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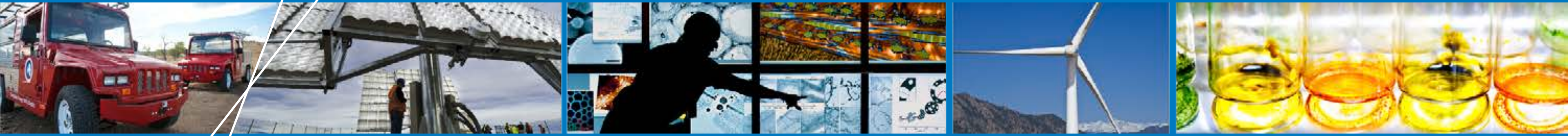
A Spatial-Economic Cost-Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030



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2016 International Offshore Wind Partnering Forum

Life-Cycle Cost for Offshore Wind Workshop

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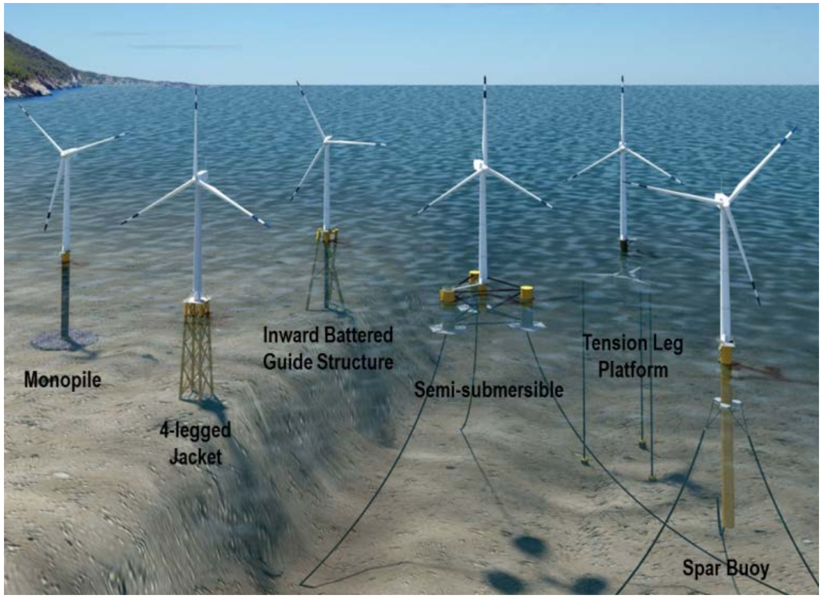
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Objectives

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

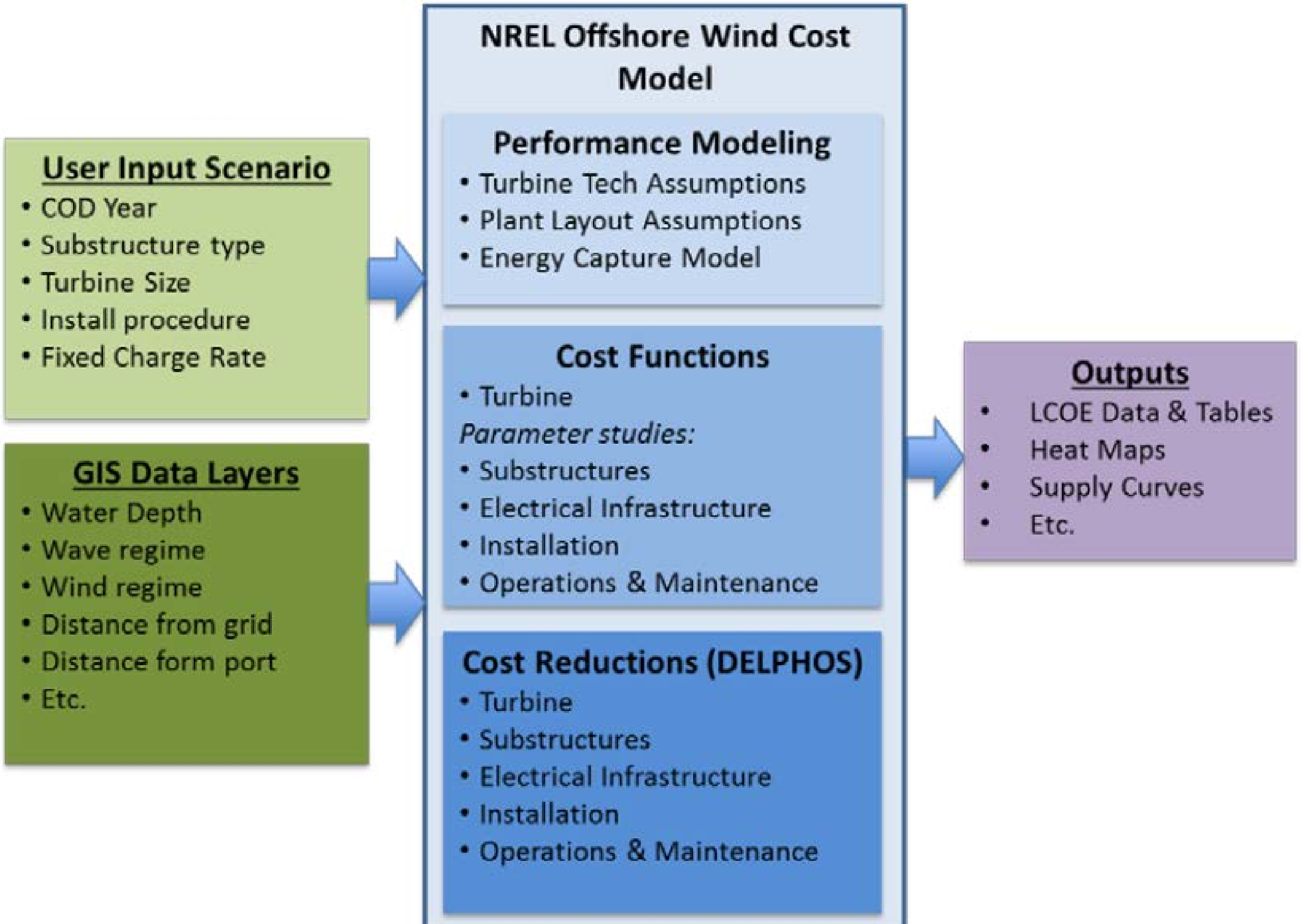


Offshore wind substructure types for varying water depths.
Illustration by Josh Bauer, National Renewable Energy Laboratory

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

General Methodology

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



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

General Assumptions

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

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

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

Several Methodological Simplifications

The following several spatial variables were not considered:

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

The following modeling generalizations were used:

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

Wind Project Layout and Performance Modeling

Coverage includes:

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

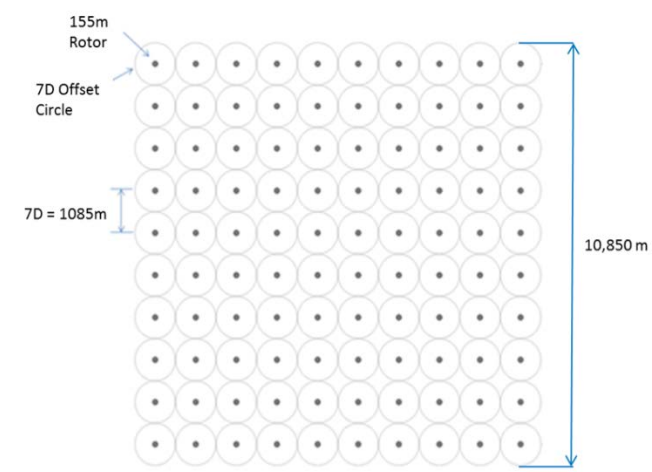
Wind project layout includes:

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

Each project layout considered independently includes:

- 7,159 distinct wind power plant layouts*
- No gaps between adjacent layouts
- No wake interaction between layouts.

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



Conceptual project layout with 100 generic 6-MW turbines

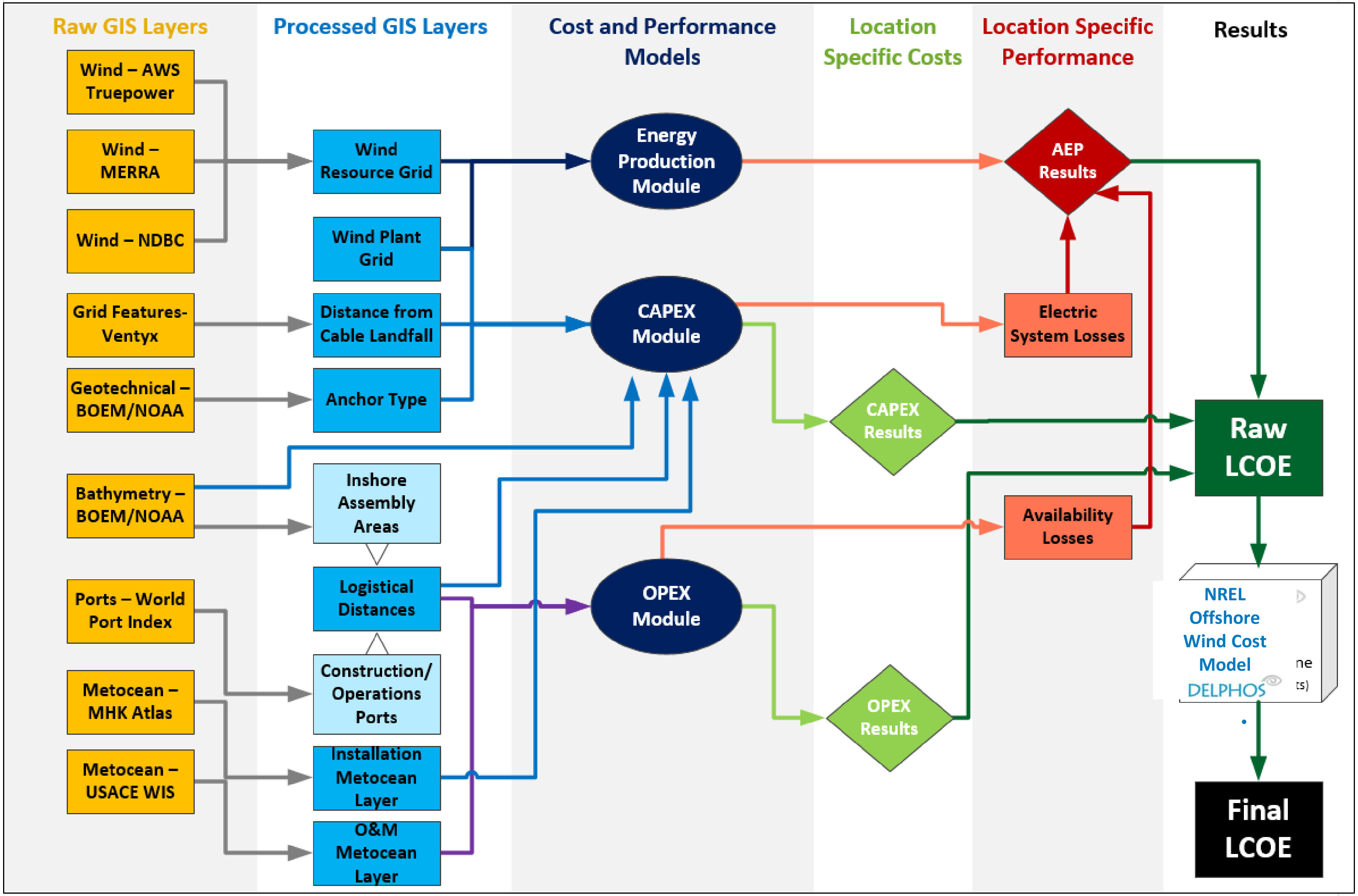
* A potential wind farm was considered to qualify if at least 50% of the turbines met the depth restriction criteria.

Cost Reduction Pathways – DELPHOS Tool

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

*DELPHOS (KIC Innoenergy 2016)

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



Spatial-economic processing framework

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

LCOE

Turbine/Substructure Unit CAPEX

Market data and NREL Sizing Tools

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

Balance of System CAPEX

NREL Offshore BOS Model and PSCAD

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

Operations & Maintenance (OPEX)

ECN Offshore Wind O&M Tool

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

Fixed Charge Rate (FCR)

Simplified Representation

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

Annual Energy Production (AEP)

openWind Enterprise, ECN O&M Tool, PSCAD

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

LCOE calculation framework and modeling assumptions

Substructure Parameter Study

LCOE

- **Substructure Unit CAPEX**
- Balance of System CAPEX
- Operations & Maintenance (OPEX)
- Fixed Charge Rate (FCR)
- Annual Energy Production (AEP)

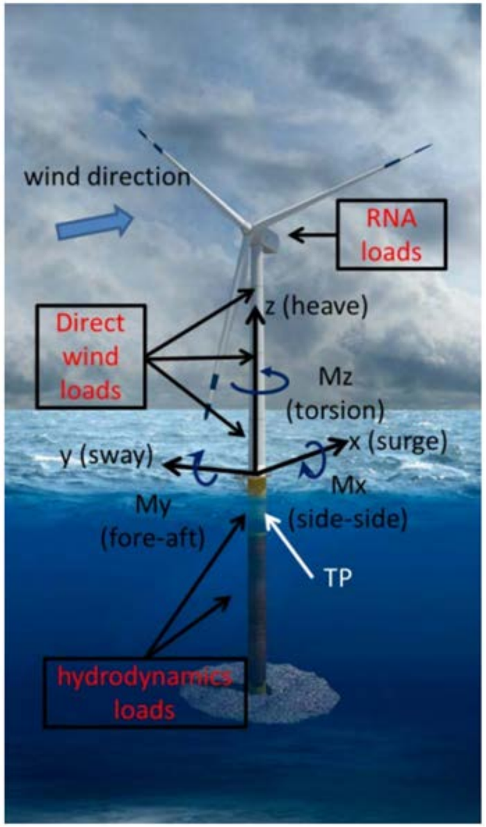
Case study: Monopile for 3-MW turbine

Cost Functions

- Turbine

Parameter studies:

- Substructures
- Electrical Infrastructure
- Installation
- Operations & Maintenance



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

Substructure Parameter Study

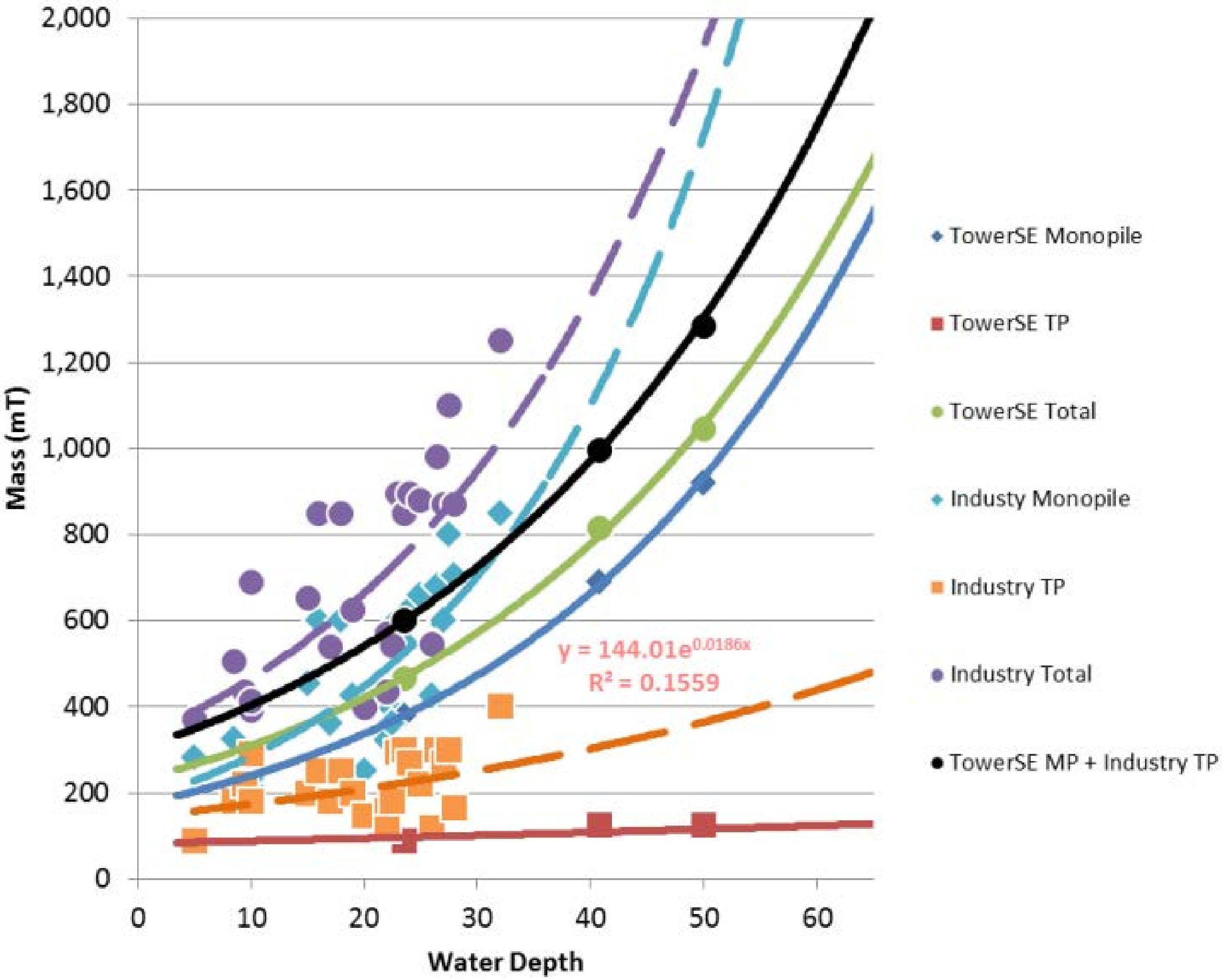
For each combination of turbine rating (3, 6, and 10 MW) and water depth we assessed:

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

Key variables: Water depth and turbine rating

Substructure Parameter Study

Substructure Unit CAPEX



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

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

Component unit cost estimates

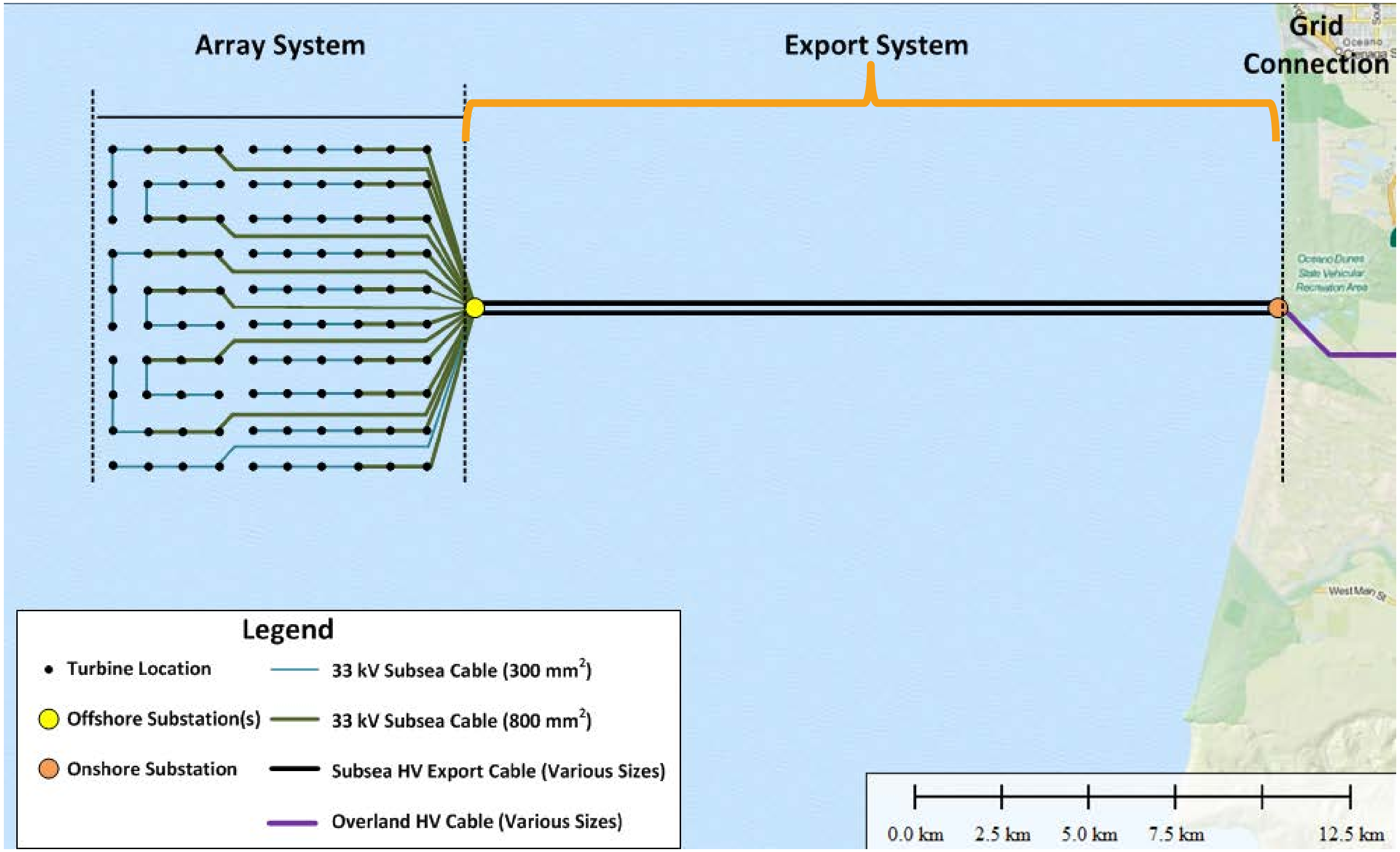
- Fabrication cost for fixed based on European market data and recent industry studies (e.g., cost reduction pathways, Great Lakes Wind Network subcontract, and so on)
- 100-unit order quantity

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

Electrical Parameter Study

Balance of System CAPEX

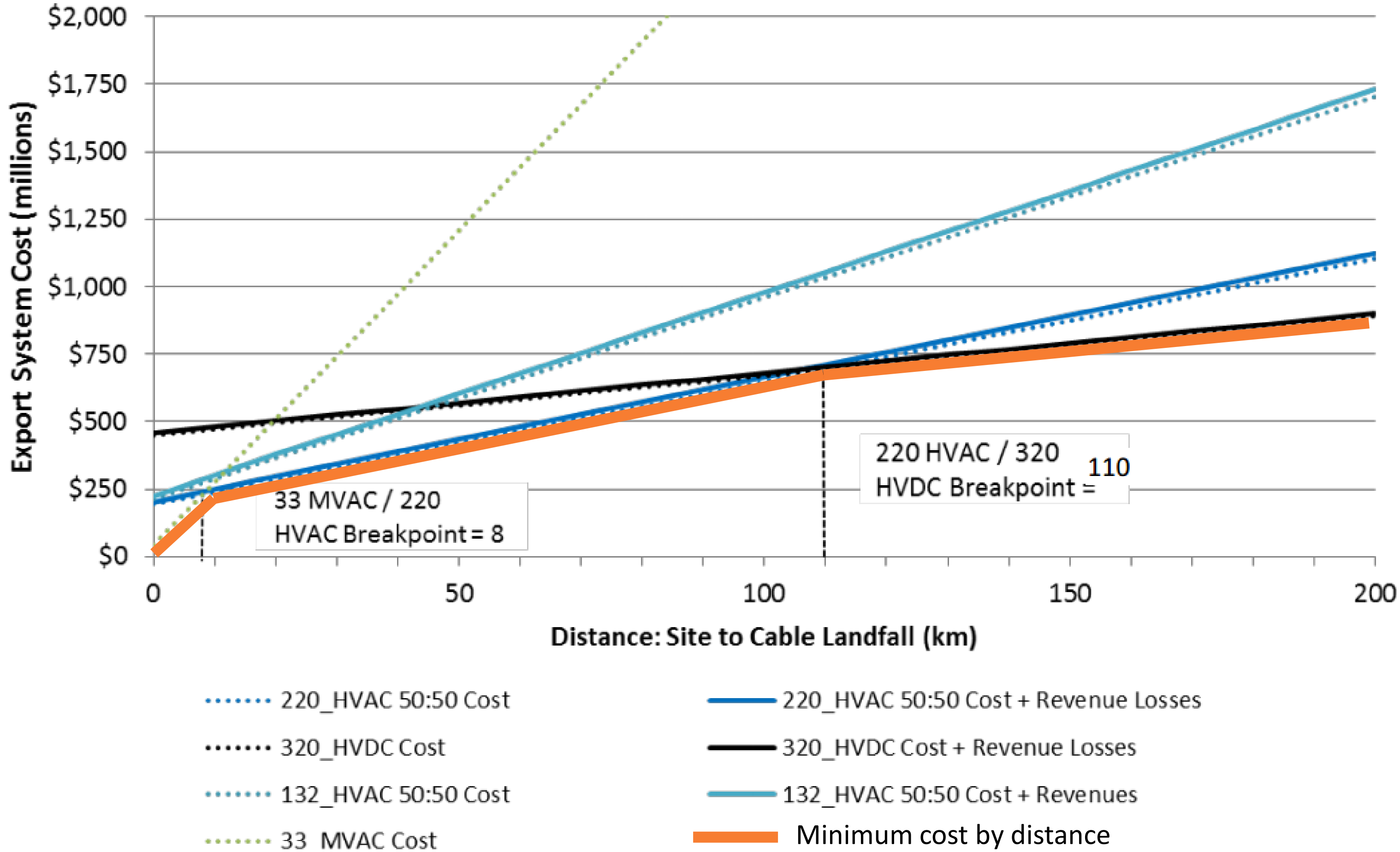
Case study: Fixed-bottom substructure export system



Map showing the boundaries among electrical infrastructure categories

Electrical Parameter Study

Balance of System CAPEX



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

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

Installation Parameter Study

Balance of System CAPEX

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

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

Installation Parameter Study

Balance of System CAPEX

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

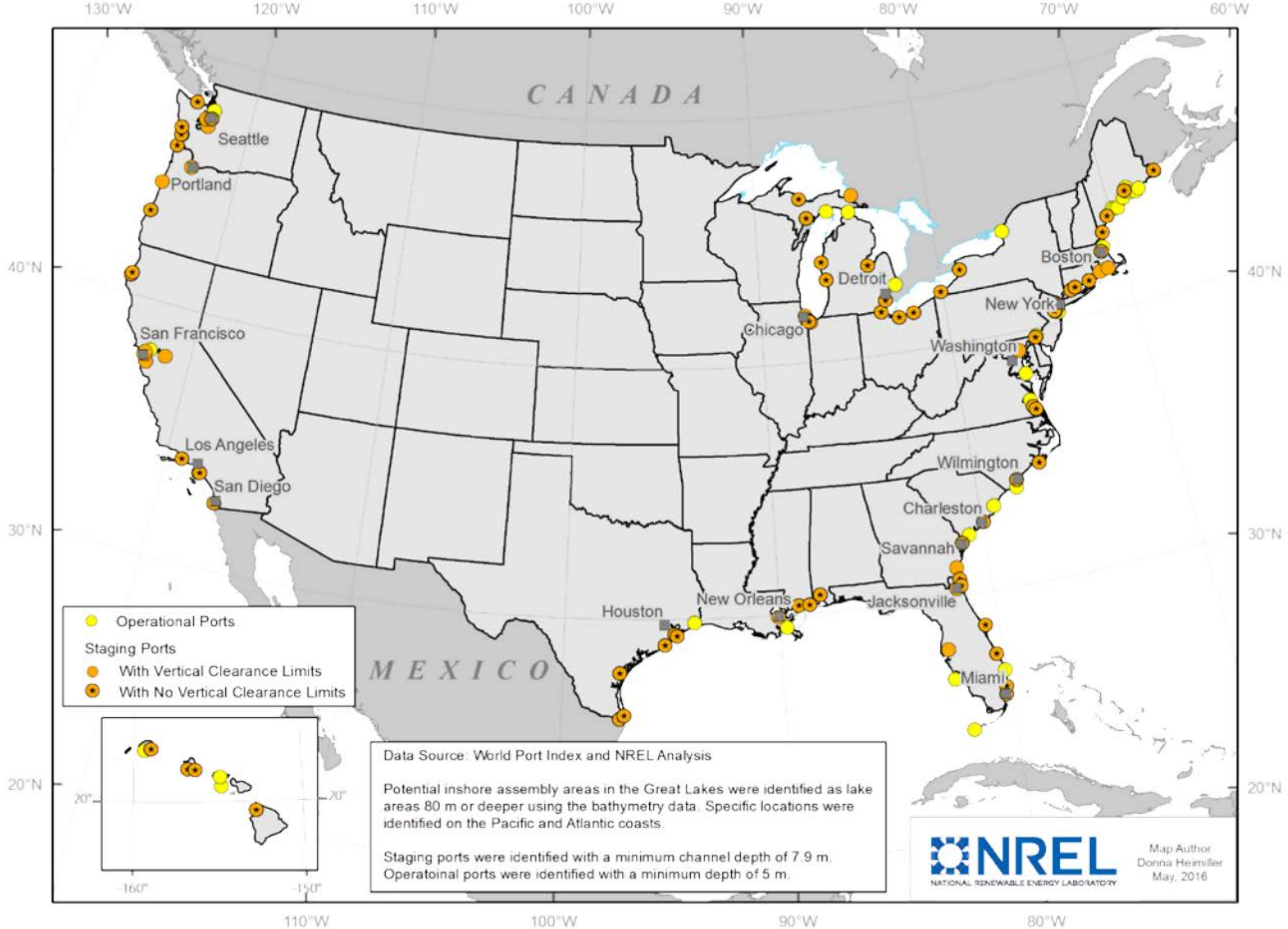
Key variables: Distance from project site to staging port, turbine size, and water depth

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

Key parameter ranges for installation

Installation Parameter Study

Balance of System CAPEX

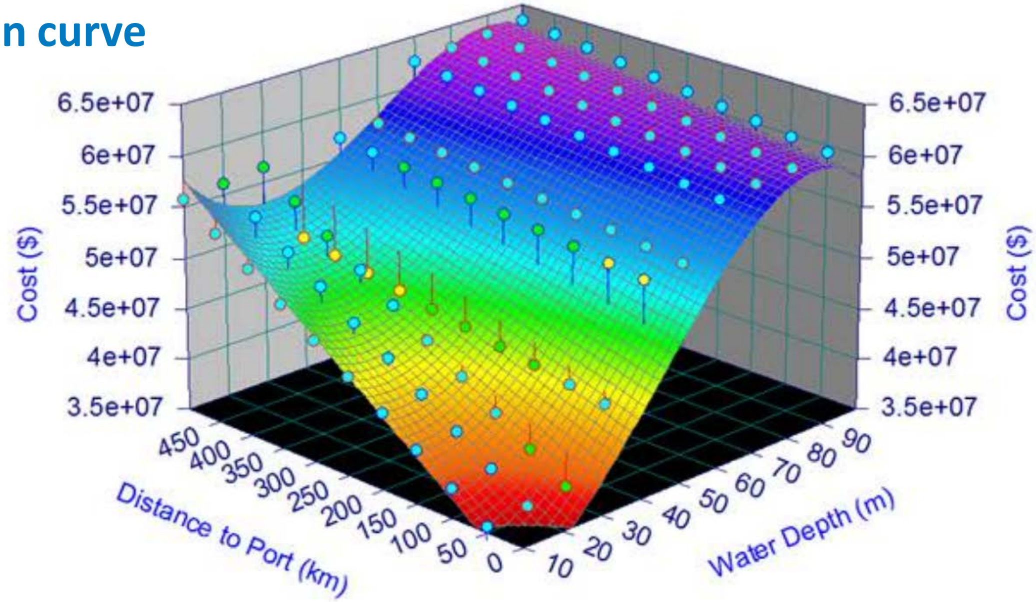


Construction and operations port and inshore assembly area locations

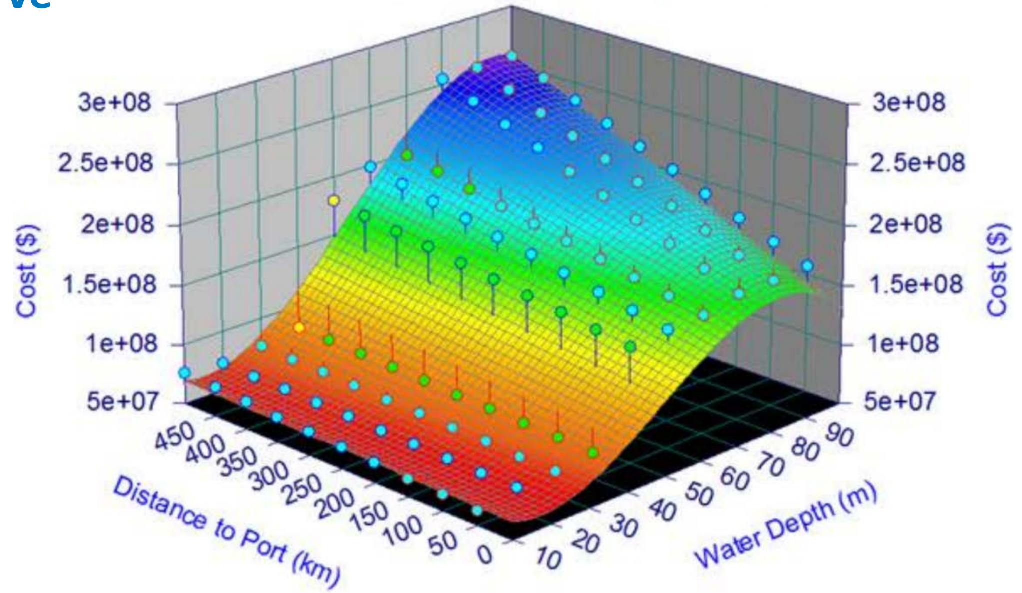
Installation Parameter Study

Balance of System CAPEX

3-MW turbine installation curve



Monopile installation curve



Operation and Maintenance (O&M) Parameter Study

Operations & Maintenance (OPEX)

LCOE

Turbine/Substructure Unit CAPEX | Balance of System CAPEX | Operations & Maintenance (OPEX) | Fixed Charge Rate (FCR) | Annual Energy Production (AEP)

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

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

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

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

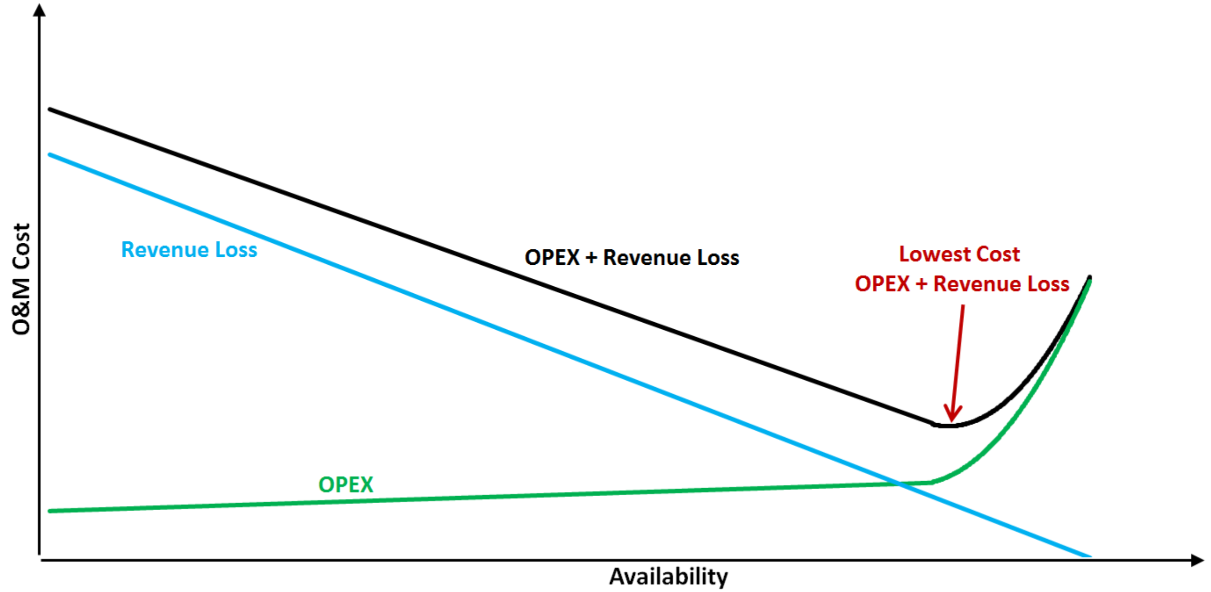
Key variables: Distance from project to operations port and meteorological ocean (metocean) conditions

O&M Parameter Study

Operations & Maintenance (OPEX)

Model Outputs:

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



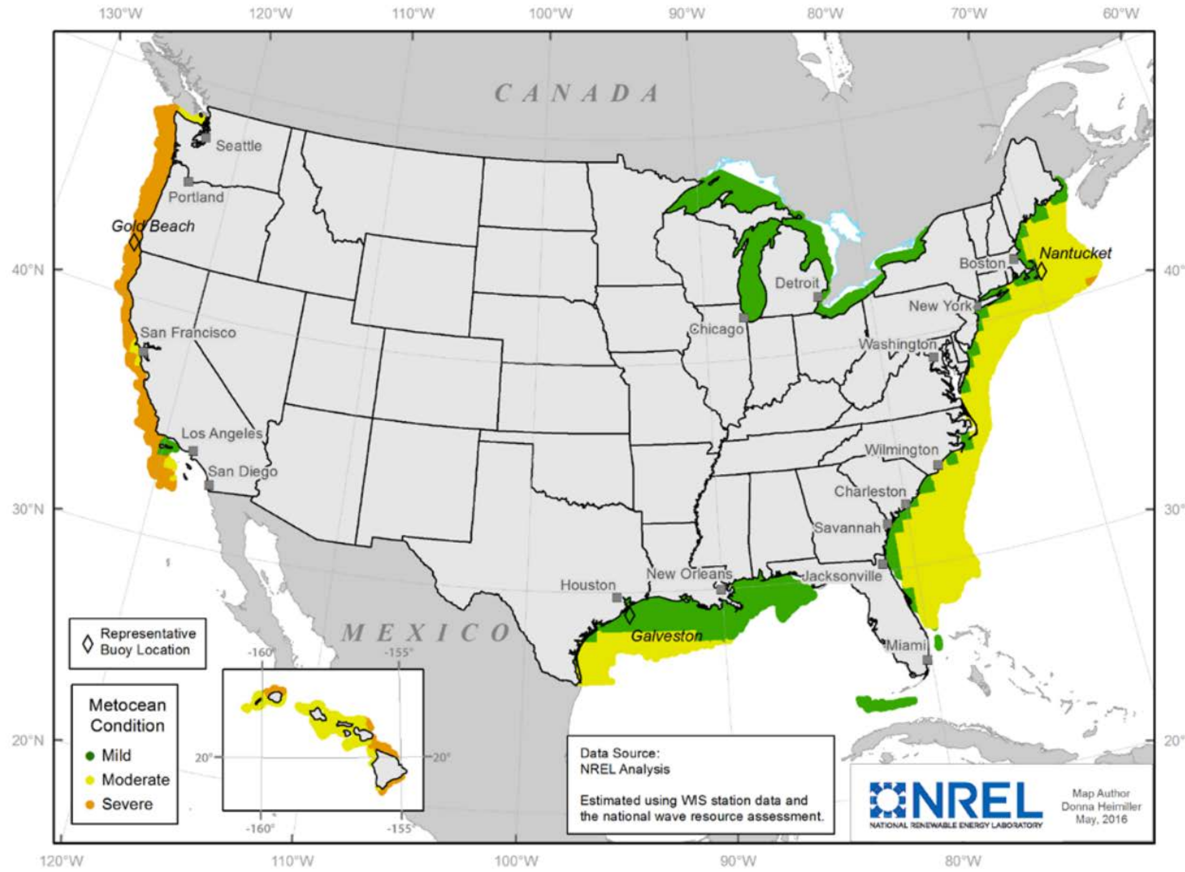
Depiction of O&M optimization criteria

O&M Parameter Study

Operations & Maintenance (OPEX)

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

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



Representative wave information system stations for O&M analysis

O&M Parameter Study

Operations & Maintenance (OPEX)

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

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

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

[a] Close to shore

[b] Medium distance

[c] Far shore

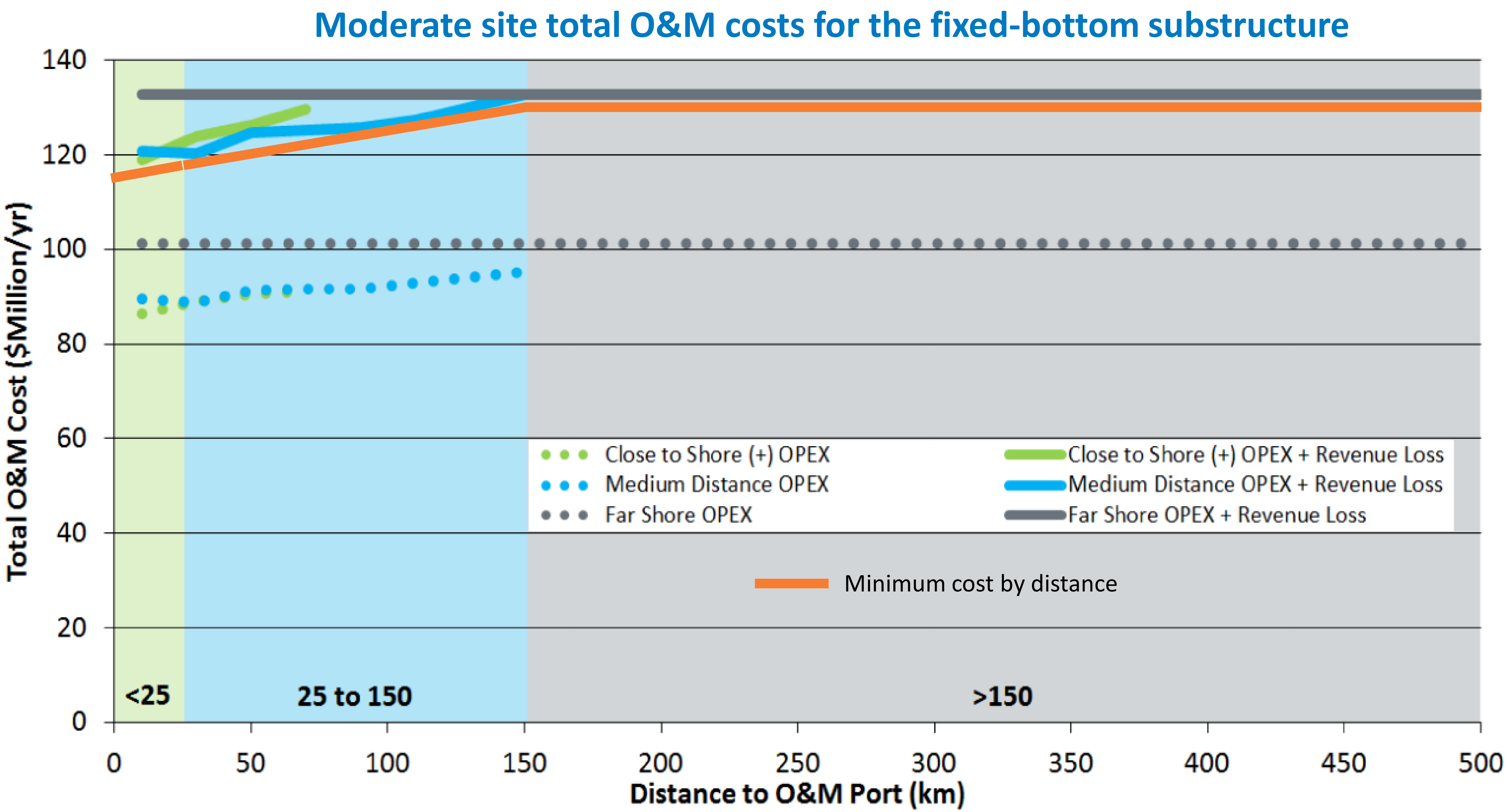
[d] Advanced close to shore

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

Matrix of operational expenditure modeling parameters

O&M Parameter Study

Operations & Maintenance (OPEX)

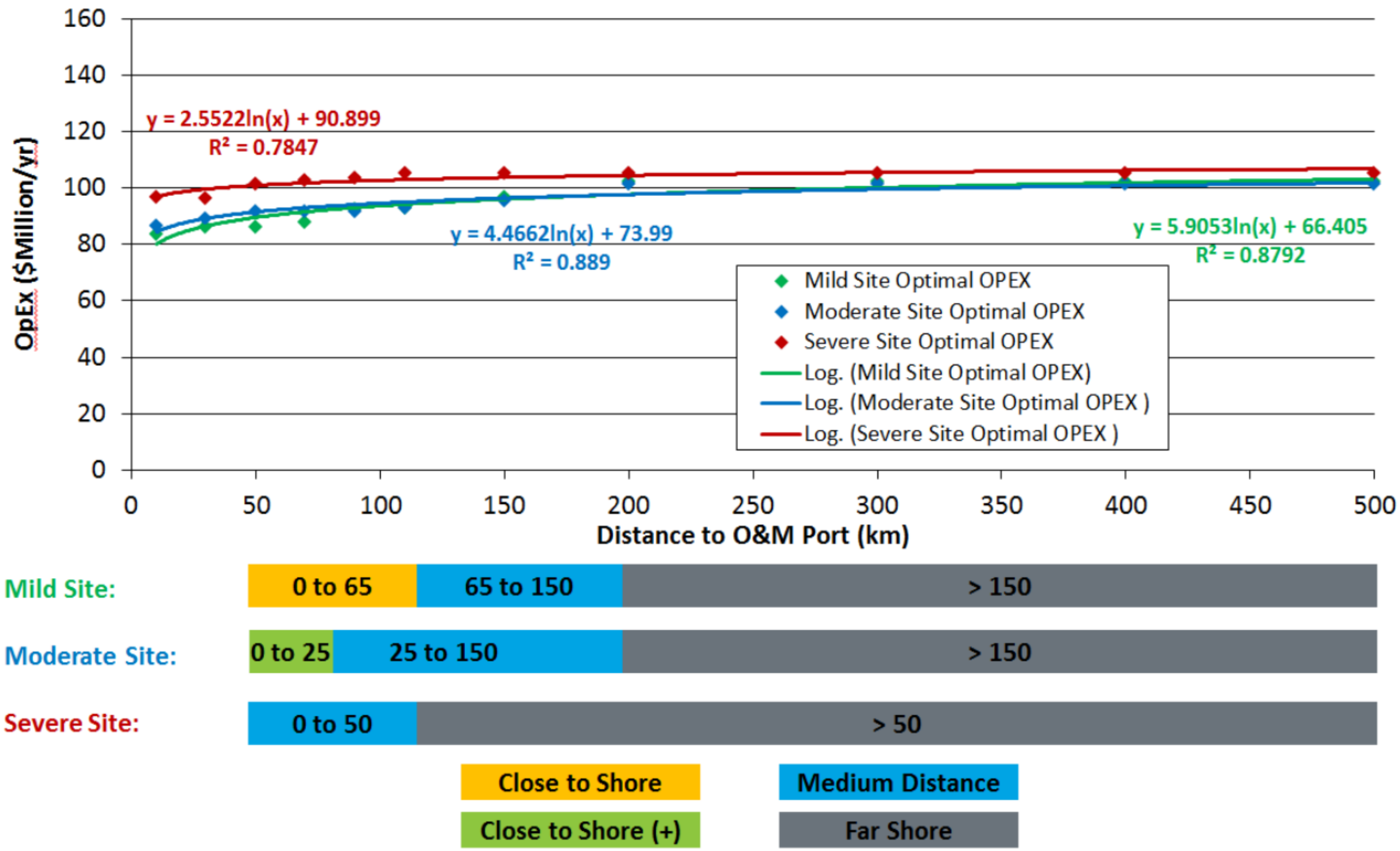


- Identifies economic breakpoints between O&M strategies for each of the three representative sites.

O&M Parameter Study

Operations & Maintenance (OPEX)

OpEx results for the fixed-bottom substructure



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

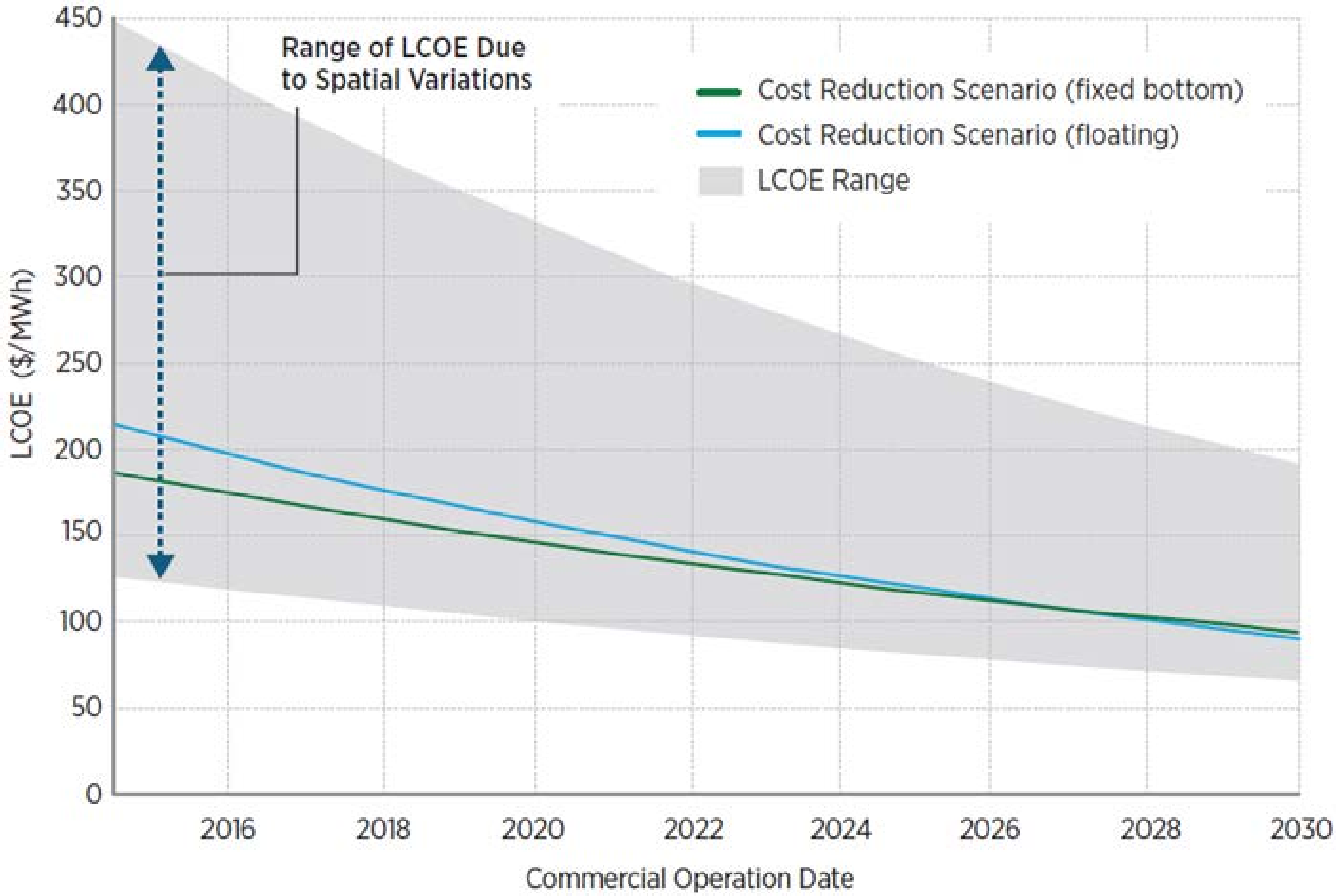
- Analysts determine how OpEx and availability might change with distance to port assuming adoption of the optimal O&M strategy at each distance
- Curves are then fitted to the OpEx and availability result data to describe the relationship between OpEx and availability.

General Limitations

General limitations of this initial assessment include the following:

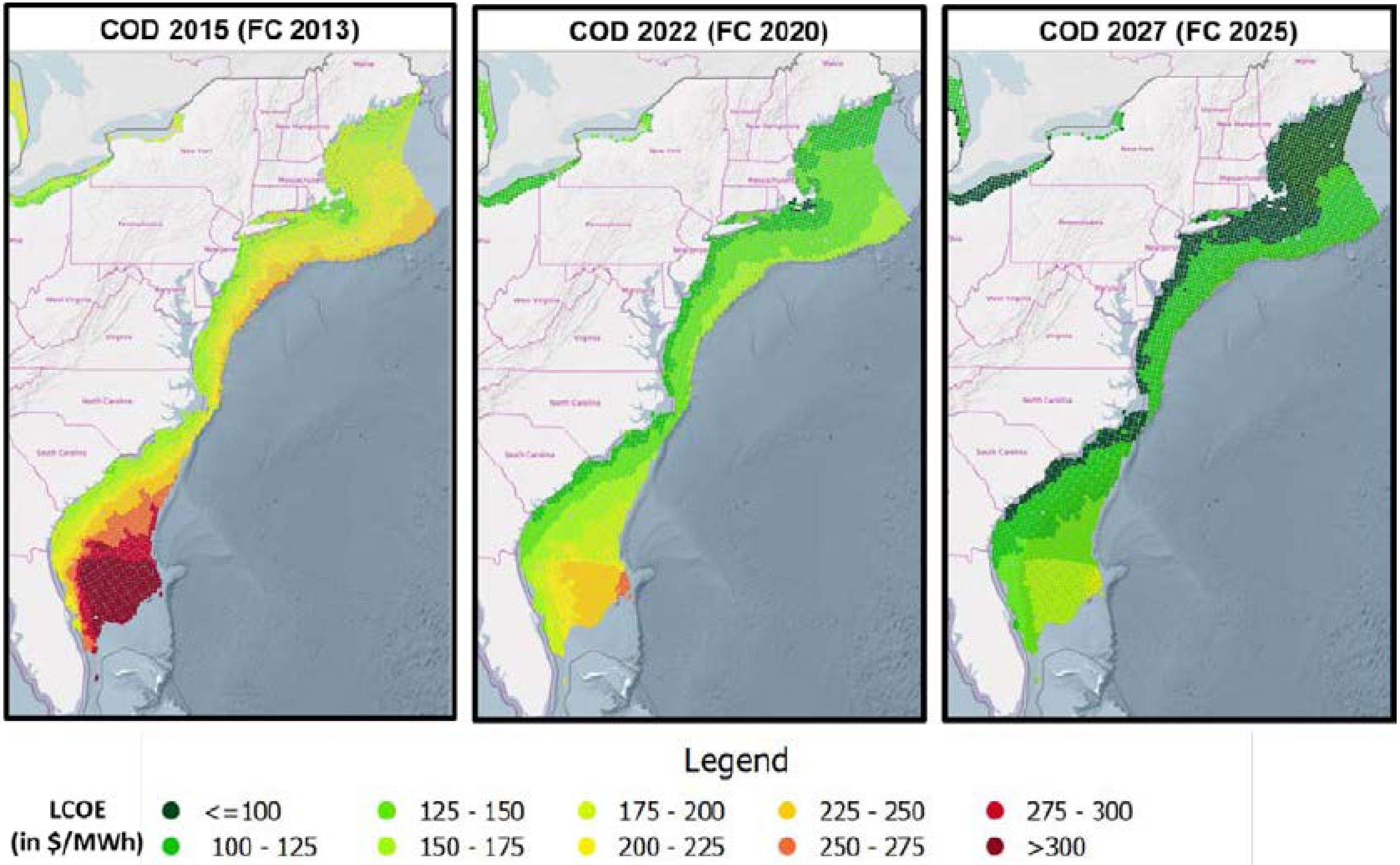
- An assumption of continued investments in technology innovation, developments, and market visibility of a robust domestic supply chain
- The need for domestic cost reductions to require additional activities to reduce risk and uncertainty of early projects, including addressing U.S.-specific challenges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

Results



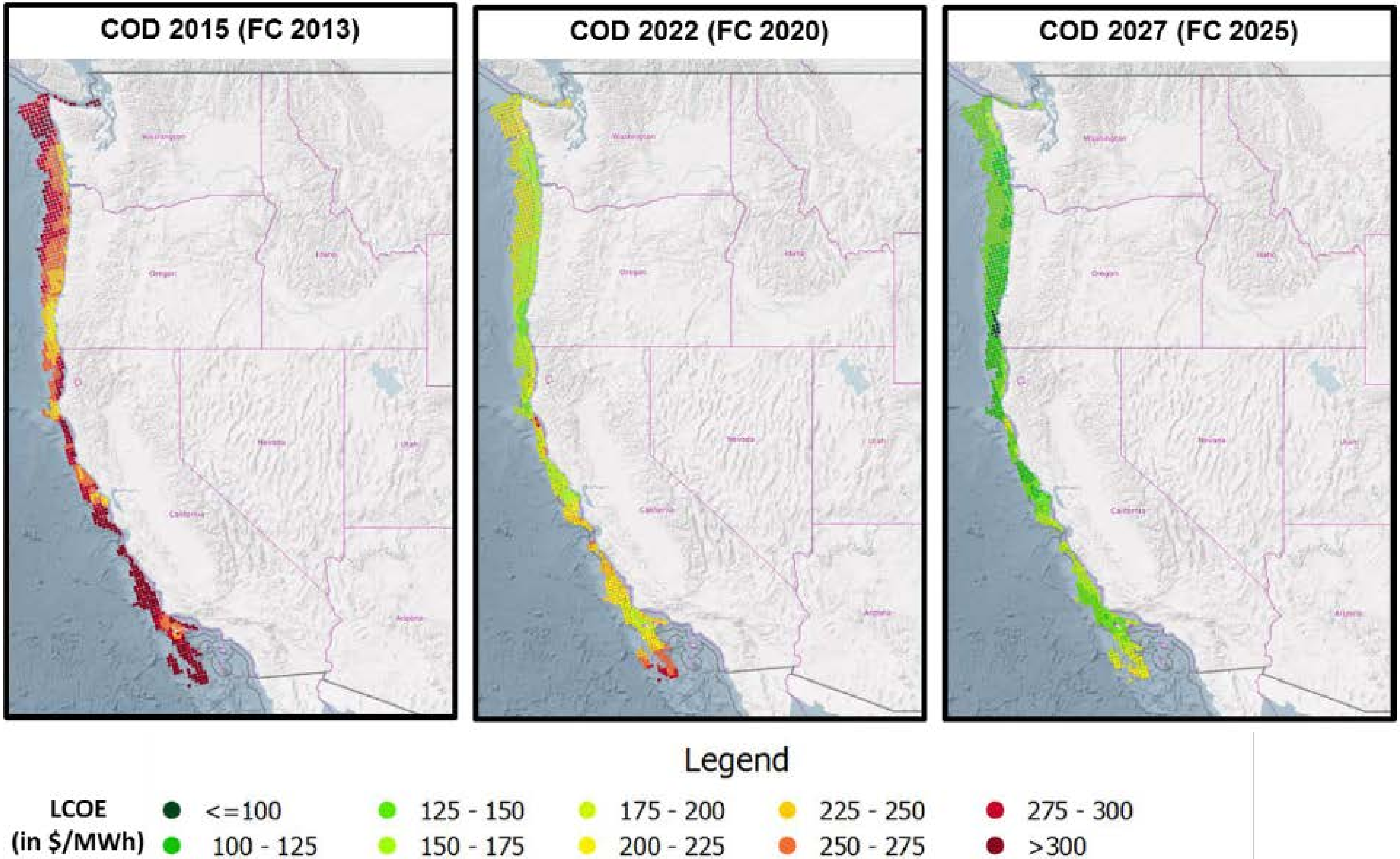
LCOE (unsubsidized) for potential offshore wind power projects from 2015-2030 (COD) throughout the technical resource area

Results: Atlantic Coast



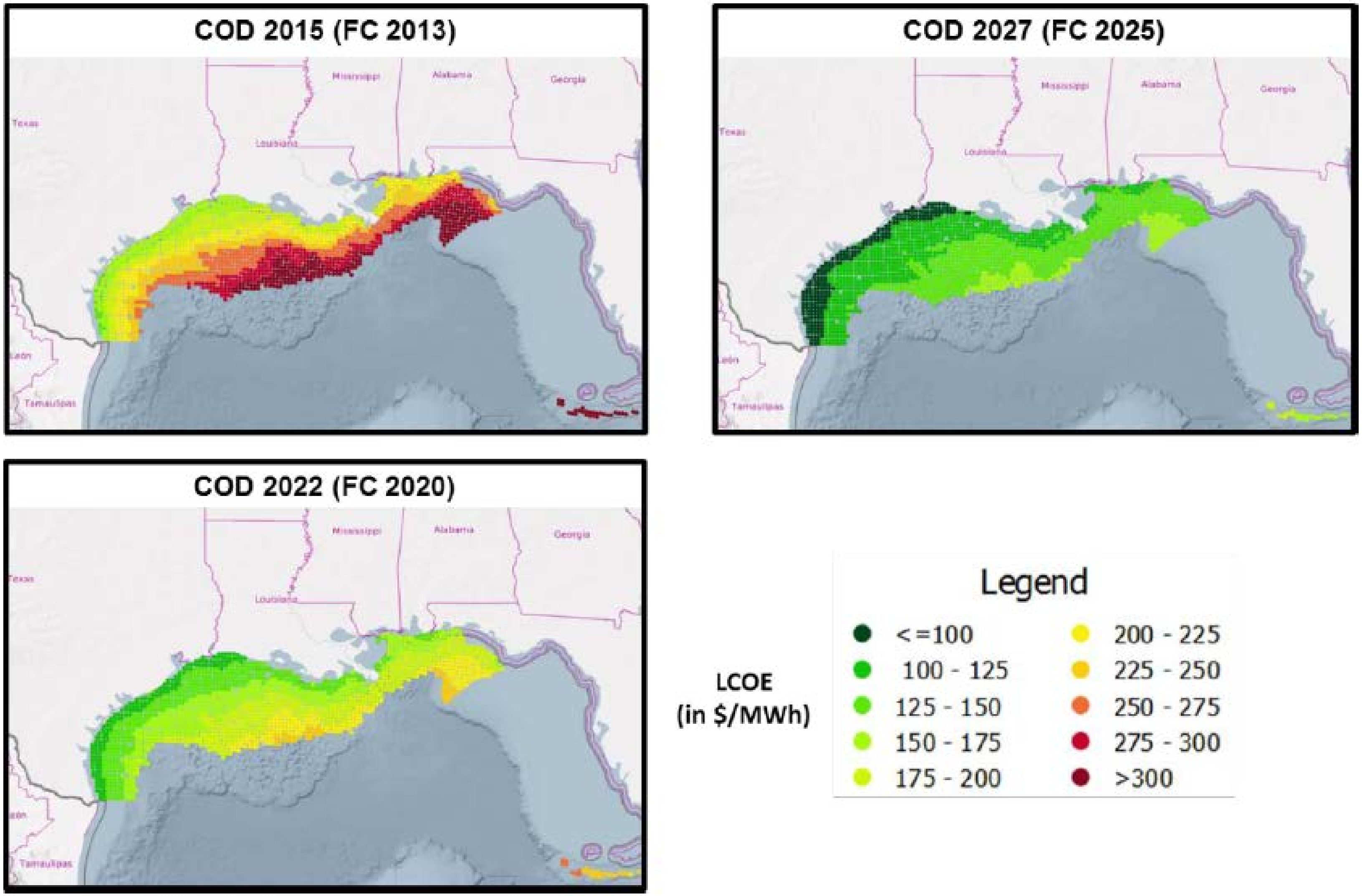
Estimated LCOE in the Atlantic Coast region

Results: Pacific Coast



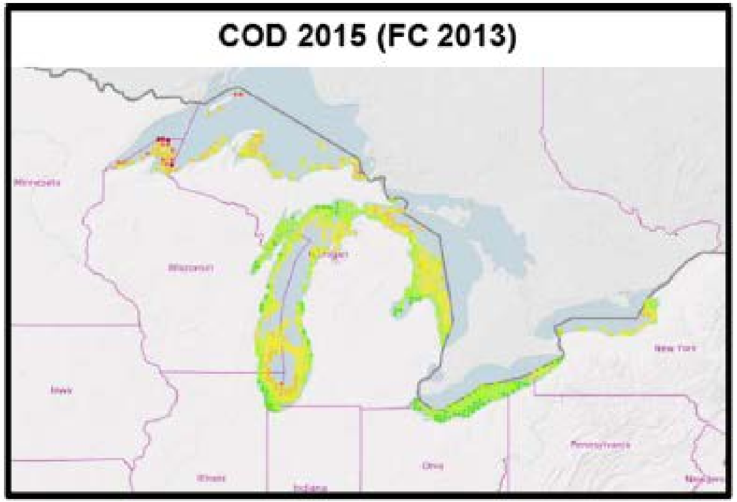
Estimated LCOE in the Pacific Coast region

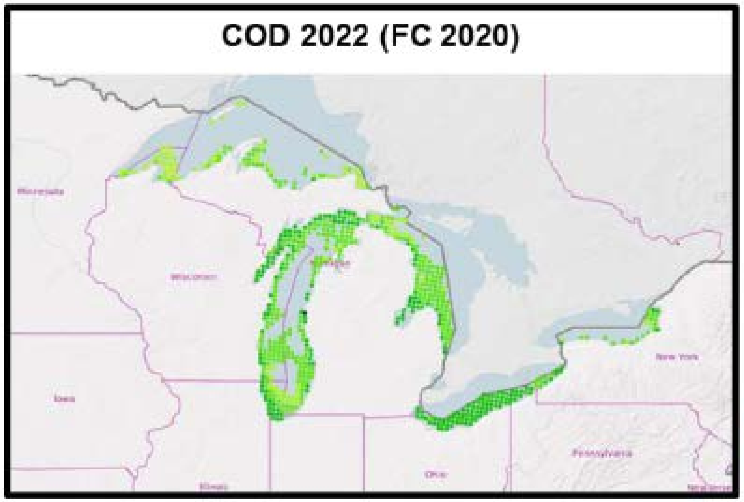
Results: Gulf Coast



Estimated LCOE in the Gulf Coast region

Results: Great Lakes





LCOE (in $/MWh)

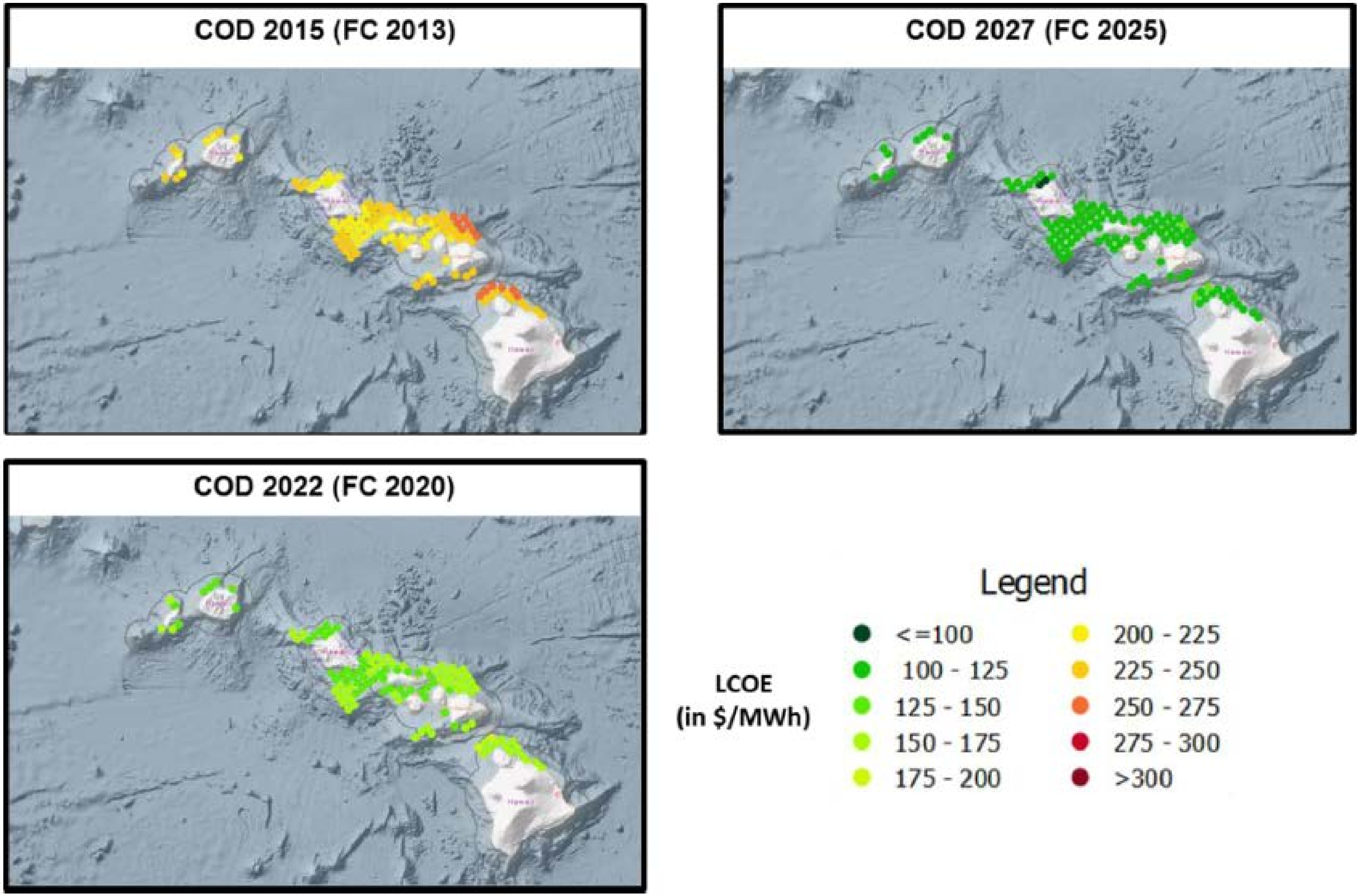
Legend

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

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

Estimated LCOE in the Great Lakes region

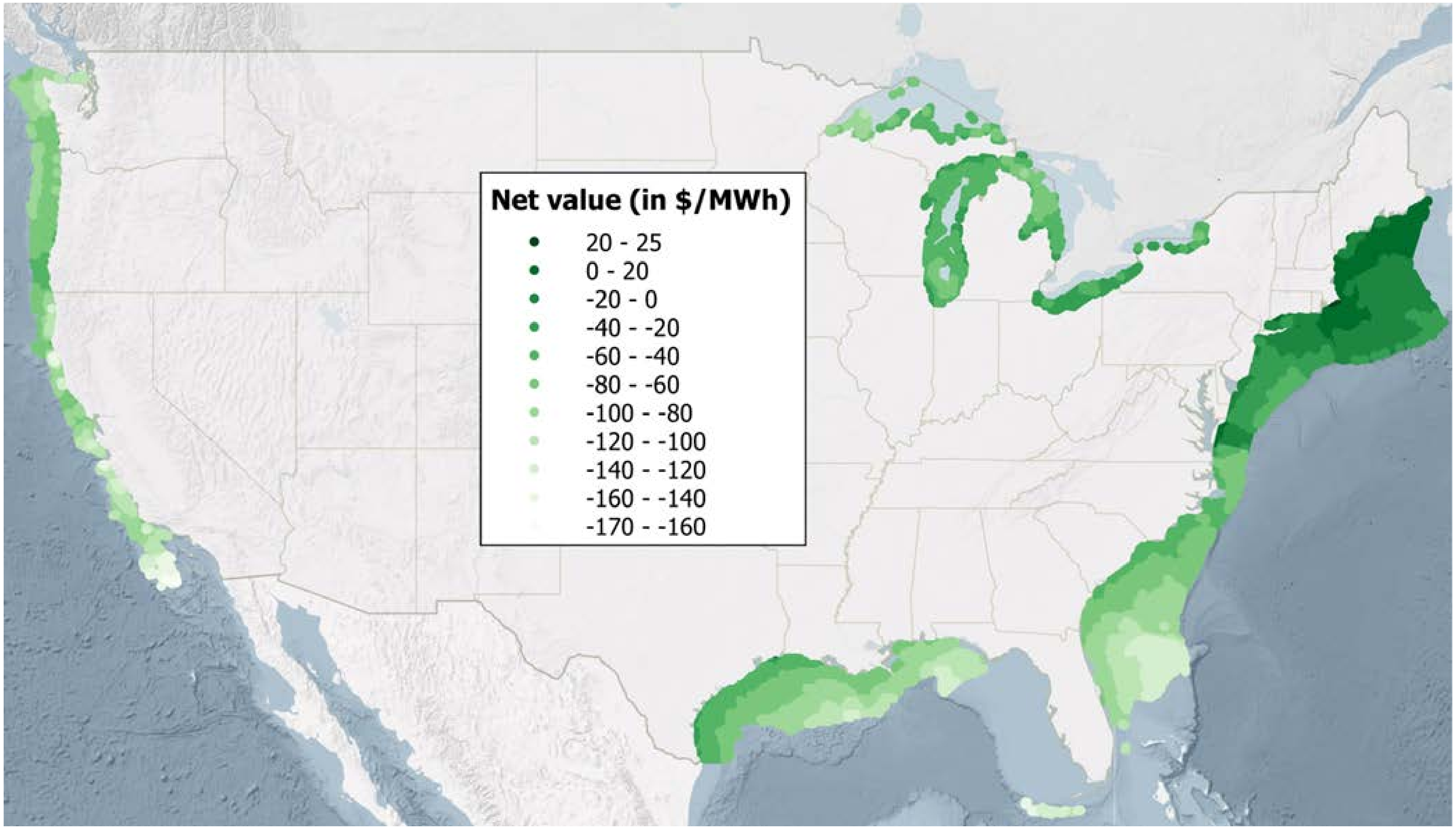
Results: Hawaii



Estimated LCOE in Hawaii

Results: Economic Viability

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



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

Conclusions

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

References

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