	0.073045955
AN6	0.99646	0.020474401	0.081683	0.087993572
AN7	0.999167	0.008333333	0.246117	0.123019526
AN8	0.998056	0.013821385	0.084295	0.074720613
AN9	0.997222	0.016516344	0.071955	0.082639197
AN10	0.999412	0.005882353	0.069311	0.090133265
Speed	1	0	0.081175	0.078480717

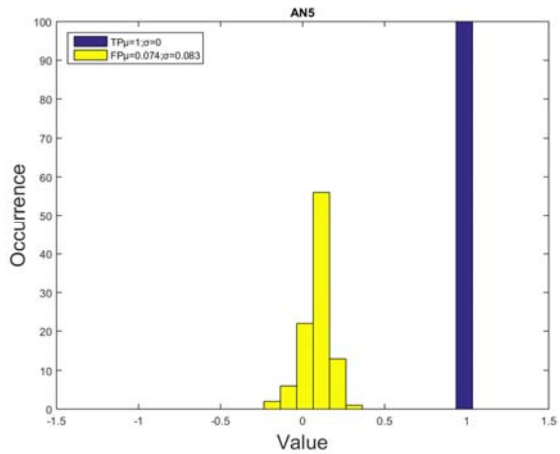
Randomized Training Data Results
AN3



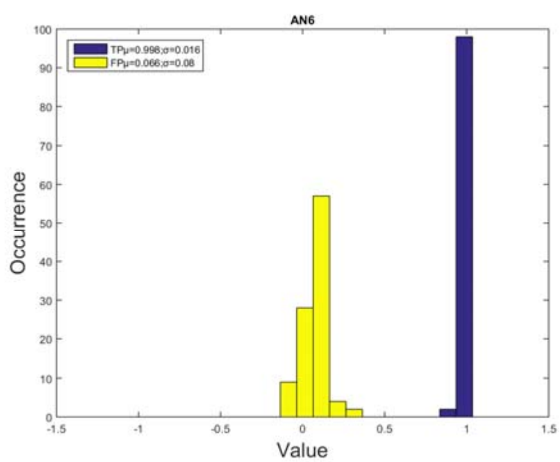
AN4



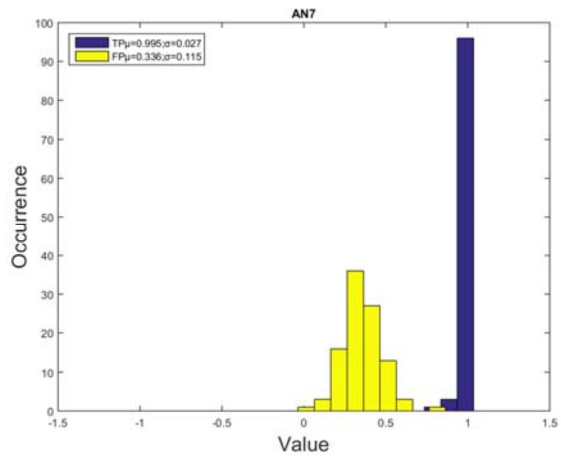
AN5


AN5
TPμ=1;σ=0
FPμ=0.074;σ=0.083
Occurrence
Value
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
1.5

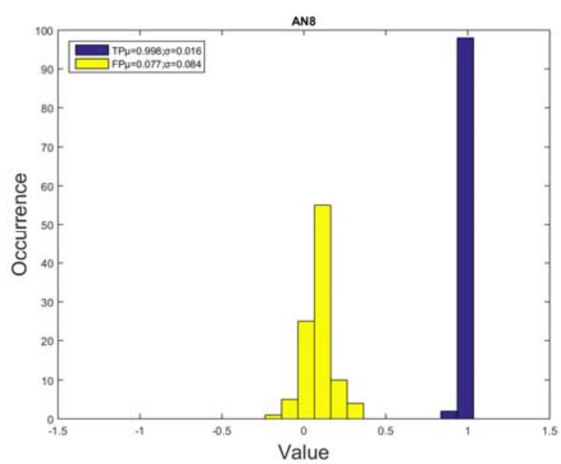
AN6


AN6
TPμ=0.998;σ=0.016
FPμ=0.066;σ=0.08
Occurrence
Value
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
1.5

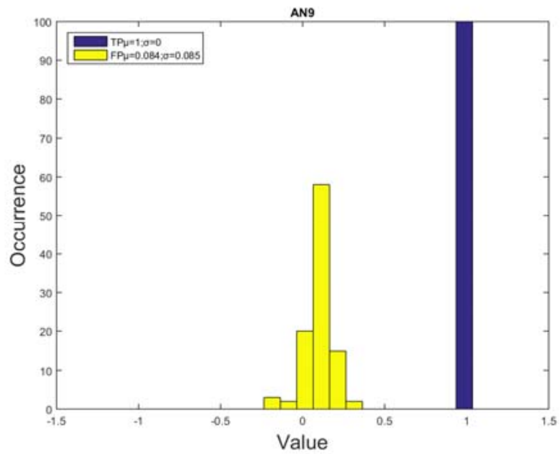
AN7


AN7
TPμ=0.995;σ=0.027
FPμ=0.336;σ=0.115
Occurrence
Value

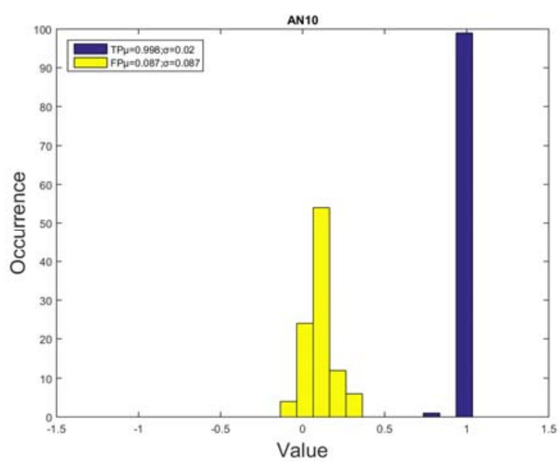
AN8


AN8
TPμ=0.996;σ=0.016
FPμ=0.077;σ=0.084
Occurrence
Value

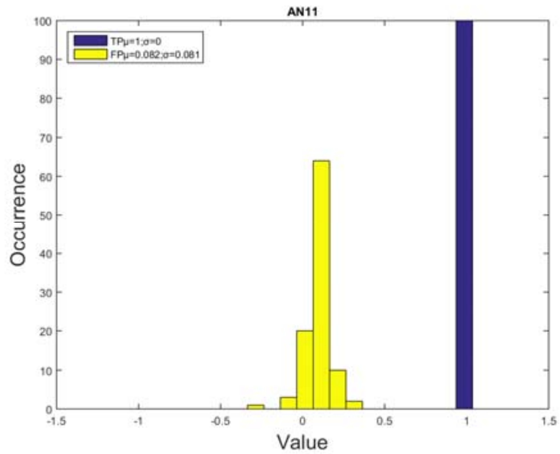
AN9


AN9
TPμ=1;σ=0
FPμ=0.084;σ=0.085
Occurrence
Value
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
1.5

AN10


AN10
TPμ=0.998;σ=0.02
FPμ=0.087;σ=0.087
Occurrence
Value
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
1.5

SPEED



Mean and Std deviation results for Randomized training data

Sensor	TP Mean	TP Std Dev	FP Mean	FP Std Dev
AN3	0.999091	0.009091	0.150438	0.094203
AN4	1	0	0.073797	0.077164
AN5	1	0	0.074342	0.083282
AN6	0.99775	0.015929	0.065845	0.080281
AN7	0.995024	0.026587	0.336307	0.115449
AN8	0.997778	0.015634	0.077082	0.084448
AN9	1	0	0.083999	0.084666
AN10	0.998	0.02	0.087384	0.086933
Speed	1	0	0.082222	0.081463

References:

1. Wind Turbine Gearbox Vibration Condition Monitoring Benchmarking Datasets (private) http://en.openei.org/datasets/dataset/wind-turbine-gearbox-condition-monitoring-vibration-analysis-benchmarking-datasets
2. Gearbox Reliability Collaborative Gearbox 1 Failure Analysis Report December 2010 – January 2011 http://www.nrel.gov/docs/fy12osti/53062.pdf
3. Wind Turbine Drivetrain Condition Monitoring During GRC Phase 1 and Phase 2 Testing http://www.nrel.gov/docs/fy12osti/52748.pdf
4. Gearbox Reliability Collaborative Project Report: Findings from Phase 1 and Phase 2 Testinghttp://www.nrel.gov/docs/fy11osti/51885.pdf

ACKNOWLEDGEMENT

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- **MOWER = Maryland Offshore Wind Energy Research**

Reducing Costs in the Offshore Wind Sector: From Modular design to a Healthy Flow of Knowledge

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In the context of the usage of modularization in designing wind turbines, a key problem remains, that is often quite difficult to have a healthy flow of knowledge between several sub-suppliers. In the case of Siemens, their direct drive machines have 90% of the modules outsourced transforming the company into an assembly shop. The paper argues that in order to keep costs as low as possible and to ensure a small lead time, the contractor and its sub-suppliers have to exchange knowledge. The reason standing behind this is to reach the same standard plug settings, connection standards and software standards. Even when one of the sub-suppliers disappears, the manufacturing company must be prepared to replace him with another one that can develop the same standards. The purpose of this paper is to develop a method that will generate a healthy flow of knowledge between participants minimizing the risk of complacency as much as possible.

Reducing costs in the Offshore Wind Sector: From modular design to a healthy flow of knowledge

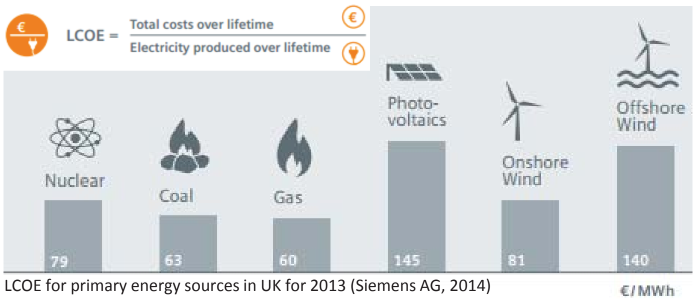
Matei Rogin -
Master student of
Product Development
& Innovation

Supervisor:
Erik Skov Madsen

Agenda:

1. The need for cost reductions
2. The Lego concept
3. Standardization & Outsourcing
4. The power of knowledge, a case from the industry
5. The Knowledge Hub grid
6. Creation of knowledge
7. The focus of the study
8. Case study: The flow of knowledge
9. Just In Time in the Offshore Wind Industry

Commitment for cost reductions



LCOE for primary energy sources in UK for 2013 (Siemens AG, 2014)

Energy levels are increasing every day

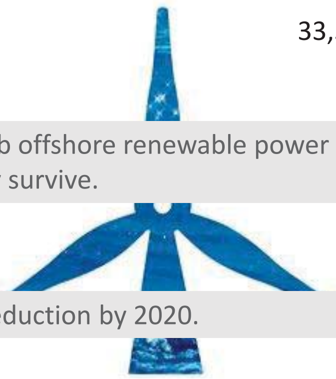
Europe makes no exception with an average growing rate of 2%.

By 2050 a doubled consumed level of energy has to be covered.

The European Union proposed its climate and energy package the "20-20-20 target".

Europe will add to its capacity 600 TWh from renewable sources

33,3% wind energy : 76,7% onshore + 33,3% offshore



As European governments start to curb offshore renewable power subsidies, utilities, wind turbine makers and installers are racing to cut costs to help the industry survive. Reuters, 2014

Offshore wind must have a 40% cost reduction by 2020. Dong Energy

Modularization → the Lego concept

Concept borrowed from the automotive industry.

The module= component or a group that can be removed from the product without destroying it as a unit.

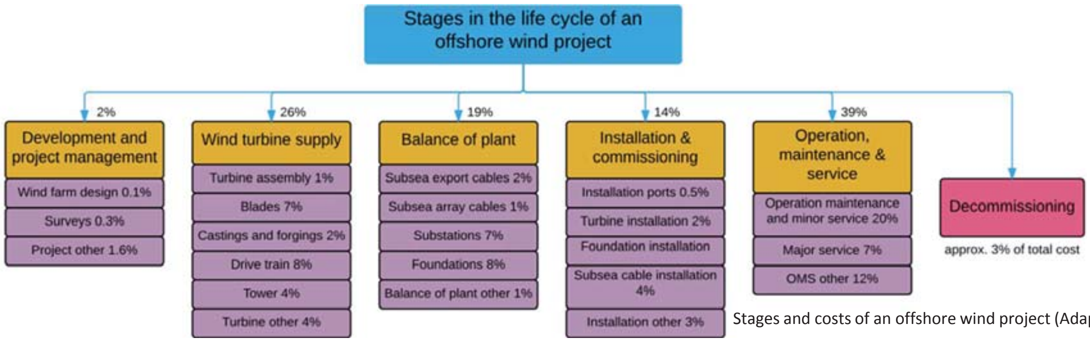
Modularization is the level of module utilization by minimum interactions between modules.

It's a birth to grave concept, from designing the machine till the decommissioning stage (Cronin, 2015).

The final assemblers aim at reducing:

- production process complexity,
- increase automation along the assembly line
- achieve higher integration between production and delivery systems (Zaganoli & Pagano, 2001)

Production variety is leveled and cost efficiencies are achieved through usage of same components in different models (Calabrese,1997; Muffatto, 1999).



Stages and costs of an offshore wind project (Adapted BVG Associates, 2014)

Modules are smaller so they do not overload the lifting equipment.

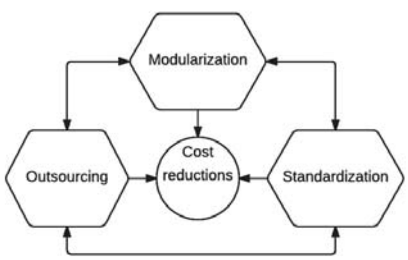
Reduced risk of faulty electrical systems due to the fact that modules can be tested before mounting them offshore.

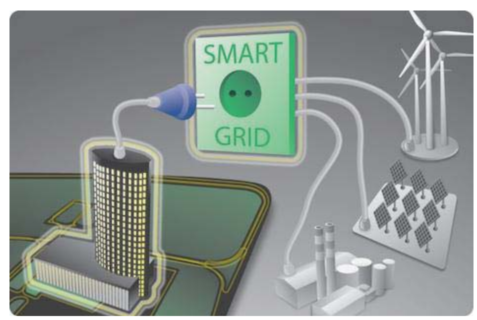
It is easier to guide maintenance operators through the process of maintenance, because of the logic behind the modularization concept.

It facilitates the disassembling process helping the operator to comprehend and eliminate the risk of mistakes.

Easier to decommission. The magnets from the generator are a module, making it easier just to unplug them and recycle the copper.

The impact of modularization on the industry





Standardization

"a collection of the unified rules on repetitive matters under certain constraints" (Jiang et al., 2014)

Dividing the wind turbine into modules that would later on be standardized could enable mass production of 80% of the components of a wind turbine (Dong Energy, 2014)

Standardization can guide innovation, by wasting less and focusing on the relevant aspects (Jiang et al., 2014)

Outsourcing

Outsourcing involves contracting out a supplier to do a task the company holds no competitive advantage for.

Modularization can be used to divide the value chain into modules and so non-core modules can be outsourced.

The resources required to deliver the non-core modules of the value chain in-house can be invested in core modules (Mikkola, 2003).

The power of knowledge

Offshore Wind Programme Board

Sharing best practices as a way of achieving cost reductions

The offshore wind programme board is a taskforce formed from developers, supply chain people and government representatives who's purpose is to drive cost reductions

Developer Days

All project directors were invited to attend an initial one day workshop.

Purpose: To drive cost reduction through sharing of best practice

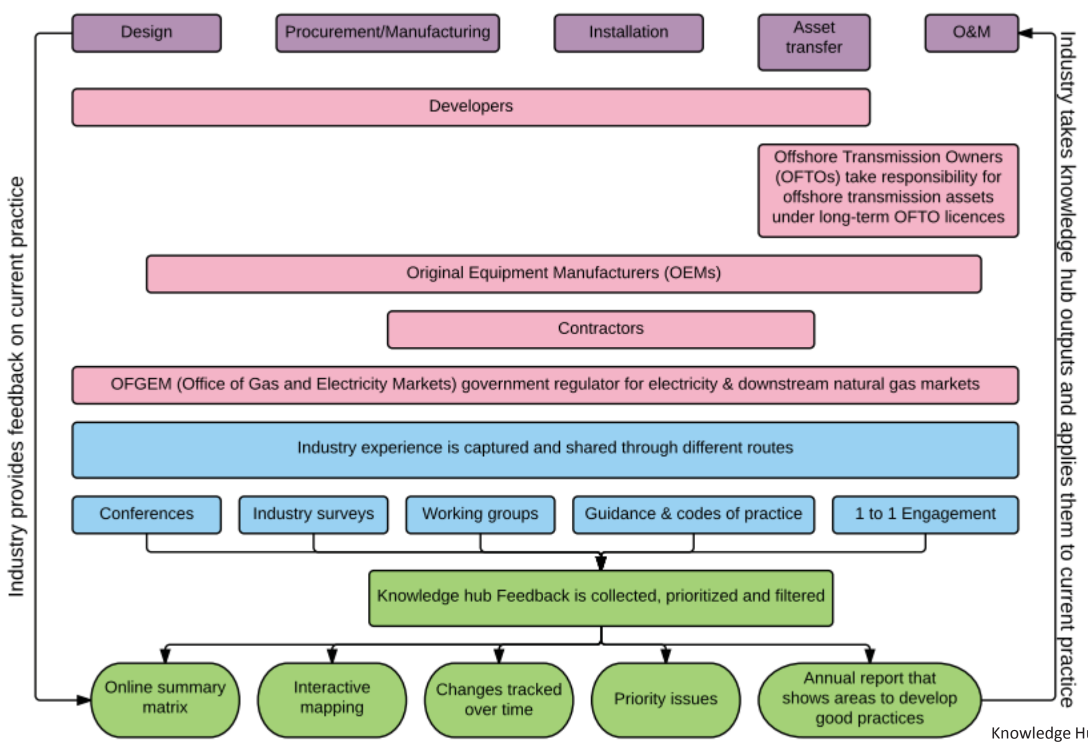
Agenda: project lessons learnt, key industry issues, knowledge management

Some of the lessons learned

- Site selection
- Reduce time to construct: early generation & reduced LCoE
- Maximize onshore work/preparation
- Ensure safe work environment
- Encourage competition for WTGs to develop mature industry
- Industry standard terms & conditions as starting point
- Optimize crew transfers and offshore accommodation to maximize productive time offshore

Adapted from Alastair Dutton, 2015

The Knowledge Hub Grid



Knowledge Hub Grid (Alastair Dutton, 2015)

The nature of knowledge

The objectivist perspective

It is possessed by individuals, but it can exist in separate form, meaning it is codifiable (Hislop, 2013).

Knowledge can be developed "free from individual subjectivity". In this way knowledge is perceived as a conglomerate of facts and laws which are not effected by social norms or time.

TACIT knowledge is possessed by people shaping the way they think & act. It is almost impossible to codify because it is embedded in the subconscious.	EXPLICIT knowledge can be separated from both individual and social value systems and it can be codified in a tangible form.
INDIVIDUAL knowledge is the one that is possessed by an individual	GROUP knowledge sums up the knowledge possessed by individuals plus extra knowledge that cannot be traced to any individual.

Types of knowledge (Donald Hislop, 2013)

The practice based perspective

1. Knowledge cannot exist outside people that possess it and is inseparable from practices and activities of those people (Hislop, 2002).

2. The socially constructed nature and cultural connection that knowledge incorporates.
- The social constructed nature applies to the creation and interpretation of knowledge.
- The cultural connection is represented by the meaning that people attach to it.
- Knowledge having a "hidden" meaning results in a reflection of the values of the society in which the individuals are leaving in.

Knowledge processes are influenced by pre-existing values and assumptions that its employees have.
This results in a filtering in which it is decided the importance of data while the one that is not relevant is ignored.

Sensible knowledge (Strati, 2007)

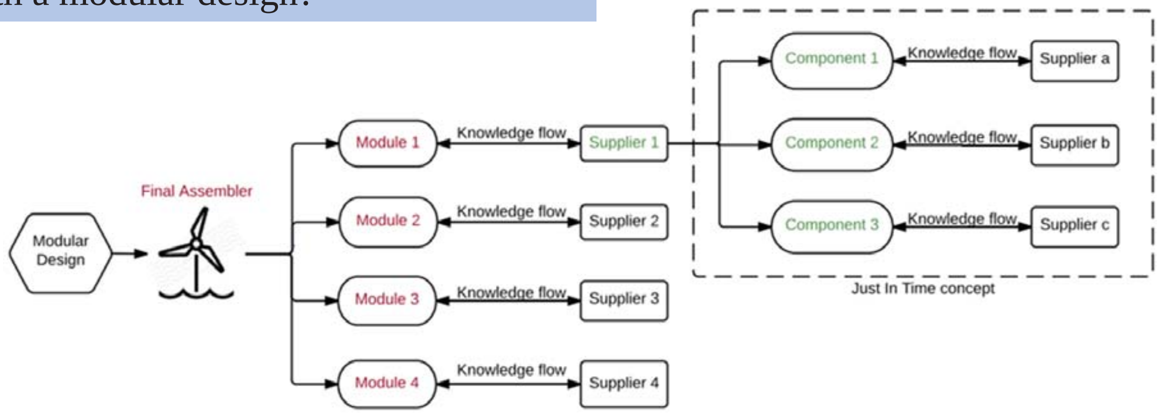
↓

Thickness of the planks

The focus of the study→ Mixed method research

How can a healthy flow of knowledge be created and maintained for an offshore wind turbine with a modular design?

What is the percentage with which the RONA changes for the final assembler when the Just in Time concept is applied for Tier 2 of suppliers?



How can the flow of knowledge be mediated between sub-suppliers and final assembler in the offshore wind sector in order to generate cost efficiency?

Case study: The flow of knowledge

Modularization through outsourcing of the non-core modules creates a complex network of modules & suppliers. For the network to work properly a constant flow of knowledge must be created.

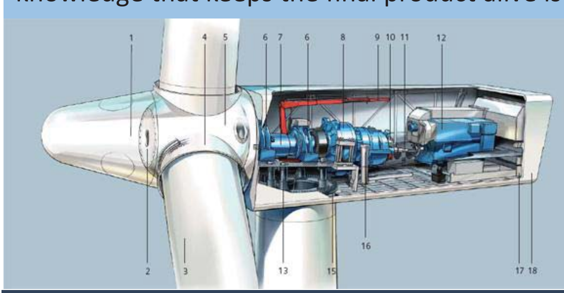
The flow of knowledge is born when the final assembler starts the early supplier involvement in the NPD and lasts throughout the lifecycle.

Every participant in the ecosystem must understand how the flow of knowledge that keeps the final product alive is created and maintained.

Project capacity	630MW	Project cost	2200 mil €
Turbine model	SWT-3.6-120	Location	North Sea
No. of turbines	175	Homes powered/ year	446201

Wind park details (4Coffshore, 2015)

Siemens's wind turbine SWT-3.6-120 is a geared machine and it will be studied in the context of the London Array wind park.



1 Spinner	10 Brake disc
2 Spinner bracket	11 Coupling
3 Blade	12 Generator
4 Pitch bearing	13 Yaw gear
5 Rotor hub	14 Tower
6 Main bearing	15 Yaw ring
7 Main shaft	16 Oil filter
8 Gearbox	17 Generator fan
9 Service crane	18 Canopy

For the SWT-3.6-120 the suppliers for each module will be determined.

Final assembler, tier 1 suppliers and NGOs that are involved in the offshore wind sector will be part of the study.

SWT-3.6-120 (Siemens AG, 2013)

Just In Time in the Offshore Wind Industry

The "Just in Time" concept was borrowed from the Japanese car manufacturer Toyota.

It reduces flow times within production but also response times from suppliers and to customers (Leistner, 2010).

The offshore wind energy is a "heavy industry" and it requires stocks of spares in order to cover the unexpected failures of wind turbines (Cronin, 2015).

The "Just in Time" concept cannot be applied on tier 1 of suppliers, but it can be applied on tier 2 of suppliers due to the light nature of the industry (Cronin, 2015).

The "Just in Time" concept requires a healthy flow of knowledge in order to be implemented, so that the components would be at the buyer exactly when they are required

Just in Time Manufacturing (MG, 2014)

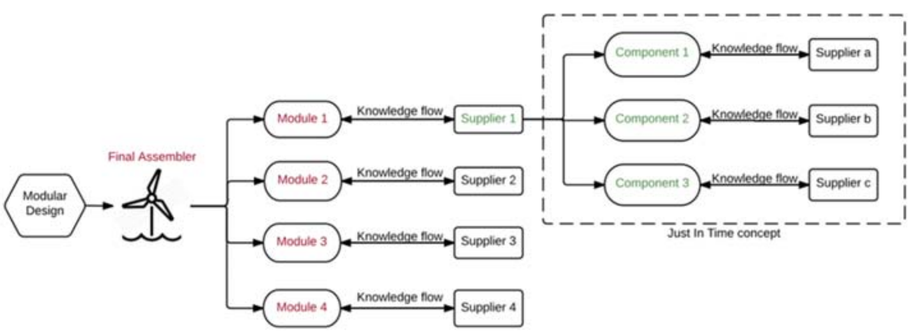
Applying the JIT concept for Tier 2 suppliers will result in minimum stocks (stocks required for rework) (Suri, 1986).

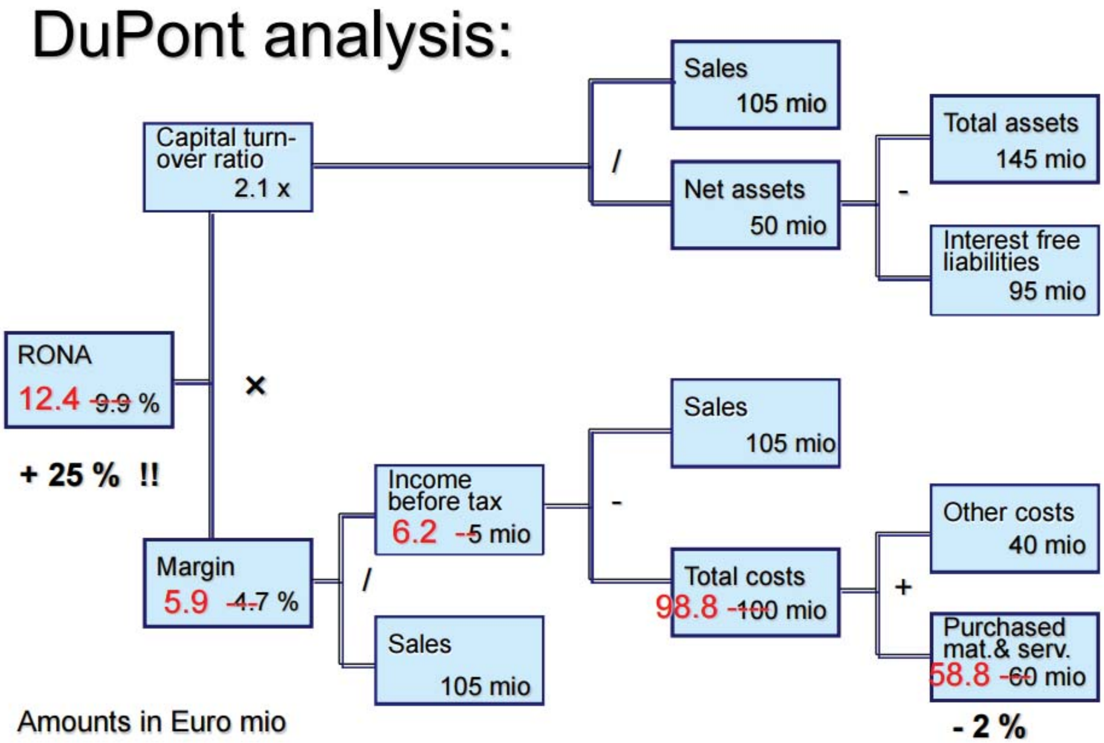
JIT can be a double edged sword, it enables cost reductions for key positions in the value chain, but on the other hand resources are required for strengthening the flow of knowledge (Van Weele, 2010).

The costs with having a stock will be calculated for tier 1 supplier.

After the JIT concept is applied a new price for the purchased modules that include the new stock costs will be calculated.

A DuPont analysis will be made that will outline a higher return on net assets for the final assembler.





DuPont analysis (Van Weele, 2010)

Financial tool to calculate the company's return on investment based upon sales margin and capital turnover ratio (Van Weele, 2010).

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Return on Investment (ROI) Modeling of Offshore Wind Farm O&M to Support Strategic Technology Insertion

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Operation and maintenance (O&M) costs make up 17-28% of the total lifecycle cost of offshore wind farms. O&M costs are directly related to the reliability of turbines and their sub-assemblies. Loads on the sub-assemblies that result in mechanical failure mechanisms are one of the main contributors to maintenance costs of the wind turbines. The alignment of the wind turbine`s rotor with the direction of the wind affects the amount of loads on the sub-assemblies. The angle between wind directions and wind turbine`s rotor is called yaw angle or yaw misalignment. Variations in yaw angle change the loads and subsequently the reliability of the wind turbine and its sub-assemblies. Vanes on the nacelle is the traditional way to address this issue however, wake effects and feed-back nature of this method does not give accurate readings. Light detecting and ranging (LIDAR) systems are proved to be a more accurate alternative. A Lidar system can be used to minimize the yaw error through laser detection methods. Implementation of LIDAR systems improves both the reliability and production of the offshore wind farm, in other words avoids future costs and increases revenue.

In order to calculate the return on investment for implementing the LIDAR system, an O&M cost model will be developed. The O&M cost modeling is performed using discrete-event simulation (DES) based models. DES incorporates the timing and sequence of events which is crucial in calculating return on investment (ROI) of implementing new technologies or policies. We calculate the O&M costs with and without the LIDAR system to calculate the ROI in order to determine the economic feasibility of the systems. The outcome of this research is a model that technology providers (and O&M managers) can use in their internal business planning and engagements with customers to support business cases for strategic management and the insertion of their approaches.

Return on Investment (ROI) Modeling of Offshore Wind Farm O&M to Support Strategic Technology Insertion

October 1, 2015

Roozbeh Bakhshi

Introduction

- Operation and maintenance (O&M) costs make up 17-28% of the total lifecycle cost of offshore wind farms.
- O&M costs are directly related to the reliability of turbines and their sub-assemblies.
- Loads on the sub-assemblies that result in mechanical failure mechanisms are one of the main contributors to maintenance costs of the wind turbines
- The alignment of the wind turbine`s rotor with the direction of the wind affects the amount of loads on the sub-assemblies

Introduction

- The angle between wind directions and wind turbine`s rotor is called yaw angle, yaw error or yaw misalignment.
- Variations in yaw angle change the loads and subsequently the reliability of the wind turbine and its sub-assemblies

Source: YouTube screenshot

- Yaw misalignment can be static or dynamic. Static yaw misalignment depends on the accuracy of the wind direction measurement system whereas the dynamic misalignment comes from the yaw control system.
- Static yaw misalignment can be as high as 10º, dynamic can be even larger.
- Yaw misalignment reduces the power production for wind speeds below the rated speed. ($Power \propto cos^3\alpha$)
- Yaw misalignment also affects the loads on components of the turbine. As a result the reliability of components is different than the case of a complete alignment.

Approach

- Technology providers need business cases that demonstrate the economic value of their technology
- These are “cost avoidance” (not cost savings) business cases, which require the calculation of accurate ROIs
- While many life-cycle cost models have been developed, existing models generally do not have the capability to calculate the stochastic ROIs needed to produce business cases
- The O&M cost modeling is performed using discrete-event simulation (DES) based models
- DES incorporates the timing and sequence of events which is crucial in calculating return on investment (ROI) of implementing new technologies or policies

Discrete-Event Simulation

- Discrete-event simulation based life-cycle cost model that samples time (or cycles) the failure distributions
  - Dynamic simulation (models changes over time)
  - State variables change only at a discrete set of points in time (i.e., at "events")
  - Event = an occurrence to the system at an instant in time that may change the state of the system (successive changes are separated by finite amounts of time)
  - Timeline = the sequence of events and their calendar times
  - Stochastic = having a probability of occurrence
- The output of the simulation is the total life-cycle cost and the availability of the system.

Life Cycle Cost Modeling

- A life cycle cost (LCC) model for a wind farm with condition monitoring systems (CMS) can be formulated as:

$$LCC = C_R + C_{Per}$$

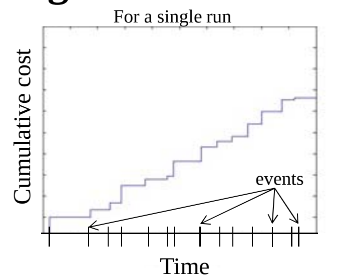
$$C_R \rightarrow C_{CM} + C_{PM} + C_{PL}$$

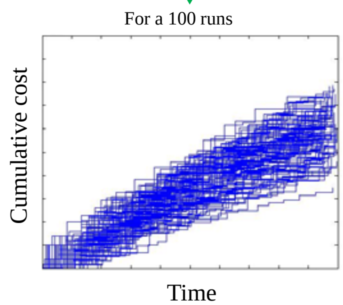
$$C_{PM} \rightarrow C_{CMS} + C_S$$

C_R	=	Cost associated with reliability
C_{Per}	=	Cost associated with performance
C_{CM}	=	Cost of corrective maintenance
C_{PM}	=	Cost of preventive maintenance
C_{PL}	=	Cost of production loss
C_{CMS}	=	Cost of CMS based maintenance
C_S	=	Cost of scheduled maintenance

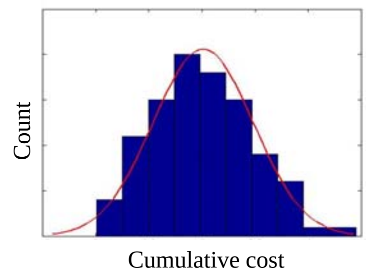
Modeling Cost Using DES

1) Each event has a cost
2) These events are stochastic, so if we run the simulation 100 times, we get 100 different results





3) These cost can be plotted in a distribution



Weighted Average Cost of Capital (WACC)

- The money required to finance a project could be raised through different ways (debt finance, equity,…). Each of these components has a different required rate of return and the weighted average of various components is called weighted average cost of capital or WACC
- The WACC incorporates the cost of money into the life-cycle cost calculation, and is a function of time
- All existing life-cycle cost models for offshore wind O&M either completely ignore the WACC (implicitly assuming it is zero, e.g., the ECN models), or they assume that the WACC is constant in time.

$$WACC = R_e \frac{E}{V} + R_d (1 - T_c) \frac{D}{V}$$

R_e: cost of equity
R_d: cost of debt
E: market value of equity
D: market value of debt
T_c: corporate tax rate

$\frac{E}{V}$: percentage of financing that is equity
$\frac{D}{V}$: percentage of financing that is debt
$V=D+E$: total market value of the financing

ROI

$$ROI = \frac{LCC_{no-tech} - LCC_{tech} - C_{tech}}{C_{tech}}$$

LCC_{tech} = life-cycle cost after implementing the new technology or management approach

$LCC_{no-tech}$ = life-cycle cost without the new technology or management approach

C_{tech} = cost of implementing the new technology or management approach

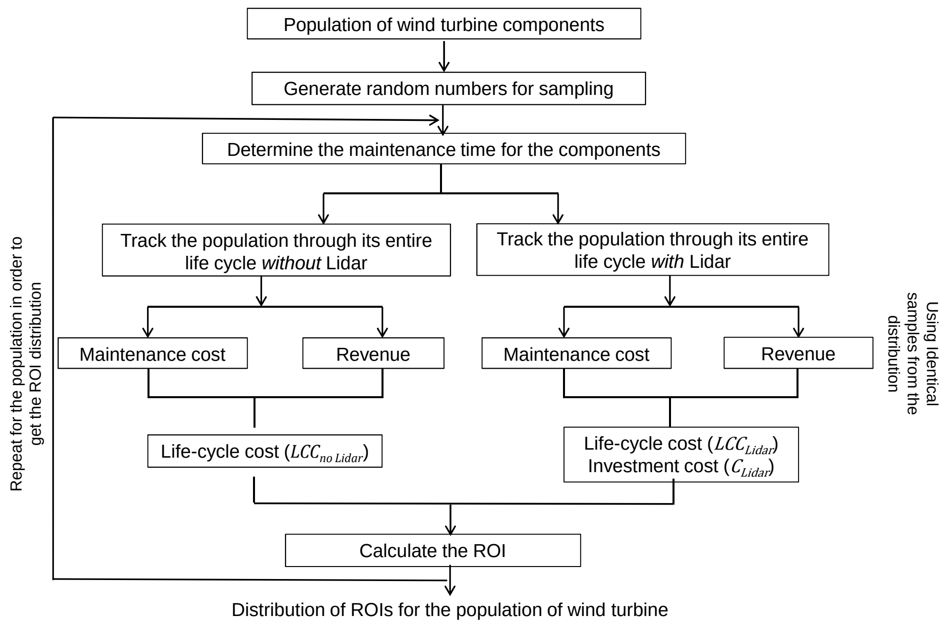
- Management of the analysis is not trivial to implement because of the stochastic nature of the problem, i.e., identical time histories (with different technology or management have to be compared).
- ROI is dependent of the timing of events (which are affected by the management approach) because the life-cycle cost depends on the estimation of weighted average cost of capital (WACC).

Case Study: Yaw and Lidar

- Light detection and ranging (LIDAR) is a system that`s used to determine the direction of wind 40 to 400 m ahead of the turbine. LIDAR is used to reduce the yaw misalignment.
- Implementation of LIDAR systems improves both reliability and production of the offshore wind farm, in other words avoids future costs and increases revenue.

Source: Avent Lidar Technologies

Model Flowchart



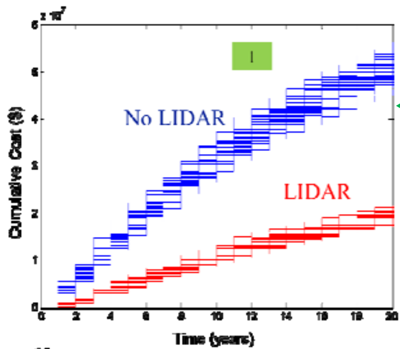
Analysis Assumptions

- An offshore wind farm with 30 turbines was assumed. Each turbine has 5 sub-components. A LIDAR system moves from one turbine to another every 2 weeks. Cost of LIDAR is $120,000

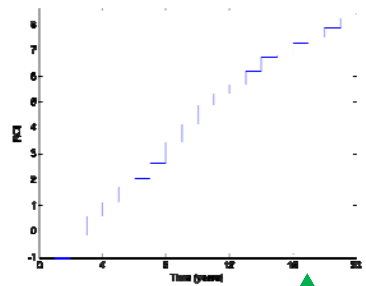
Sub-component	Replacement Cost ($)
Gearbox	300,000
Generator	150,000
Pitch Control	50,000
Rotor & Blades	200,000
Electronics	10,000

- Static yaw angle without LIDAR correction is assumed to follow a normal distribution with a mean of 7º. After correction the yaw misalignment will follow a normal distribution with a mean of 1º.
- Energy production data obtained from Windstats.
- Reliability data (Weibull parameters) for components in the case of no LIDAR are collected from Tavner et al. (‘*IET Renewable Power Generation*’, 2009)
- Effects of yaw angle on reliability is work under progress.

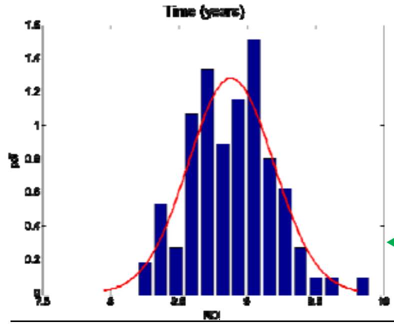
Results



Life-cycle cost over 20 years with and without LIDAR for an offshore wind farm with 30 turbines



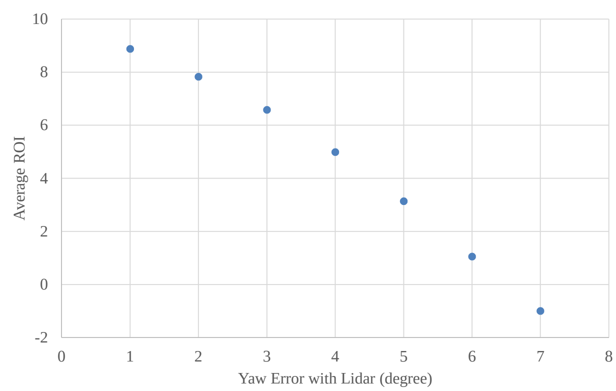
One time history of the ROI over 20 years



Distribution of ROI after 20 years for 100 time histories (runs of the simulation)

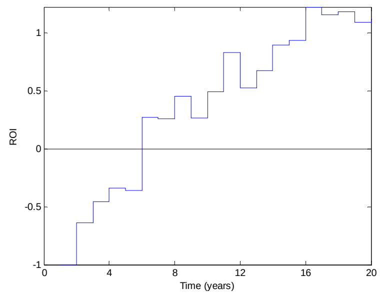
Results (continue)

Sensitivity of ROI with the yaw angle correction that it allows. Before implementing Lidar, yaw is assumed to be 7°

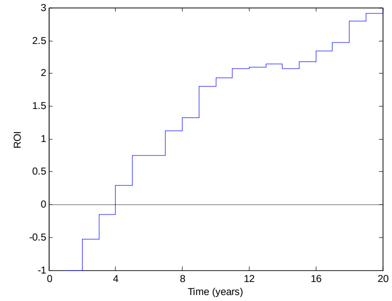


ROI at Different Yaw Angles

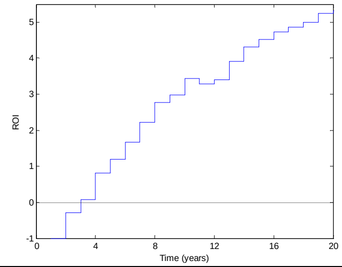
No lidar, YA=7→ Lidar, YA=6



No lidar, YA=7→ Lidar, YA=5



No lidar, YA=7→ Lidar, YA=4



Lessons Learnt from Whole Life Costing Applications

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As the whole life cost of projects continually gets difficult to estimate over the number of target years, the need to effectively cost a project from start to finish is paramount. The influence of uncertainty on KPIs such as cost and equipment performance promotes the need for adequate means to measure its impact. Adequate whole life costing can assist in realizing value from long life projects. However, with a change in price and assets over years, industries seek analytical, practical and effective approaches to improve the way this concept is applied. Hence the need to identify the best practice that cuts across various industries cannot be overemphasized. The aim of this presentation is to provide an insight in to suitable approaches for whole life costing. This presentation is structured to cover three areas:

- Firstly, results from an online survey that examines implementation of whole life cost modelling across industries will be presented. This is based on 42 respondents, where 27 have carried out projects using whole life cost modelling and 15 have not carried out projects using whole life cost modelling. All respondents agreed that whole life cost modelling is a useful approach and should be considered in all decision making. Some of its benefits were mentioned to include: effectively calculating the long term cost of a project. The presentation will cover further details about the results from the survey that gives an insight as to what best practice could involve.
- Secondly, a detailed case study from the defense sector will be presented by covering the cost drivers and estimation approach. This will involve presenting an overview of the input and output for a maintenance oriented contract. The case study will offer an insight in to the steps that were followed to develop the life cycle cost model.
- Thirdly, the lessons from the case study and the survey will be analyzed with respect to the wind turbine sector. This will aim to build on what the current challenges are and provide an insight as to where the future challenges lie.

Lessons Learnt from Whole Life Costing Applications

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1/10/2015

Contents

- Whole life cost modelling
- Case studies
- Online Survey results
- Guidance proposed
- Conclusion

Whole life cost modelling (WLCM)

DEFINITION

WLC is the cumulative cost of a capability or service over its contract duration

MOTIVATION

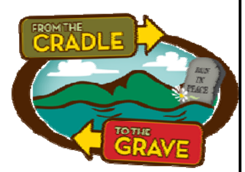
To enable investment options to be more effectively evaluated.

To consider the impact of all costs rather than only initial capital costs.

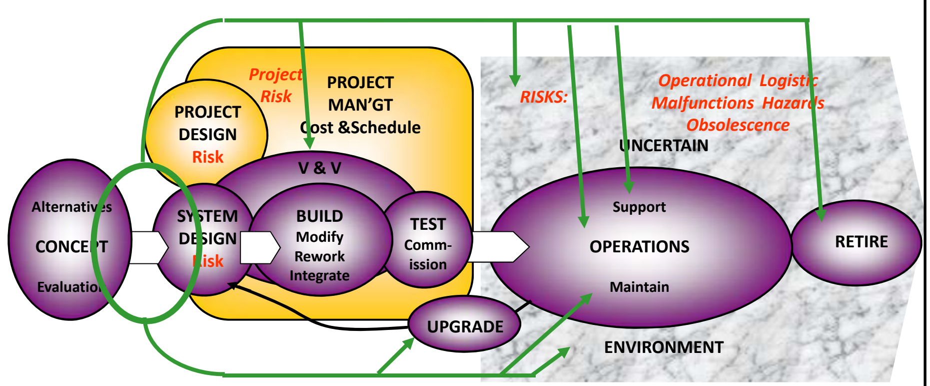
To assist in the effective management of completed buildings and projects.

To facilitate choice between competing alternative.

Source: "Life cycle costing--theory, information acquisition and application", Woodward, 1997



Whole life cycle



Case studies

Case study 1

Whole life cost modelling applied to assist a Nordic aerospace industry in deciding whether to invest in new aircraft fleet or sustain their current fleet.

Scenarios

- cost to modify and operate existing fleets until 2030?
- cost to acquire and operate a new fleet until 2045?
- cost to modify and operate existing fleet until 2030 and then acquire and operate new fleets until 2045?

Techniques used

Parametric cost estimation, expert knowledge, peer revi[…] discounting technique, discussion with client.

Source: https://flyawaysimulation.com/downloads/x-plane-10/

Case study 1: aerospace

Advantages

- Reach cost effectiveness
- Increased capability
- Improvement on the analysis of data used for comparison

Lessons learnt

- Comprehensively define client needs
- Direct access to clients is essential
- Employ qualified individuals
- Review cost models for validity of data
- Benefits of applying sensitivity analysis

Total system life cycle support

Source: www.army-technology.com

Case study 2: fashion mill

An investment appraisal carried out in a fashion mill

3 cases considered

- Install loom A
- Install loom B or
- Install loom C

Technique used - Activity based costing, Expert knowledge, extensive market research

Advantages

- Increased profitability
- Reduced maintenance

Source: http://www.themanufacturer.com/

Case study 3: Defence

Supply Chain	Engineering	Maintenance	Performance	Training	Commercial	Mission
Stock Level	Rate of Change of Demand	Platform Maintenance Policy	Customer demand usage	No. of Students	Exchange rate	Priority of Actions
MTBF	Query Volume	Maintenance Schedule	Customer actual usage	No. of Trainers	Debtor days	Readiness
Arising Rate	Query Response Time	Facilities Capacity	Unit cost per unit of operation (flying hour/ days at sea/theatre)	No. of Courses	Creditor days	Type of Contract
Turn-Round-Time	Quality of Response	Labour Availability	Maintenance event per unit usage	Length of Course	Risks & opportunities	Administratio n
Lead Time	Labour Cost	Labour Effectiveness	Training pass rate	Training Facilities	Overhead costs	
Repair Cost	GFX/Core/Sub-contractor Labour Skill	Labour Cost	Revenue rate		Inflation	
Purchase Cost	Information Support	Emergent work	Supplier influence		Tax	
Demand Satisfaction Ratio	Equipment Complexity	GFX supply			WACC	
Obsolescence	Calibration & Test	Material Availability				
Transport Cost		Consumables				
		Labour Skill				

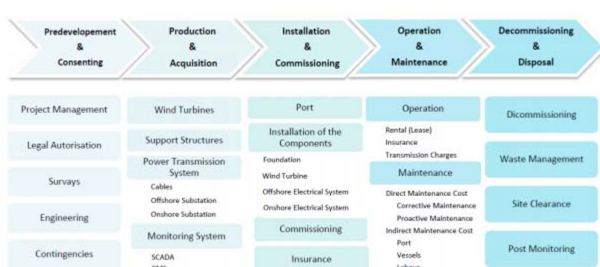
Example: WLC in Service Contracts in defence

Cranfield UNIVERSITY

Case study 4: Wind Turbines and Wind Farms

Cranfield UNIVERSITY

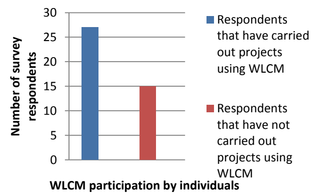
- Approximately 75% of the total cost of energy for a wind turbine is related to upfront costs such as the cost of the turbine, foundation, electrical equipment, grid-connection and so on (Source: The Economics of Wind Energy - A report by the European Wind Energy Association).



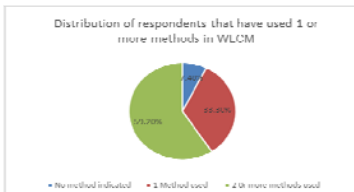
(Source: Mahmood Shafiee, Feargal Brennan, Inés Armada Espinosa, Whole Life-Cycle Costing of Large-Scale Offshore Wind Farms, 2014).

Online Survey

- Total survey respondents



- Method Distribution



- Industrial application
- Tools and methods
- Reasons for using Whole life cost modelling
- Views on Whole life cost modelling
- Challenges of whole life cost modelling
- Over 25 working days and a total of 42 responses were collated.

Overview of survey results

- Large variety of industries participated: defence, aerospace, oil and gas, nuclear
- 44 % of respondents (17) over 31 years of experience
- 59% of respondents (22) have carried out WLCM
- 81 % of respondents found WLCM beneficial
- Different roles including: cost engineer, cost manager, project controls manager, quantity surveyor, etc.
- Varying definitions of WLC, overall: the total cost of ownership from concept to disposal
- Industry specific terminology for defining life cycle stages
- In-house tools commonly developed; various methods such bottom up, parametric, regression analysis, top down

Benefits of WLCM

- WLCM considered to be essential and useful for reaching value for money
  - To determine the long term benefit and cost of a project which will aid in decision making and setting budget.
  - Used to compare capital expenses and operating expenses so as to ensure that best mix of option is selected.
  - Used to know the total cost of ownership of an asset and to define the optimum design option

Source: www.tech.co

Challenges with WLCM

- Size and complexity of model
- Quantifying environmental cost
- Lack of investment in the processes required to carry out WLCM
- Disposal of contaminated product and how it is handled with associated risk.
- Managements' unwillingness to consider the life cycle.
- Considering the issue of obsolescence & technology progress
- Lack of reliable data and difficulty in gathering data
- Measuring risk and uncertainty
- Differing technical assumptions

Good practice for WLCM

- Recommendations to improve WLCM:
  - Improve data quality
  - Use numerous methods
  - Simplify models to a level to fully comprehend
  - Have a clear scope/target for WLCM
  - Establish adequate means to communicate with the customer and the supply chain
  - Make sure good level of experienced personnel involvement
  - Validate and verify models, tools and data input

Lessons learnt from the survey

- Those longer in cost engineering are more likely to apply WLCM
- WLCM can be highly beneficial for decision making
- Most interest in WLCM in construction, oil and gas, and defence sectors
- Largely a common understanding of WLC – asset life; cradle to grave
- WLCM applied for early stage decisions, long term decisions, optimum design decision, total cost of ownership, etc.
- Largely in-house (MS Excel) based tools developed for bespoke purposes
- Documenting lessons learnt is still challenging and potentially reduces improvements in WLCM

Best practice guidance

Guidance proposed

1) Understand customer requirement
2) Understand a system and how cost is generated through the use of the system
3) Consider the significant period of decision to be made
4) Define and document terms
5) Modelling should be carried out by qualified individuals.
6) Choose an appropriate model with well-defined boundary
7) Build a dynamic model
8) Conduct sensitivity analysis
9) Choose best option with NPV
10) Where data is unavailable use and document assumptions and get client to approve them.

Summary and Future work

Summary

- Four Case Studies presented to realise how WLCM can assist with improving projects
- Through an online survey key challenges, processes and definitions identified
- A 10 step process proposed as best practice guide for WLCM

Future work

- Methods to manage risk and uncertainty in WLC since most projects have long time scales.
- Further evaluation of different WLCM approaches needed
- A generic cost breakdown structure should be developed for industries especially those with emerging technology

Potential Life-Cycle Cost Reductions for Offshore Floating Wind energy

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To increase the share of wind energy in the global wind energy market, wind farm developers look towards alternative sites offshore where larger wind resources and surface area are available. The more challenging deployment of wind turbine systems in the offshore environment leads to the evaluation of the value chain and life cycle to identify areas with potential for cost reduction and to make cost-competitive offshore wind farms. In deep waters, where floating foundations are necessary to maintain energy market competitiveness, the trend so far has been to 'marinize' onshore horizontal axis wind turbines, under the assumption that it is the optimal design for floating applications despite the very different operating conditions found offshore. However, this is not necessarily the case and alternative concepts, such as vertical axis wind turbines (VAWTs), may provide more competitive offshore energy generation systems due to inherent advantages. An overview of the advantages and disadvantages of this turbine type is presented, both qualitatively and quantitatively. A case study of determining the levelized cost of energy for the DeepWind floating VAWT concept is also presented. Finally, an outlook of the positive impacts of numerical wind turbine design tool development and design process development on life cycle cost reduction is illustrated.

Potential life-cycle cost reductions for offshore floating wind energy

Michael Borg
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Technical University of Denmark

International Workshop on Life-Cycle Costing of Offshore Wind Turbines and Farms
October 1st 2015, University of Maryland

Outline

- Introduction
- Offshore wind life cycle value chain
- Floating wind turbine system
- Alternative concepts
- The case for floating VAWTs
- Improved design tools for cost reduction
- Conclusions

Introduction

Introduction

Why offshore wind energy?

Need for more sustainable energy technologies

↓

Wind energy is one promising technology

↓

Offshore: more wind and less obstacles for larger turbines

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Wind energy is one promising technology

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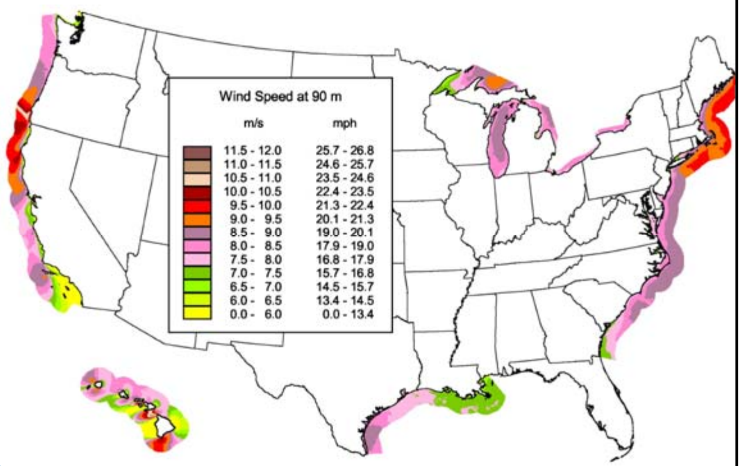
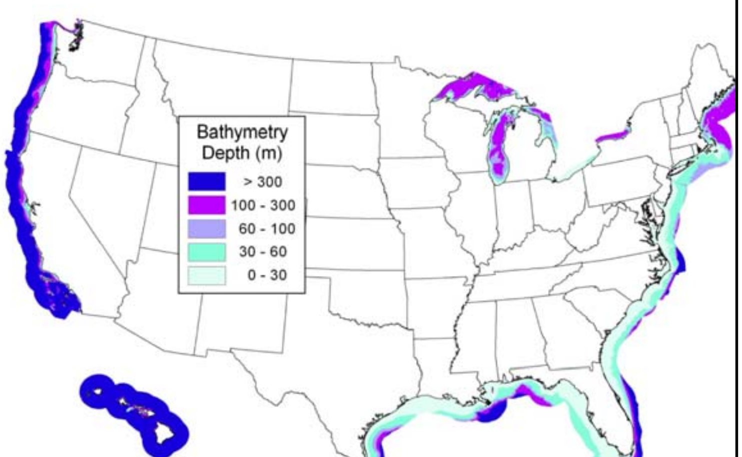
Offshore: more wind and less obstacles for larger turbines



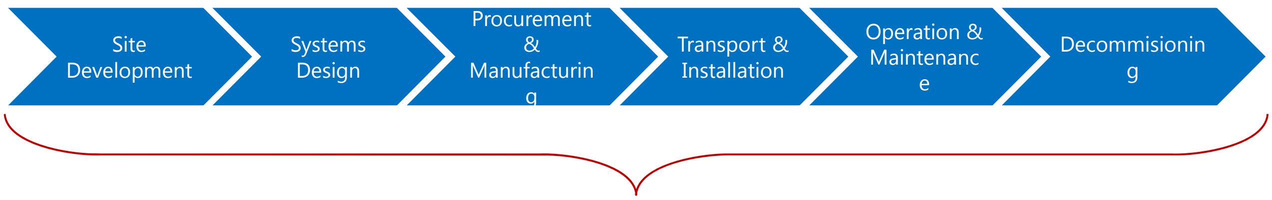
Introduction

Why floating offshore wind energy?

- Fixed foundations not *economically* feasible in water depths >50m
- Transition to floating foundations
- Trend so far to 'marinize' onshore wind turbines
- Need to evaluate all turbine concepts for floating wind

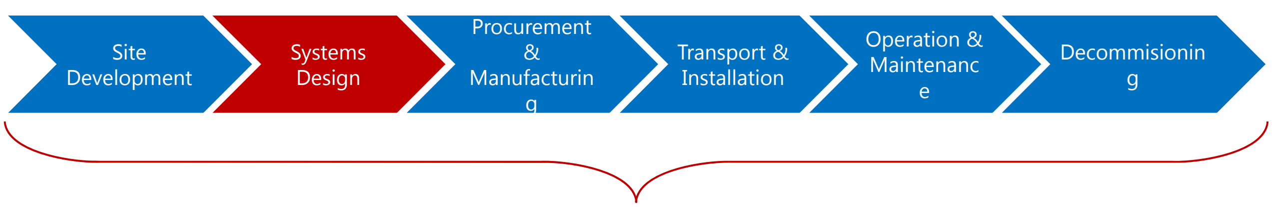


Offshore Wind Value Chain



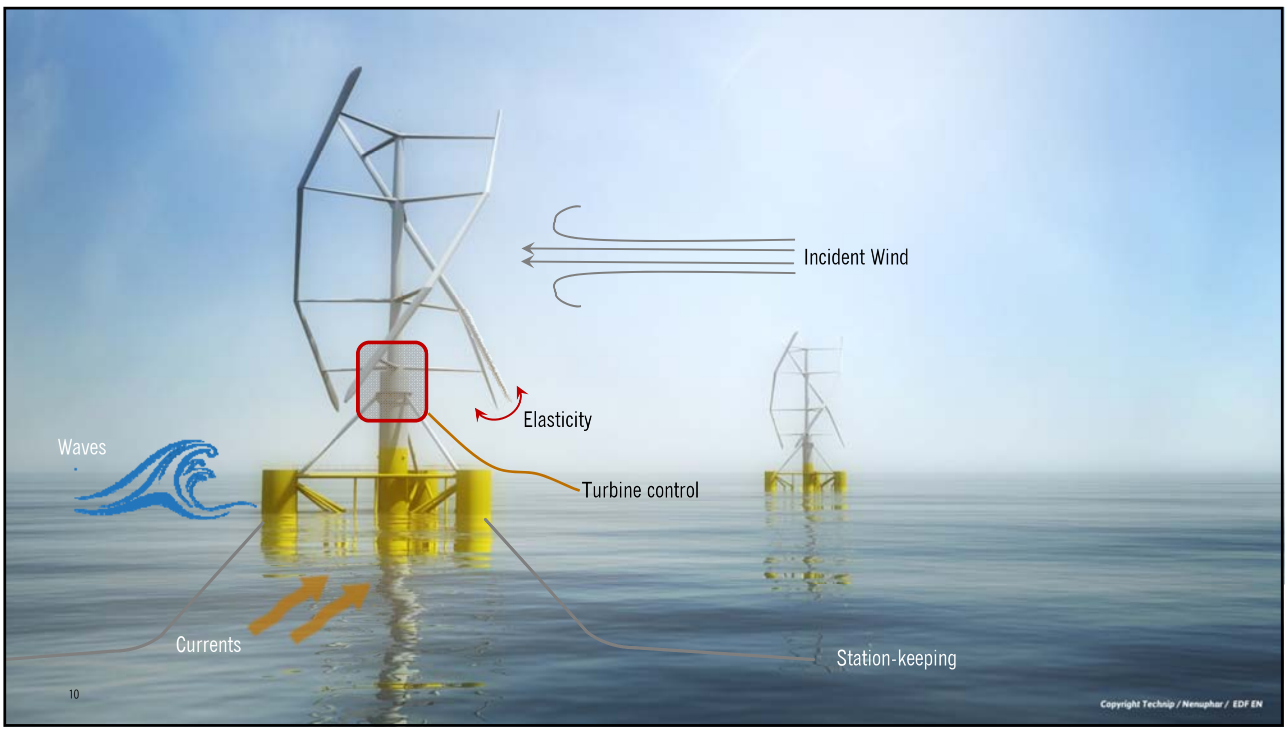
Contributors to the final cost of energy

Offshore Wind Value Chain



Contributors to the final cost of energy

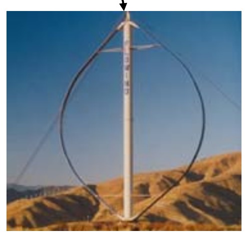
Floating wind turbine systems



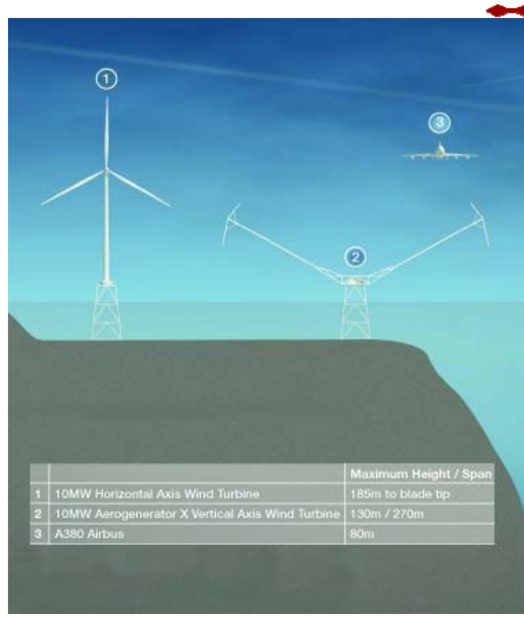
Alternative concepts: HAWTs vs VAWTs

- Two main types of wind turbines
  - Horizontal-axis
  - Vertical-axis



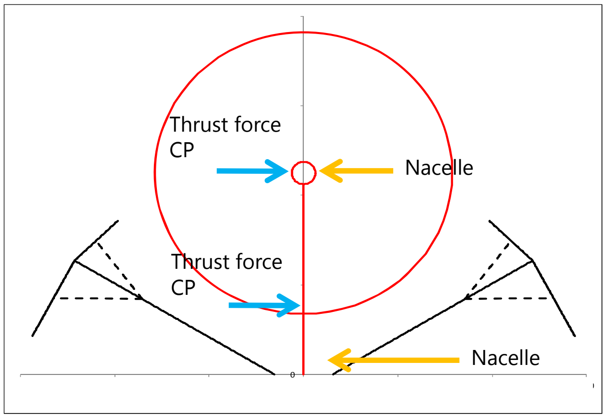


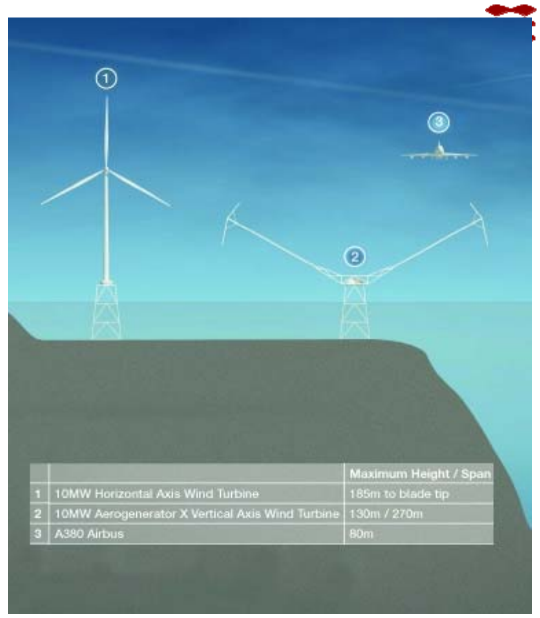

HAWTs vs VAWTs



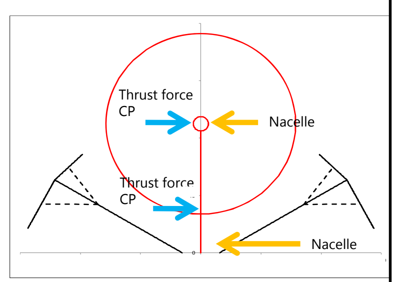
		Maximum Height / Span
1	10MW Horizontal Axis Wind Turbine	185m to blade tip
2	10MW Aerogenerator X Vertical Axis Wind Turbine	130m / 270m
3	A380 Airbus	80m

HAWTs vs VAWTs





HAWTs vs VAWTs



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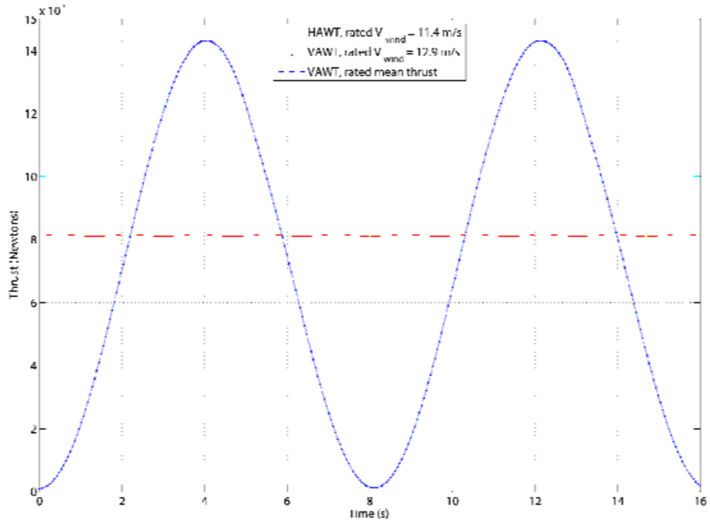
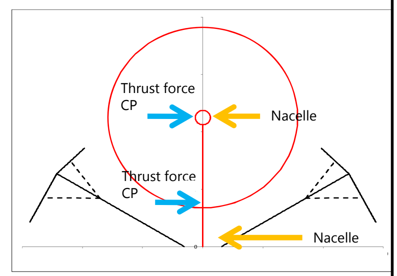
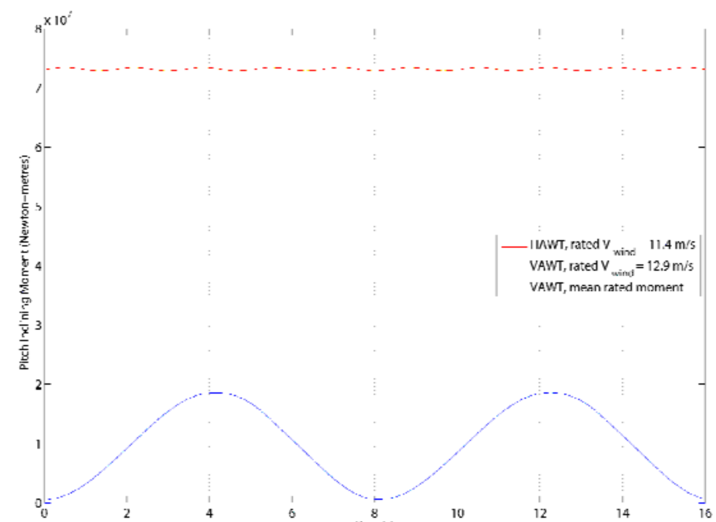
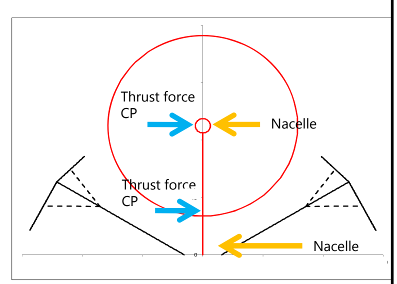




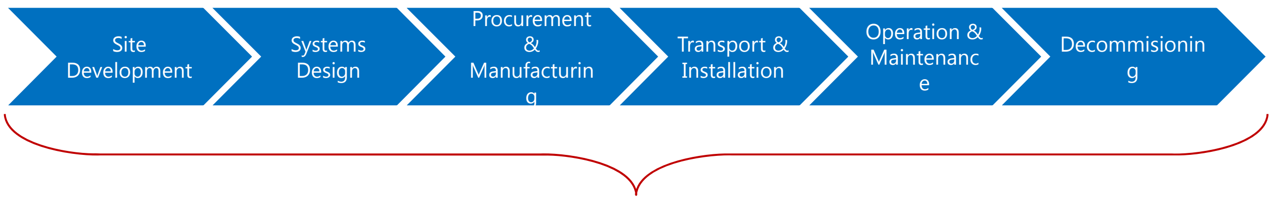
HAWTs vs VAWTs





Improved design tools for cost reduction

Offshore wind value chain



Contributors to the final cost of energy

Improved design tools for cost reduction

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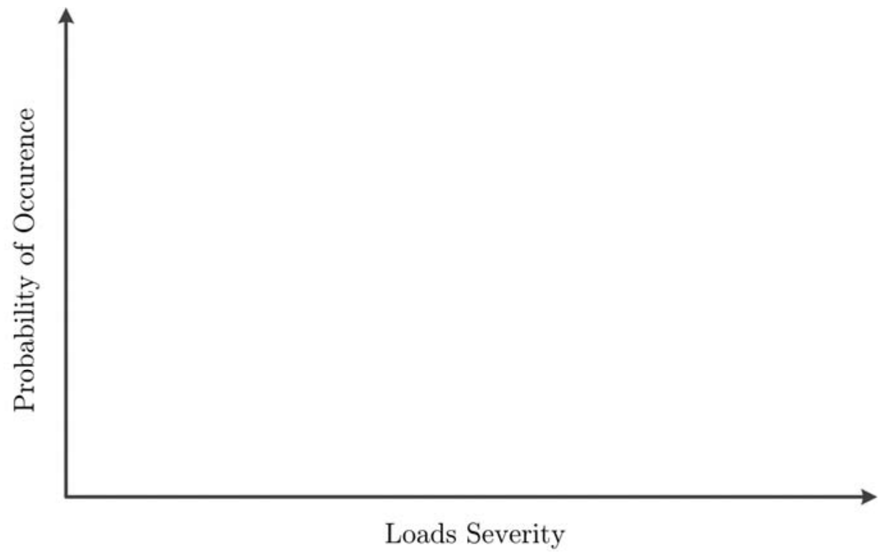
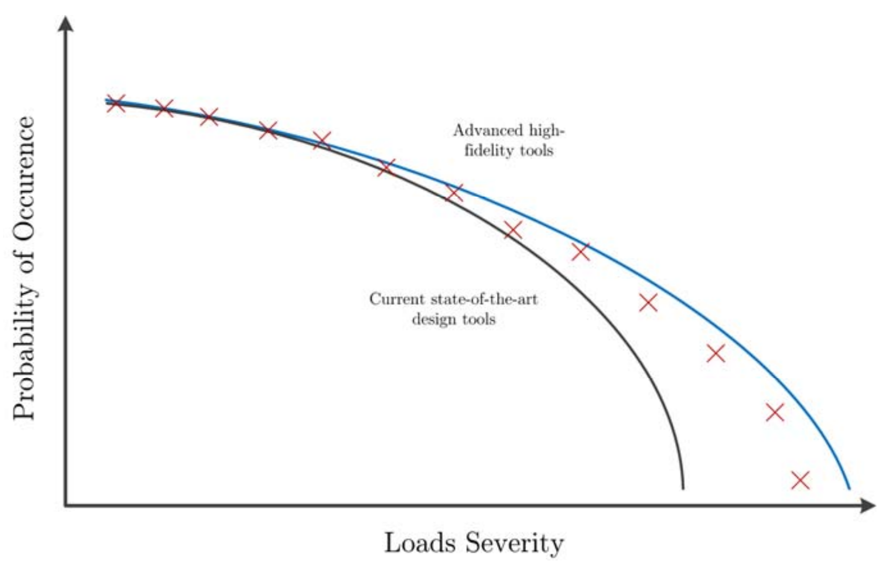
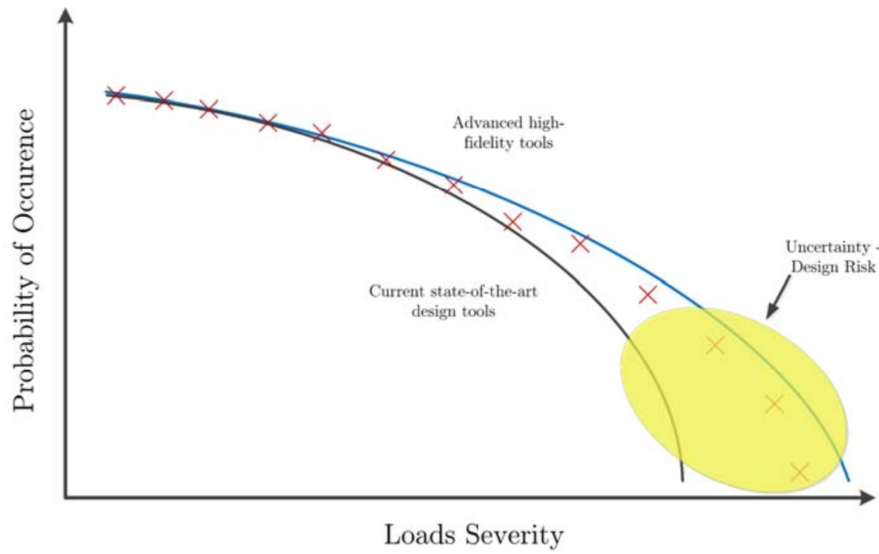


Improved design tools for cost reduction

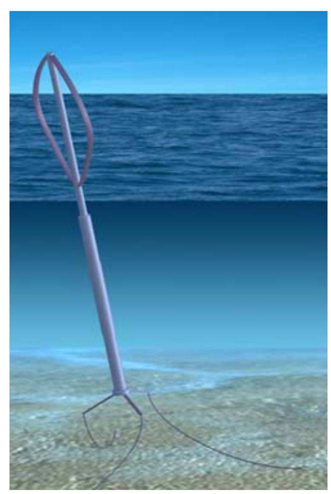


Improved design tools for cost reduction



DeepWind case study

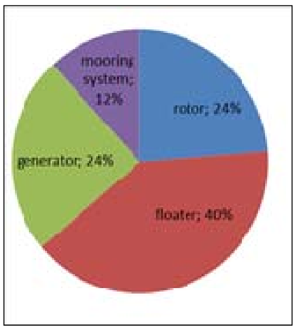
- EU Future Emerging Technologies 4-year R&D project
- Floating VAWT concept. Design methodology:
  – Simple and more reliable through reduced no. of components
  – Design for mass production manufacturing
  – Upscaling potential
- Results:
  – 5MW system detailed design
  – 20MW conceptual design

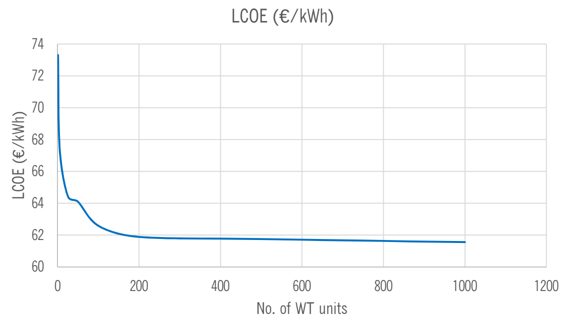


DeepWind LCOE model

- Levelized cost of energy model, based on (Myhr, 2014)
- Combining capital and operating costs for a 25-year lifetime and range of wind farm size

Unit capital costs breakdown





Future Challenges

- Implementing integrated design methodologies
- ‘Class’ design versus site-specific design ⟶ mass production
- Quantifying concept-dependent O&M costs
- Convincing industry to support alternative concepts

Conclusions

- Explore alternative concepts for significant change in cost of deep-sea offshore wind energy
- Holistic and integrated system design vs. segregated design
- Reducing costs through improved design tools
- DeepWind floating VAWT concept case study

Thank you for your attention

Acknowledgements

EU FP7 DeepWind (2010-2014) - This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 256769

EU FP7 INFLOW (2011-2017) - This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No

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Wind Turbines Operation and Maintenance Optimization: The Impact of an Accurate Vertical Wind Profile Estimation

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Prognostic and health management (PHM) models, in general, are developed to link failure mechanism studies to system lifecycle management. Underestimation or overestimation of wind characteristics at a wind farm, as an input for a PHM model, would have significant impacts on performance and economics of wind turbines. Although the conventional power law approximation has been used as a first guess for onshore/offshore wind assessments at the turbine hub height, the wind speed extrapolations are not an accurate representation of the vertical wind profile complexity. Hence, more accurate prediction and optimization of turbine maintenance periods could provide a significant wind energy cost reduction. In this work, a Remaining Useful Life is assumed to be predicted for a wind turbine with uncertainty, and the optimum predictive maintenance date is obtained using Real Options Analysis with generated random wind speeds. The optimum maintenance date with generated random wind speed at the turbine hub height, based on an average of one month (July 17- August 17, 2013) wind speed measurement period in Maryland Wind Energy Area extrapolated from buoy data is compared with that from Light Detection and Ranging (Lidar) technology. The results show the optimum maintenance opportunity was almost 2.8 times earlier from Doppler wind Lidar data compared to that from buoy data. This difference showed the importance of wind speed measurements on obtaining the optimum predictive maintenance date. However, further study with larger measurement periods is needed to prove it.

Maintenance Optimization of a Wind Turbine: The Impact of Wind Speed Measurement Accuracy

N. Goudarzi[1], X. Lei[1], A. St. Pe[2], S. Rabenhorst[2], R. Delgado[2], P. Sandborn[1]

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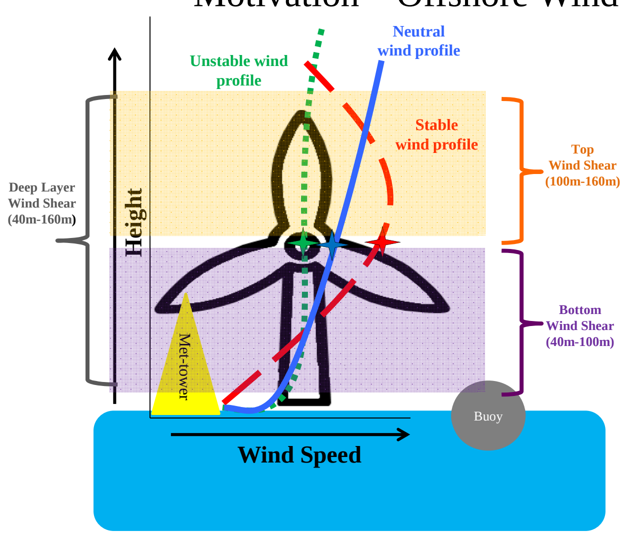
International Workshop on Life-cycle Costing of Offshore Wind Turbines and Farms
University of Maryland, College Park, Maryland, USA
October 01, 2015

Motivation – Offshore Wind Profile

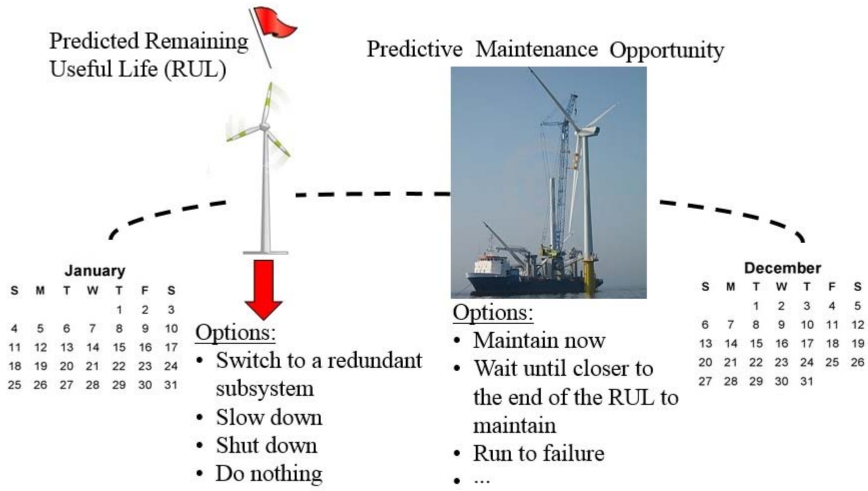


- Limited measurements = poor understanding of marine atmosphere complexity
- '**Power Law**' extrapolations assume uniform low wind shear (0.10-0.14) in **neutral vertical wind profile**

$$P_w = \frac{1}{2}\rho A u^3$$

Which wind profile represents the actual wind speed variation along the wind turbine height?

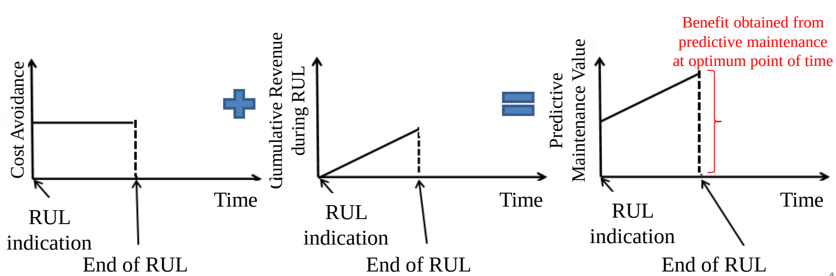
Motivation - Maintenance Options



If the ***value*** of exercising each option can be determined, the management would have a basis upon which to make a decision.

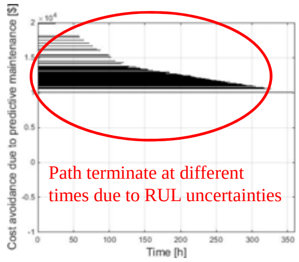
Predictive Maintenance Options

- Real Options: The flexibility to alter the course of action in a real assets decision, depending on future developments.
  - The buyer of the option gains the right, but not the obligation, to engage in the transaction at the future date
- The Real Options created by Prognostics and Health Management (PHM)
  - 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
  - Value returned by the option = cost avoidance and cumulative revenue during RUL
  - Letting the option expire = do noting and run the turbine to failure

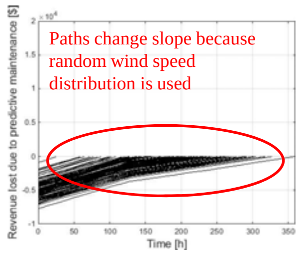


Predictive Maintenance Options

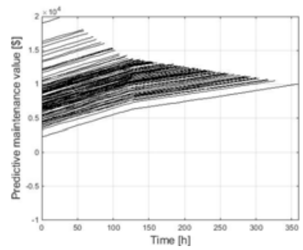
- Considering the uncertainties in the RUL predictions and future wind speeds:



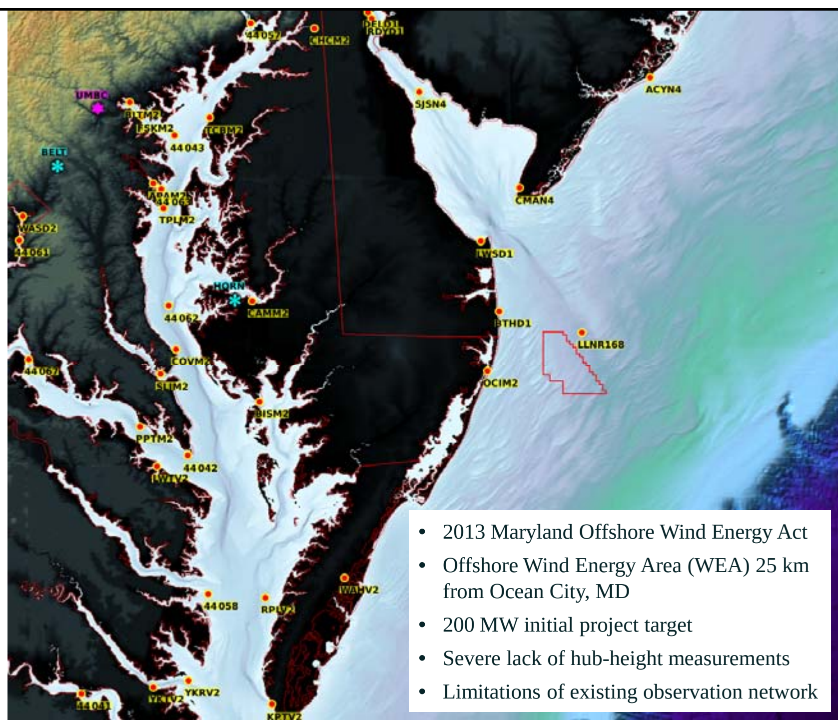
Cost avoidance paths



Revenue lost paths



Predictive maintenance value paths

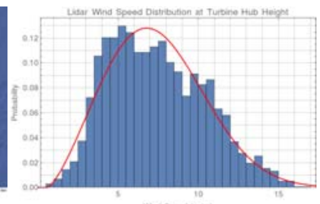


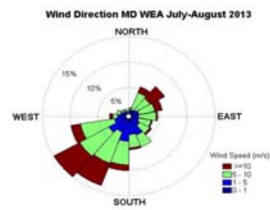
- 2013 Maryland Offshore Wind Energy Act
- Offshore Wind Energy Area (WEA) 25 km from Ocean City, MD
- 200 MW initial project target
- Severe lack of hub-height measurements
- Limitations of existing observation network

Methodology - Data Collection

- Wind turbine: Vestas V112-3.0 MW Offshore
- Wind speed simulation
  - July 17-August 31, 2013 wind data within Maryland's Offshore Wind Energy Area (WEA) from Buoy 44009 and Lidar (installed in Ocean city)
  - Monte Carlo simulation used to generate stochastic wind speed paths
  - Power Law used to transfer buoy height wind speed to hub height and direct Lidar data were used
- Time to Failure (TTF)
  - Represents how RUL is used up for the subsystem with PHM prediction (assuming turbine fails thereafter)
  - Uncertainties of predicated RUL and wind considered

Location of NOAA Buoy 44009





Methodology - Valuation

- Cost Avoidance (CA (t))
  - Maintenance cost (parts, service, labor etc.) avoidance as difference between cost of predictive maintenance (C_{PM}) and corrective maintenance (C_{CM}) :

$$CA(t) = C_{CM} - C_{PM}$$

$$C_{CM} = C_{P\_CM} + C_{S\_CM} + C_{L\_CM} + C_O$$

$$C_O = EP \cdot DE$$

- Cumulative Revenue (CR (t))
  - Revenue earned for the energy generated during the RUL (energy price *EP*) within and exceeding annual delivery target (if any, cumulative energy *CE*)

$$CR(t) = EP \cdot CE(t)$$

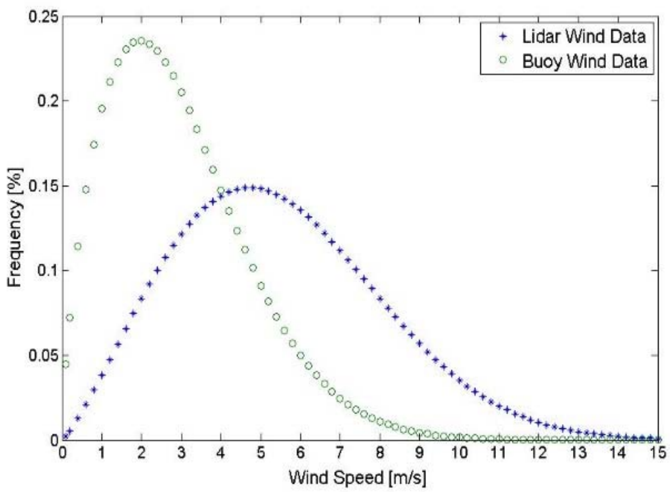
- Maintenance Value : $MV(t) = CA(t) + CR(t)$
- Predictive Maintenance Cost: $C_{PM} = C_{P\_PM} + C_{S\_PM} + C_{L\_PM}$

Methodology - Real Options Analysis

- A predictive maintenance option is created by incorporating PHM into key subsystems such that an RUL is predicted as the subsystem's health degrades.
- The option is exercised when predictive maintenance is performed before the subsystem or turbine fails.
- The option expires if predictive maintenance is not performed prior to failure.
- The present value of the option *PV(t)* on implementing predictive maintenance at time *t* is calculated by:

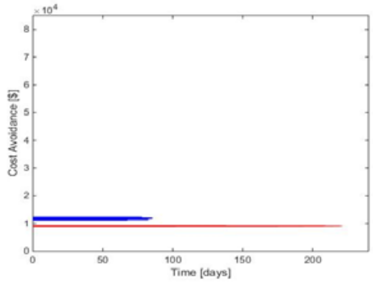
$$PV(t) = \begin{cases} \max(MV(t) - C_{PM}(t)) & 0 < t < TTF \\ 0 & TTF \leq t \end{cases}$$

Results - Weibull wind speed frequencies from Buoy and Lidar

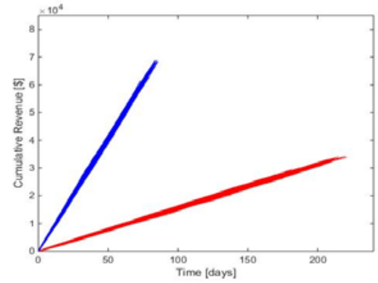


Weibull parameters	Buoy	Lidar
Shape parameter (*k*)	1.695	2.215
Scale parameter (*c*) - m/s	3.311	6.188

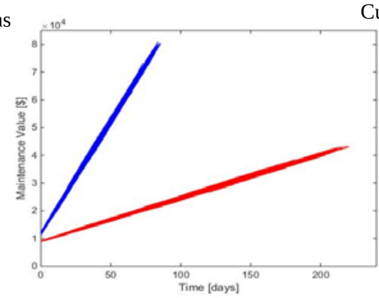
Results - Predictive Maintenance Optimization Procedure



Cost avoidance paths



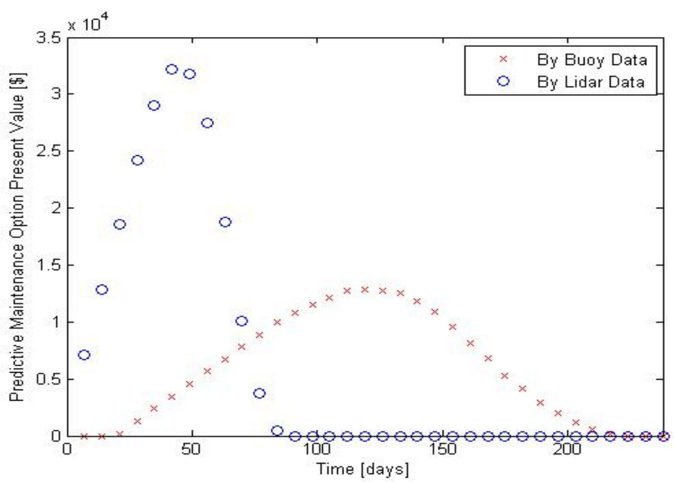
Cumulative revenue paths



Maintenance value paths

Buoy data (red)
Lidar data (blue)

Results - Predictive Maintenance Option Present Value estimates from buoy and Lidar



- The predictive maintenance option present value from Doppler wind Lidar data is 2.5 times higher than that from buoy data
- The optimum maintenance opportunity is almost 2.8 times earlier from Doppler wind Lidar data compared to that from buoy data.

Conclusion & Future Work

- While current scheduled O&Ms are based on wind forecasting from buoy data, this work shows more accurate wind prediction by using site specific wind characteristics obtained from remote sensing technologies (such as Lidar) allows to perform a more accurate O&M optimization that may lead to a reduced O&M cost. It also shows the lower O&M cost comes with shorter optimum maintenance opportunity windows.
- This work applies the ROA modeling concept and assesses the impact of uncertainties in wind speed measurements on the optimum maintenance date and expected option value.
- This work applies the ROA to assesses the impact of uncertainties in wind speed measurements on the optimum maintenance date and expected option value.
- The estimated wind profiles and associated hub-height wind speeds obtained from the power law extrapolation of buoy data offshore near the WEA are not accurate.
- Remote sensing technologies such as Doppler Wind Lidar should be employed to provide an accurate representation wind profile and thus hub-height wind distribution in front of wind turbines.
- Future work:
  - Using larger wind measurement periods.
  - Using different sites to obtain the predictive maintenance option present value.

Acknowledgment

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