NREL
Transforming ENERGY

Floating Offshore Wind Costs in CA: Initial Results

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CPUC IRP Modeling Advisory Group Webinar
August 27, 2020

Preliminary results – Please do not cite

Overview

1 Background

2 Method

3 Draft Results

4 Q&A

1. Background

Background

- This study estimates the cost of floating offshore wind for technically viable sites on the outer continental shelf off California
- This cost study was funded by the Bureau of Ocean Energy Management (BOEM) and is scheduled for publication in late October 2020
- This study is <u>not</u> a stakeholder engagement or a marine spatial planning effort to create wind energy areas under BOEM's leasing process and the study areas have not been vetted by ocean user communities
- Feedback on IRP data and modeling needs were discussed informally during monthly CPUC/NREL/BOEM Working Group Meetings and a consultation meeting with CAISO
- The analysis domain considered is bound by the 1,300-m and the 40-m isobaths and to sites with an average wind speed of greater than 7 m/s
- Within this analysis domain, five study areas were chosen for cost modeling purposes. The Levelized Cost of Energy (LCOE) of these study areas is calculated between 2019-2032 for consideration of offshore wind in California's long-term energy planning (including the Integrated Resource Planning [IRP] process coordinated by the California Public Utilities Commission [CPUC])
- The results included in this presentation are preliminary – please do <u>not</u> cite

Background

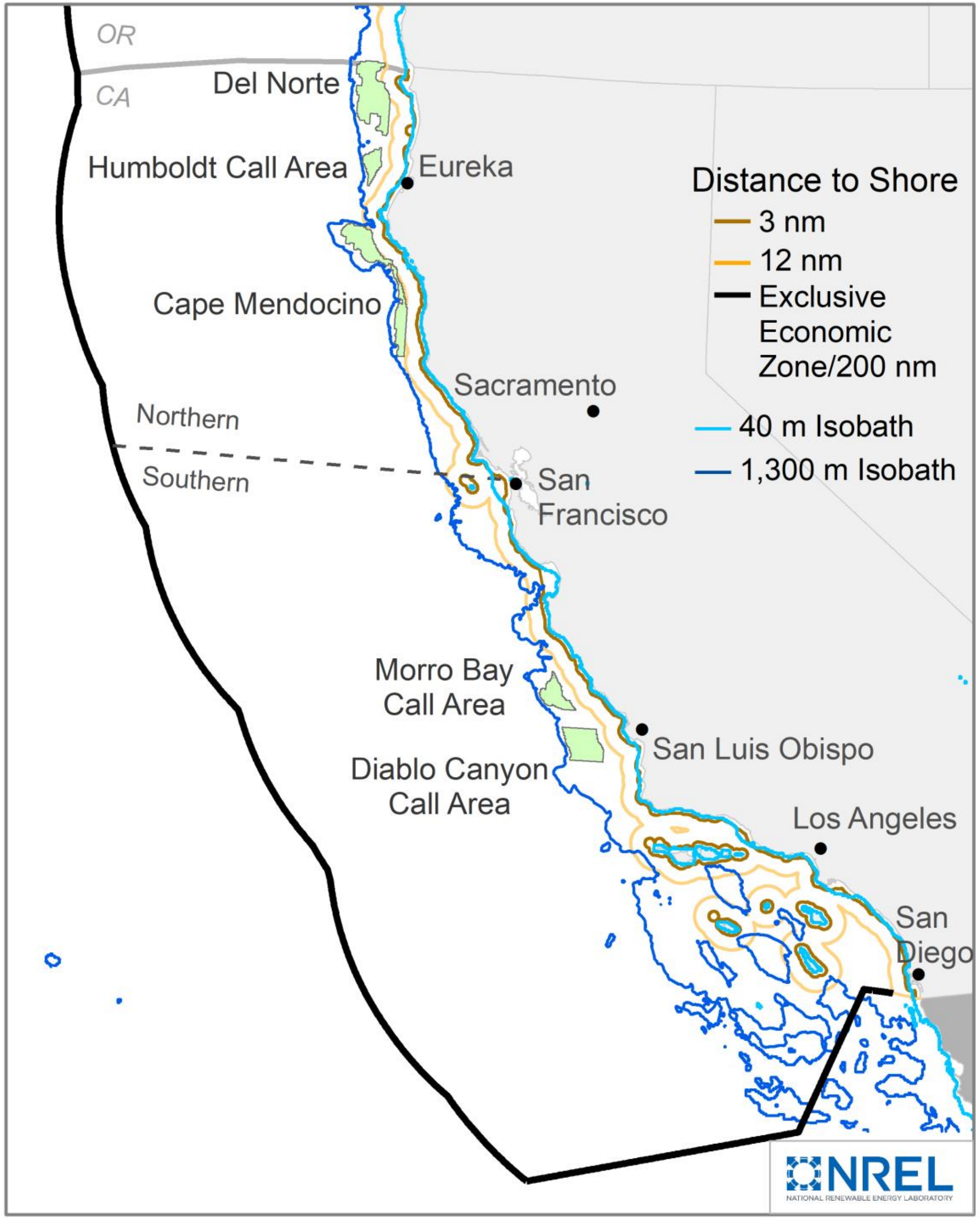
- This study builds on an earlier NREL cost assessment for California (Musial et al. 2016)
- Compared to earlier studies (e.g., Musial et al. 2016, NREL 2019/CPUC 2019), this study reflects updated technology and infrastructure assumptions, cost and resource data, and modeling capabilities. Key updates include (but are not limited to):
  - Wind speed data and representation of wake losses
  - Plant size of 1,000 MW
  - Turbine growth trajectory of up to 15 MW
  - Revised set of port and interconnection assumptions
  - Learning curve approach for projected capital expenditures (CapEx) through 2032

Sources:

Musial, W., P. Beiter, S. Tegen, and A. Smith. "Potential Offshore Wind Energy Areas in California: An Assessment of Locations, Technology, and Costs." National Renewable Energy Laboratory (NREL), 2016. https://www.boem.gov/sites/default/files/environmental-stewardship/Environmental-Studies/Pacific-Region/Studies/BOEM-2016-074.pdf.

National Renewable Energy Laboratory (NREL). "2018 Annual Technology Baseline." Golden, CO: National Energy Technology Laboratory (NREL), 2019. https://atb.nrel.gov/electricity/2018/index.html

CPUC. 2019. Inputs and Assumptions: 2019-2020 Integrated Resource Planning. https://www.cpuc.ca.gov/uploadedFiles/CPUCWebsite/Content/UtilitiesIndustries/Energy/EnergyPrograms/ElectPowerProcurementGeneration/irp/2018/Inputs%20%20Assumptions%202019-2020%20CPUC%20IRP_20191106.pdf

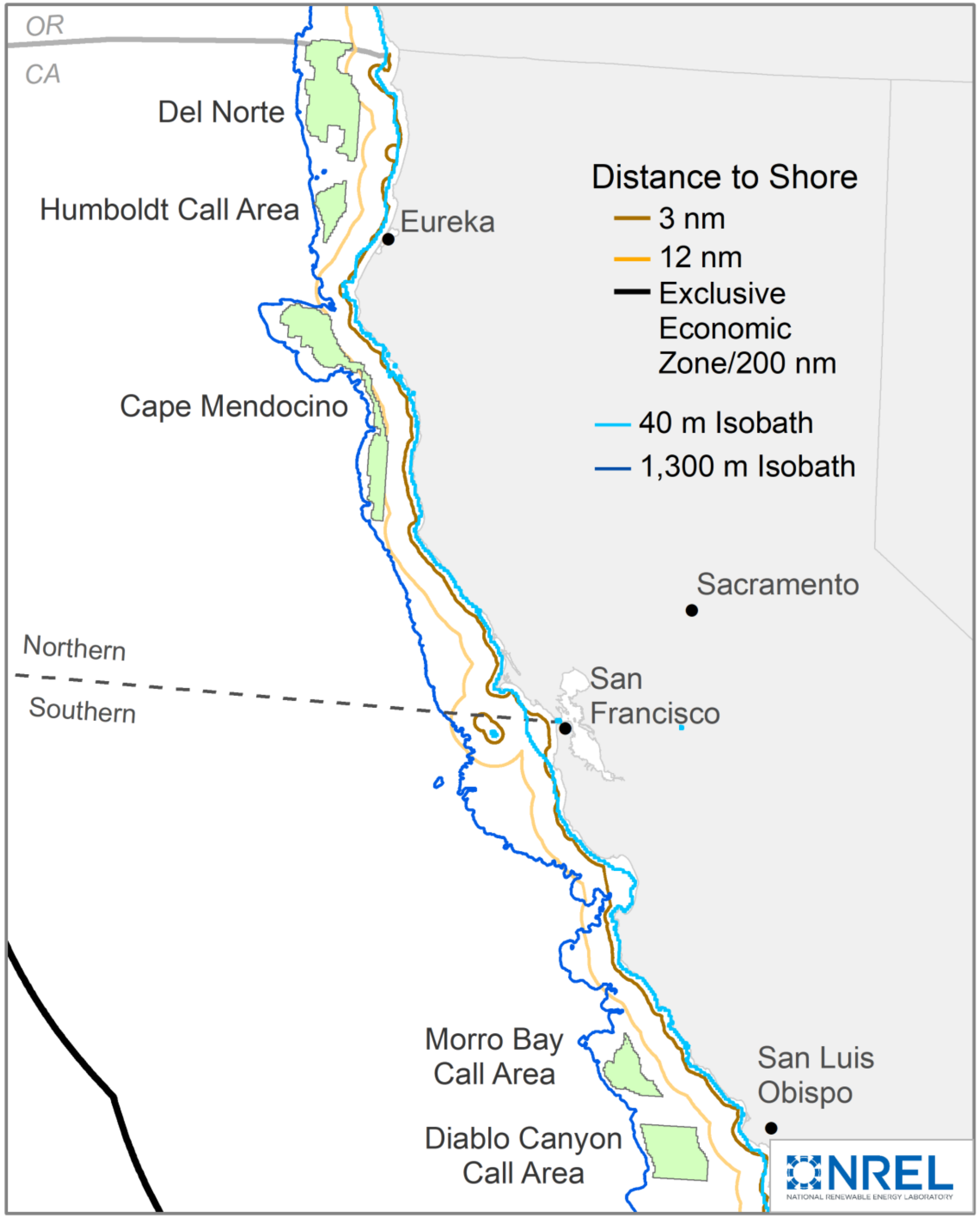


Analysis Domain of this Study

Analysis domain

- Offshore California
- Between a water depth of 40 m (light blue) and 1,300 m (dark blue)
- > 7 m/s average wind speeds

Note: The 3 nautical mile (nm) line designates the state and federal jurisdictional boundary



Study Areas

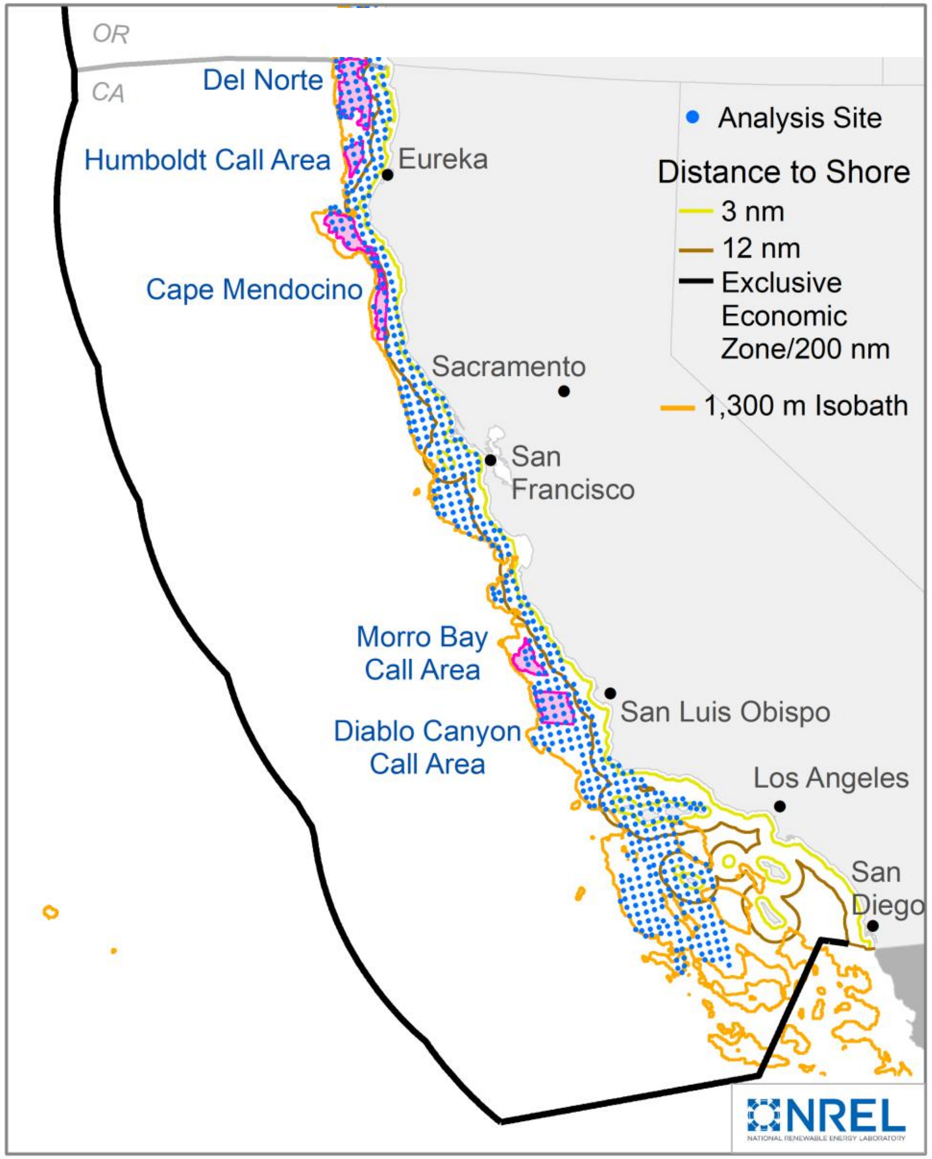
- Within the analysis domain, five study areas were chosen
- The LCOE calculated for these five study areas is intended to be “typical” for offshore wind energy development in CA
- Study areas were chosen from 2018 BOEM Call areas and prior studies (Collier et al. 2019 and Musial et al. 2016)

Five study areas (light green)

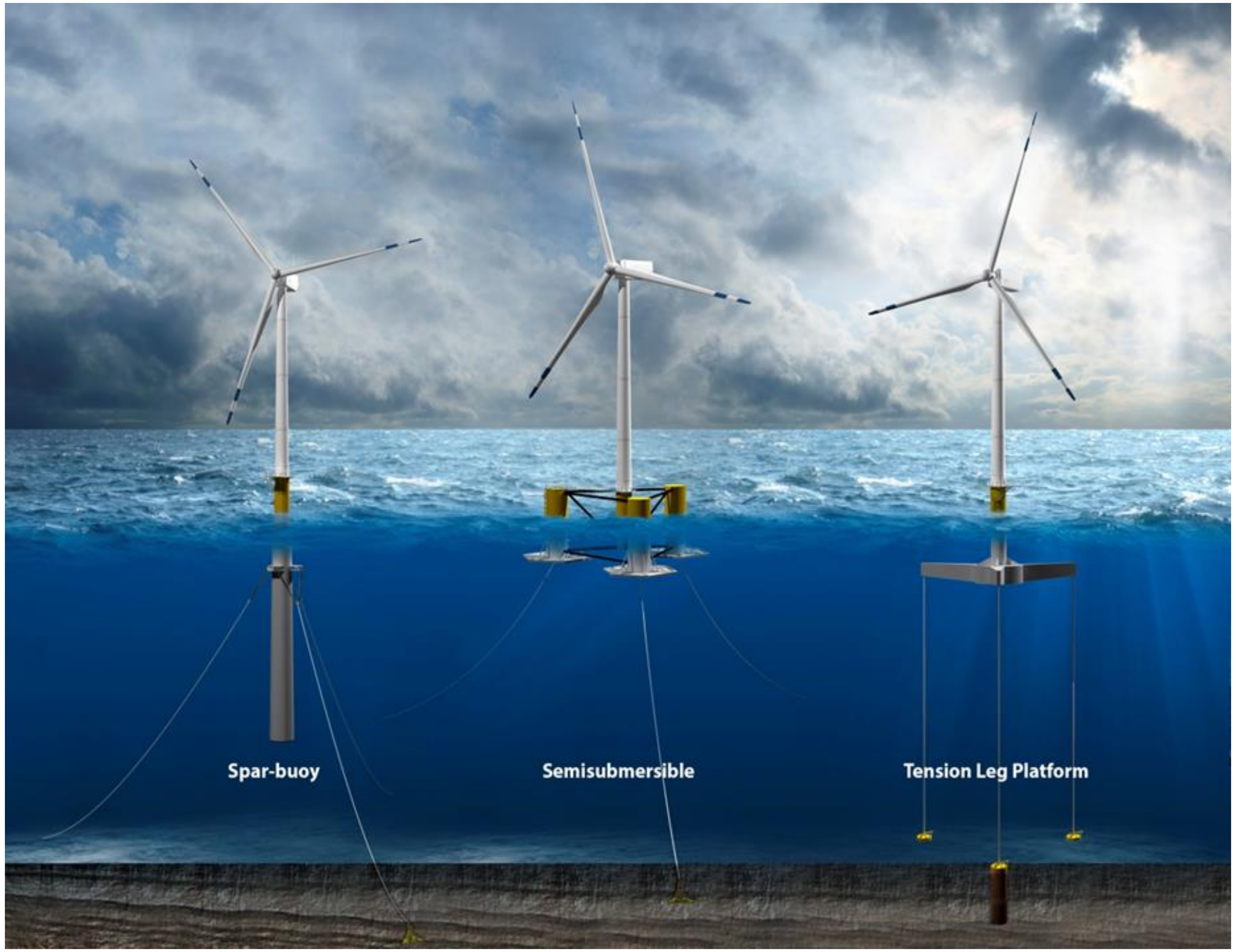
- Humboldt (Call Area)
- Morro Bay (Call Area)
- Diablo Canyon (Call Area)
- Del Norte
- Cape Mendocino

Analysis sites

- 575 individual sites (blue dots) are scattered across the analysis domain. Each site represents a 1,000 MW offshore wind plant
- Costs and wind plant performance are calculated at each site to obtain LCOE
- Results for the Study Areas represent the mean of all analysis sites contained within the Study Area boundaries



State of the Floating Wind Industry



Three Basic Archetypes of Floating Wind Platforms Derived from Oil and Gas Experience

- 82 MW of installed floating wind capacity globally
- Over 6,000 MW of floating wind in the pipeline
- Industry is transitioning from pilot scale projects (10 MW – 50 MW) to commercial scale projects > 500 MW
- Commercial scale projects are needed to be competitive
- Floating in California – What are key challenges?
  - Grid and transmission
  - Ports and Harbors
  - Deep water
  - Co-existence with military and other stakeholders
- Opportunities – Jobs/energy, independence/diversity
- 10 GW of Offshore Wind in California can supply over 15% of current electricity demand (EIA 2020)

2. Method

Levelized Cost of Energy (1/2)

$$LCOE = \frac{(FCR * CapEx) + OpEx}{AEP_{net}}$$

<u>where</u>:

LCOE =	levelized cost of energy (\$/MWh)
FCR =	fixed charge rate (%/year)
CapEx =	capital expenditures (\$/kW)
OpEx =	average annual operational expenditures (\$/kW/year)
AEP_{net} =	net average annual energy production (MWh/year)

LCOE is helpful to compare projects/technologies with <u>different cash flow profiles and over time</u>
LCOE does <u>not</u> capture the locational and time <u>value</u> of the generated energy and other services

Levelized Cost of Energy (2/2)

Definitions used in this study and for IRP/RESOLVE[1] modeling purposes

Item	Definition
CapEx	All capital expenditures up to the offshore substation, such as expenses for turbine, development, array cables, engineering and management, substructure and foundation, port and staging, assembly and installation, and plant decommissioning.
Interconnection costs	Expenditures of interconnecting a wind farm from the offshore substation to a land-based grid feature (e.g., onshore substation, transmission line), including the offshore export cable(s), offshore substation(s), and spur line(s) from cable landfall to an inland grid feature (e.g., onshore substation, transmission line). **Expenditures for onshore substation upgrades or any (high-voltage) onshore bulk transmission are <u>not</u> included**
O&M Costs	Average annual expenditures to operate and maintain the offshore wind system's equipment.
Gross capacity factor	Ratio of the system's predicted or actual gross electrical output to the nameplate output.
Net capacity factor	Ratio of the system's predicted or actual net (i.e., after accounting for losses) electrical output to the nameplate output.
WACC	Weighted average cost of capital; after-tax; does not include any impact from tax credit schemes.
Fixed charge rate (after tax)	Factor to annualize the initial capital expenditure over the financial lifetime of the project accounting for a return to debt and equity sponsors.
LCOE	Total project cost expressed in $ per megawatt-hour of electricity generated by the system over its life

[1] RESOLVE is the capacity expansion model used in the CPUC's IRP process, available at: https://www.cpuc.ca.gov/General.aspx?id=6442464143

Cost Modeling Approach (1/2)

LCOE is calculated as a function of:

Floating technology and plant characteristics

Turbine and substructure characteristics (e.g., turbine rating, power curve)
Plant size and turbine spacing

Location

Wind speed, water depth, wave height, distance to port and grid infrastructure
Technology limitations (e.g., water depth limits)

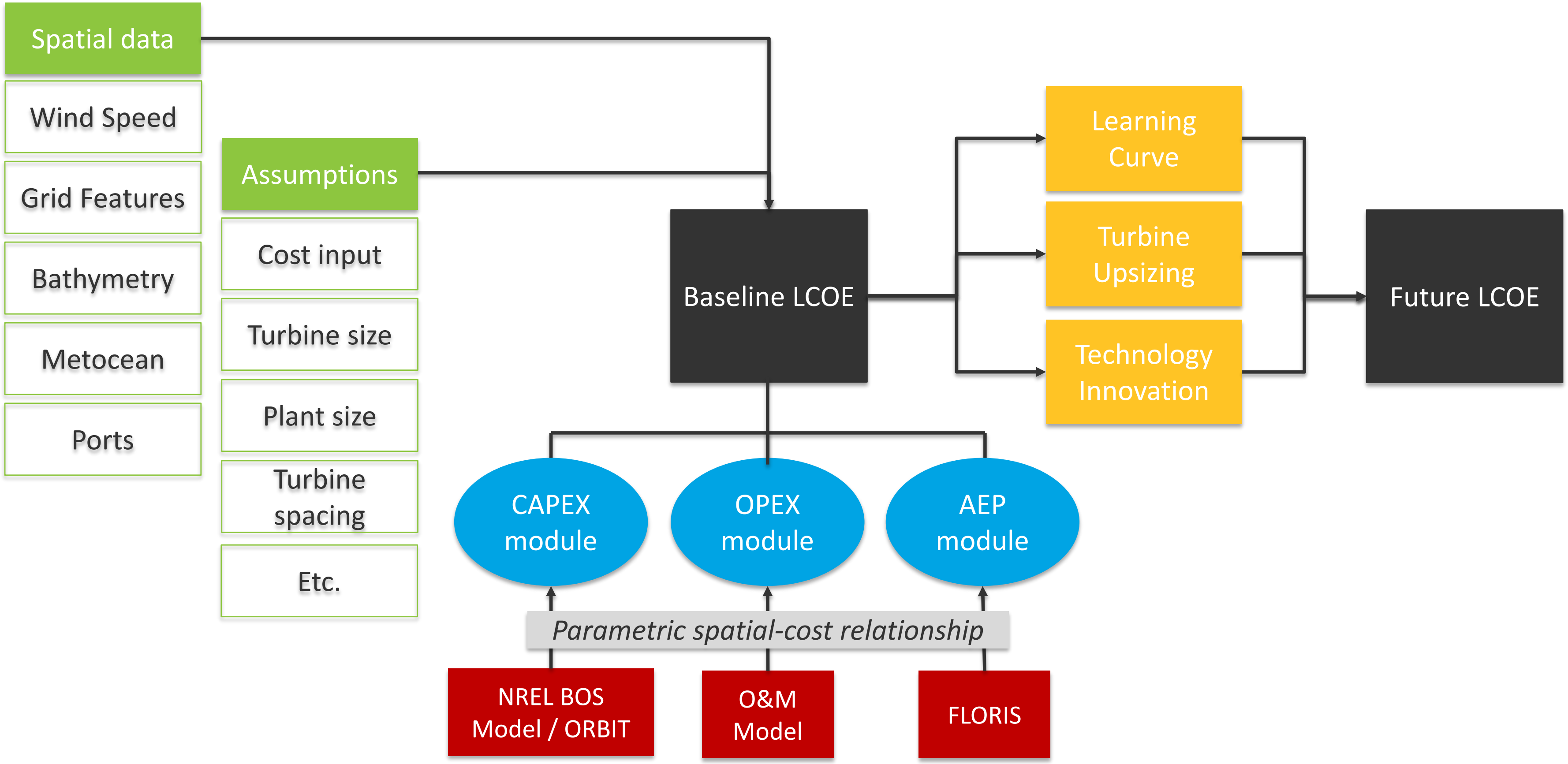
Time

Anticipated learning in supply chain, growth in turbine rating and technology innovation

Cost Modeling Approach (2/2)

LCOE is calculated using NREL's Offshore Regional Cost Analyzer (ORCA)

- Deterministic cost model that estimates the LCOE (and its constituent cost and performance components) of a commercial-scale offshore wind power plant
- Used in Prior Regional Costs Analyses (e.g., for the U.S. Department of Energy and BOEM)



Floating Offshore Wind Costs

Estimating Floating Offshore Wind Costs (1/2)

- Floating costs are calculated for a <u>commercial-scale</u> floating offshore wind plant (1,000 MW) using semi-submersible substructure technology
- Cost data were obtained from floating offshore wind developers and industry literature to calibrate the costs of the floating substructure, array, and export system costs (including an offshore substation). These are consistent with an earlier NREL study conducted for Oregon (Musial et al. 2019a)
- Because of the pre-commercial stage of the floating industry, input for expenditures other than substructure, array and export system costs were derived from fixed-bottom project data and literature, where applicable

Estimating Floating Offshore Wind Costs (2/2)

Key expenditure items	Primary Source	Fixed-bottom spill-over assumed
Turbine	Literature review	Yes
Balance-of-Station (BOS)		
Development and project management	Fraction of BOS & turbine expense	Yes
Substructure	Industry consultation	No
Turbine and substructure installation	Bottom-up modeling	No
Export cable	Bottom-up modeling and literature	No
Onshore grid connection	Literature	Yes
Soft Costs	Fraction of BOS & turbine expense	Yes
O&M		
Operations	Literature review	Yes
Maintenance	Bottom-up modeling and industry consultation	No
AEP		
Gross energy production	Bottom-up modeling	Yes
Wake losses and availability	Bottom-up modeling	Yes
Financing	Literature review	Yes

Spatial Variation in Costs

Estimating the Spatial Variation in Costs (1/3)

- The variation of costs as a function of key spatial parameters was determined by running a set of scenarios in higher-fidelity cost models
- For instance, maintenance costs were determined using the Energy Center of the Netherlands (ECN) O&M tool. This tool was calibrated to several scenarios with varying distances between an offshore wind site and its O&M base (holding all else constant) to obtain a spatially-dependent cost estimate
- Data on distance parameters, metocean conditions and wind speed was derived by combining different spatial data sets and bottom-up modeling

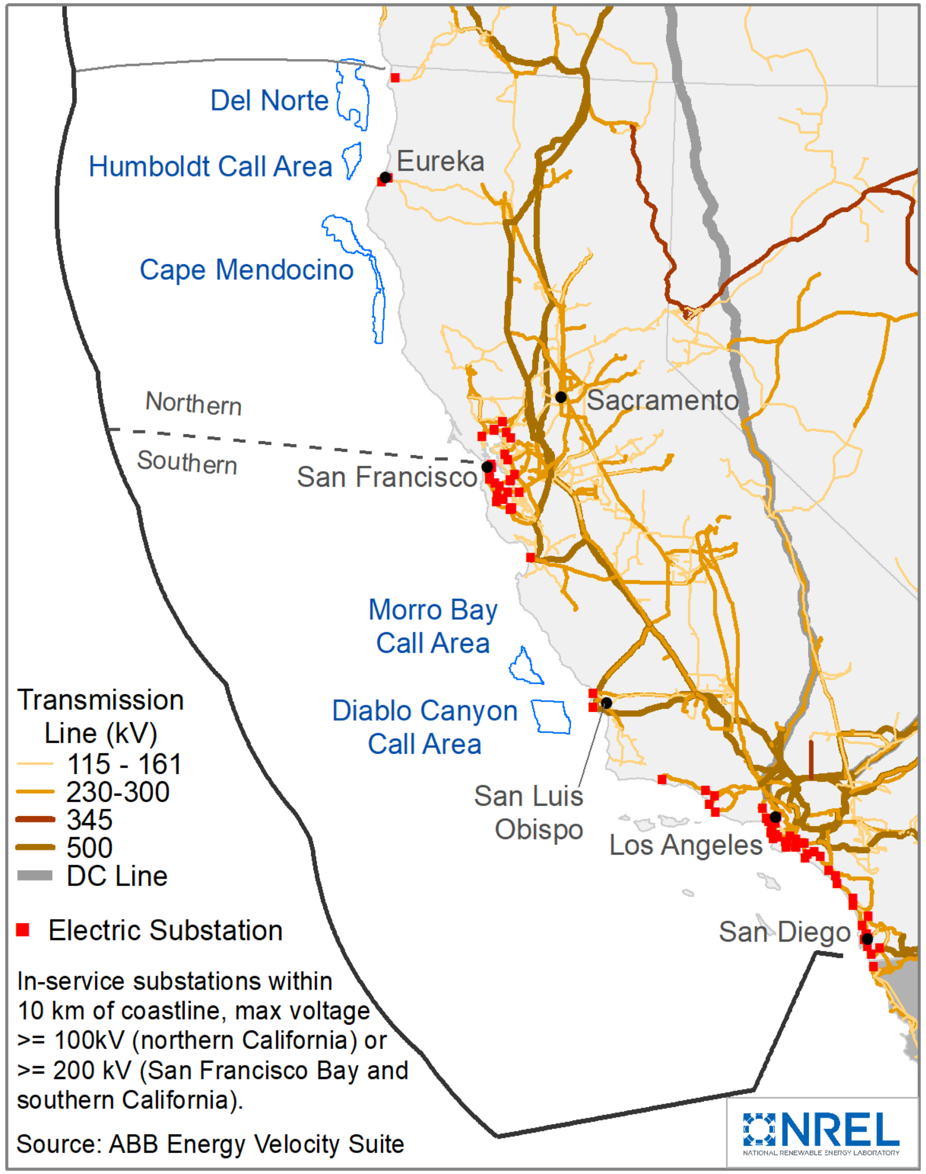
Key Spatial Parameters for Cost Modeling

	Water Depth	Distance to Shore	Distance to Port
Morro Bay	977 m	38 km	315 km
Diablo Canyon	672 m	50 km	249 km
Humboldt	806 m	40 km	55 km
Cape Mendocino	801 m	29 km	122 km
Del Norte	805 m	43 km	120 km
Analysis domain (avg)	559 m	54 km	205 km

Bottom-up engineering tools that inform the spatial cost relationships in ORCA

Cost component	Model	Source
BOS	NREL Balance of Station	Maness et al., 2017
Substructure and tower	JacketSE and TowerSE tool	Damiani, 2016
Export System Cable	PSCAD™	Manitoba Hydro International, 2020
O&M	ECN O&M	Pietermen et al., 2011
AEP	FLORIS	NREL, 2019b

Spatial Variation in Costs (2/3)



Subsea Cables

- Array cable costs increase with water depth
- Export cable costs depend on distance to shore

Grid Connection

- Candidate substations within 10 km of coast
  - ≥100 kV north of San Francisco
  - ≥200 kV in SF and south
- Transmission infrastructure is limited in region of 3 northern study areas
- Point of interconnection selection:
- Modeling generic distance of 5 km from cable landing to interconnection

Spatial Variation in Costs (3/3)

Candidate OSW Ports in California
Humboldt Bay
Port Hueneme
Los Angeles
Long Beach
San Diego

All candidate ports in California will require upgrades to enable Offshore Wind

Construction and O&M Ports

- Candidate construction ports must support turbine and substructure assembly at quayside
- Candidate O&M ports must support major component repairs
  - Heavy lift vessel for repairs at sea
  - Turbine tow-to-port
- Port selection criteria
  - Sufficient navigation channel depth and width for wind turbine installation vessels
  - Berth facilities for wind turbine installation vessels
  - Unrestricted air draft

Projecting Floating Offshore Wind Costs

Projecting Floating Offshore Wind Costs

- LCOE is assessed for three modeling years: 2019 (baseline), 2022, 2027 and 2032 (Commercial Operation Date [COD])
- Future costs are estimated from the combined effects of learning in the supply chain (e.g., economies of scale in production, standardization), technology innovation and turbine upsizing
  - Learning effects are estimated through a learning curve assessment using empirical data from fixed-bottom offshore wind projects; these are imposed on the baseline (2019) CapEx estimates
  - Turbine size is assumed to increase from 8 MW (2019) to 15 MW (2032)
  - Technology innovation is considered implicitly in the estimated learning effects and derived from literature (Hundleby et al. 2017) for O&M costs and energy production losses
- Plant size and turbine spacing is held constant at 1,000 MW and 7 rotor diameters between 2019-2032

Technology Assumptions over Time

	Unit	2019	2022	2027	2032
Turbine Rated Power	MW	8	10	12	15
Turbine Rotor Diameter	m	175	196	215	240
Turbine Hub Height	m	118	128	138	150
Turbine Specific Power	W/m^2	332	332	332	332
Waterline Clearance	m	30	30	30	30
Substructure Type	Name	Semisubmersible			
Minimum Water Depth	m	40			
Maximum Water Depth	m	1,300			
Wind Plant Rating	MW	1,000			
Turbine Spacing	Rotor diameters	7D x 7D			

Financing Assumptions over Time

- Finance terms were calibrated to align with those of today's commercial-scale fixed-bottom projects. A Weighted Average Cost of Capital (WACC) (nominal) of 5.4% and FCR (nominal) of 7.2% were derived from literature and validated through industry consultation
- Financing terms are assumed constant for model years 2019-2032 (COD)

Finance	FCR (nominal) (after tax)	%	7.2%
	FCR (real) (after tax)	%	5.3%
	WACC (nominal) (after tax)	%	5.4%
	WACC (real) (after tax)	%	2.9%
	Capital Recovery Period	yr	30
	Share of debt	%	75%
	Debt rate (nominal)	%	4.4%
	Equity Return (nominal)	%	12.0%
	Tax rate	%	26%
	Inflation	%	2.5%
	CRF (nominal) (after tax)	%	6.8%
	CRF (real) (after tax)	%	5.0%
	Project Finance Factor	%	105%
	Depreciation Basis	%	100%
	Depreciation Schedule		5-year MACRS
	Present Value of Depreciation	%	86%

Annual Energy Production

Annual Energy Production Methodology (1/3)

- AEP is calculated at 575 sites comprising the analysis space of this study

3-step approach

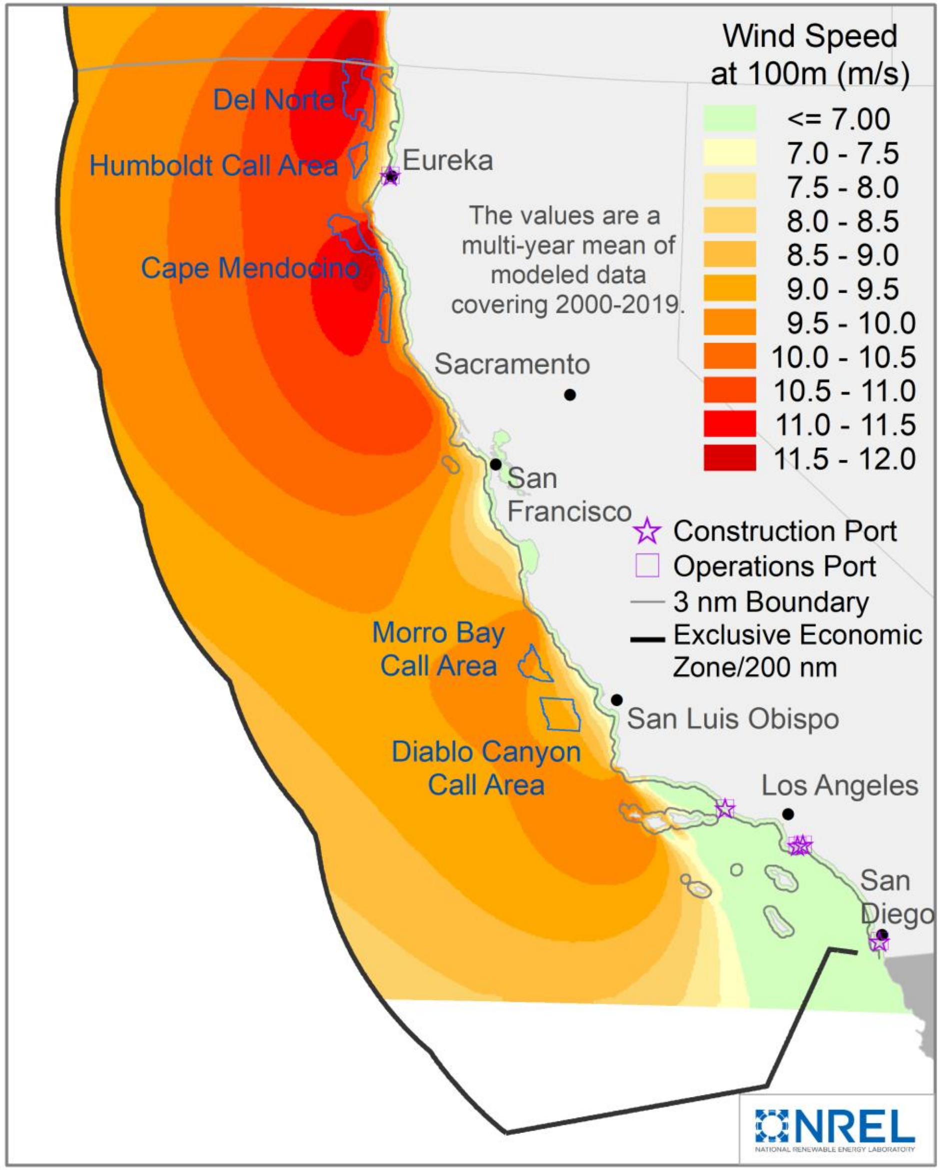
1. Define reference wind farm:
   - Site specific wind resource
   - Turbine model for each reference year (2019, 2022, 2027, 2032)
   - Wind farm layout
2. Use NREL wake loss model FLORIS[1] to compute gross capacity factor (GCF) and wake losses
3. Apply losses in ORCA (wake, environmental, electrical, availability) and obtain net capacity factors (NCF)

1) NREL. "FLORIS. Version 1.1.7" 2019. https://github.com/wisdem/floris

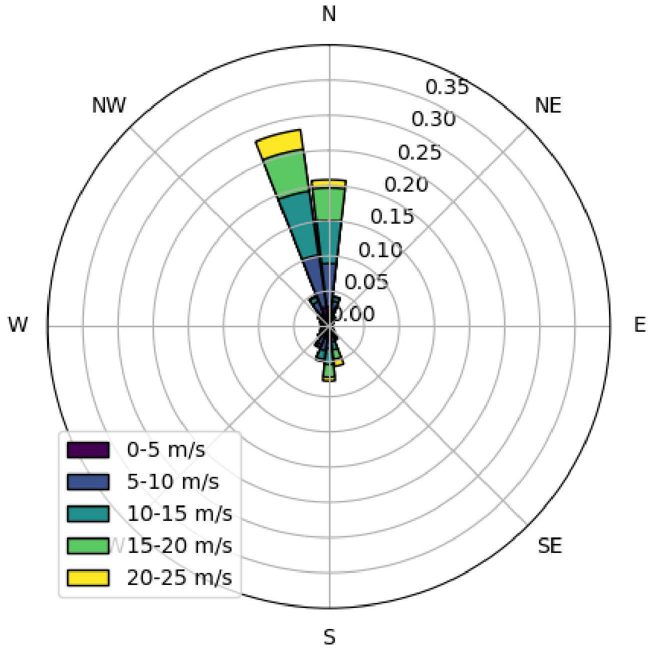
Annual Energy Production Methodology (2/3)

1) Optis et al. 2020
2) Draxl et al. 2015

- Wind resource: New Offshore Dataset (CA20) produced for BOEM IAG Task 1[1] includes new data and modeling capabilities compared with WIND Toolkit[2]
  - CA20 100-m mean wind speeds increased in many locations compared with WIND Toolkit (up to 20%). Morro Bay 9.7%. Diablo Canyon 17.4%. Humboldt 19.7%.
  - Optis et al. attributes this to different planetary boundary layer scheme and updated mesoscale model version



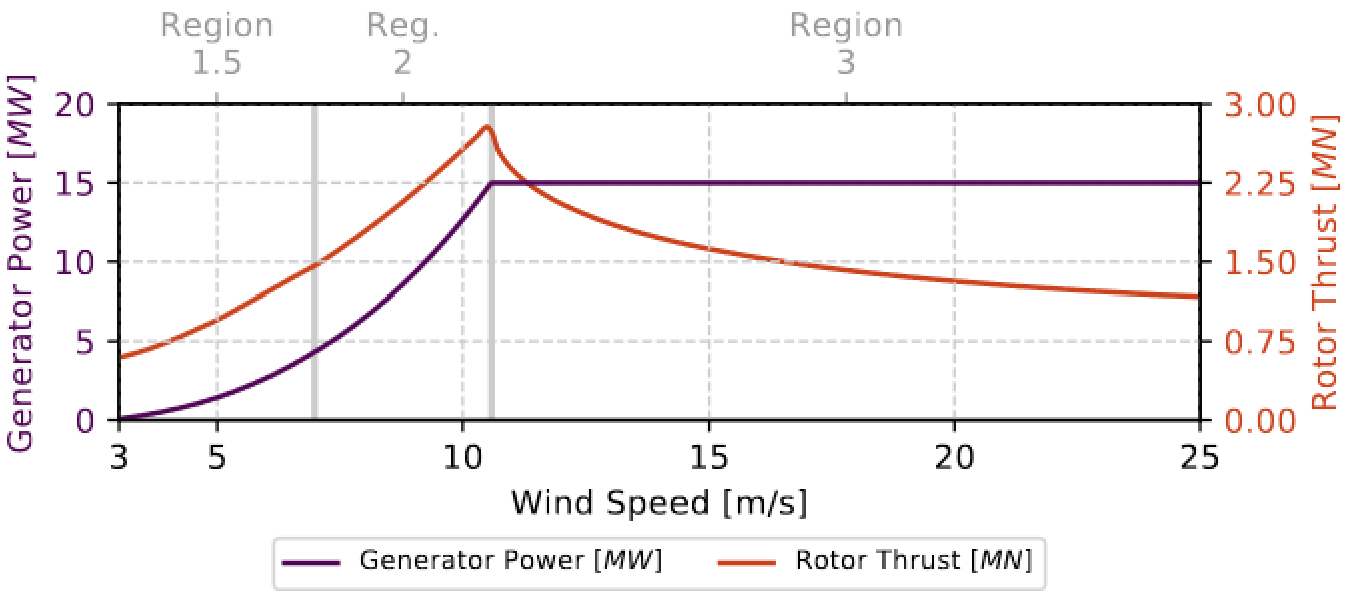
100m mean wind speed map based on data from [1]



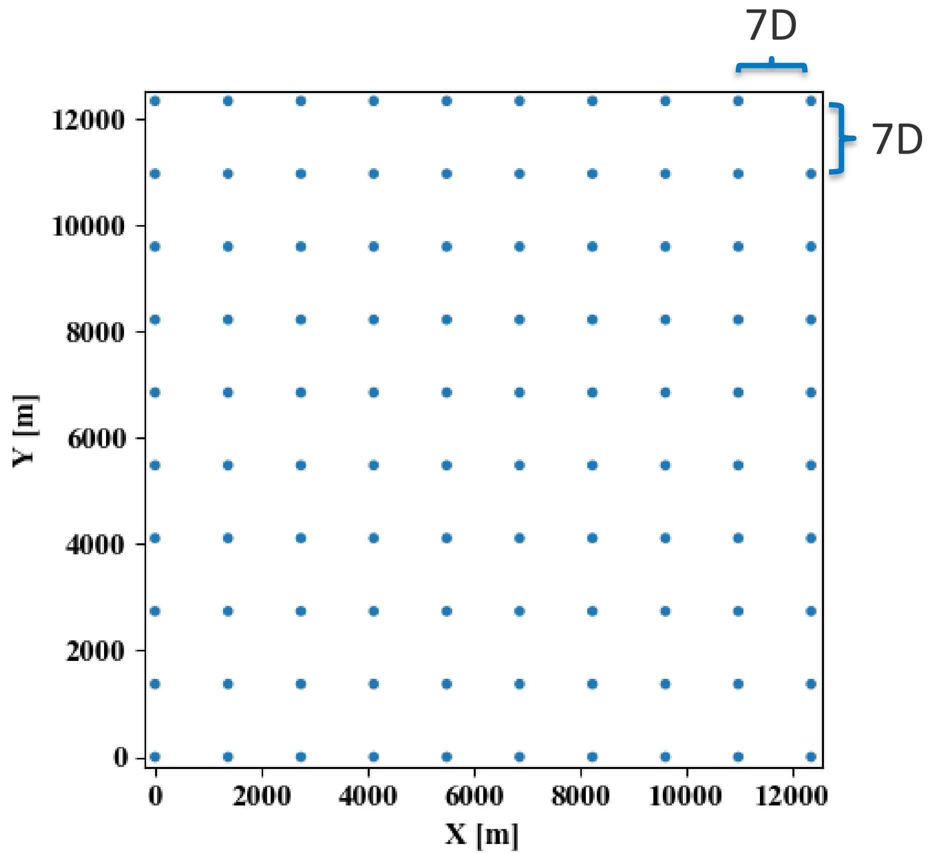
Humboldt Call Area centroid 150m wind rose

Annual Energy Production Methodology (2/3)

- Turbine: NREL 15-MW Reference[1]
- Plant: Nominally 1,000 MW square grid (7 rotor diameter spacing)



Turbine power and thrust curves from 15MW Reference[1]

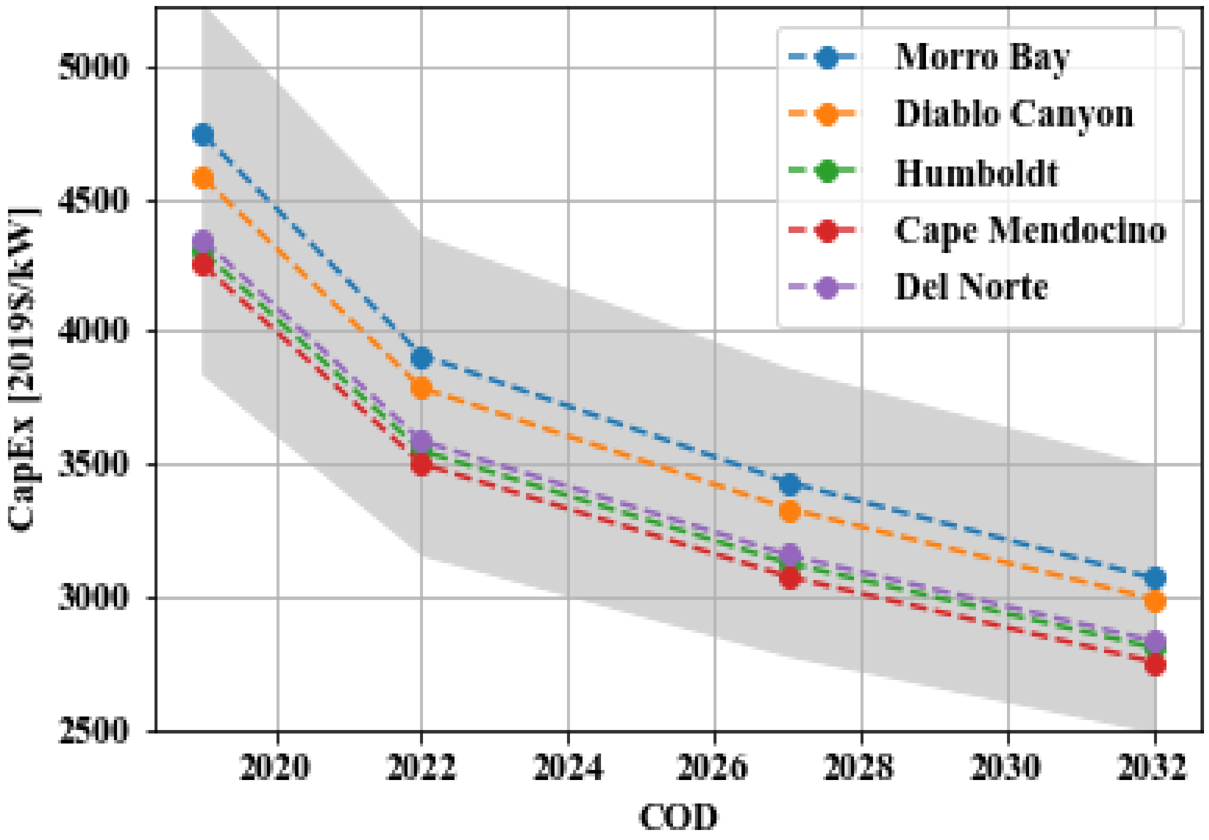


Reference plant layout for 2022 (10-MW turbine). Dot size = 1D

1) Gaertner et al. 2020

Draft Results

CapEx – CA Study Sites



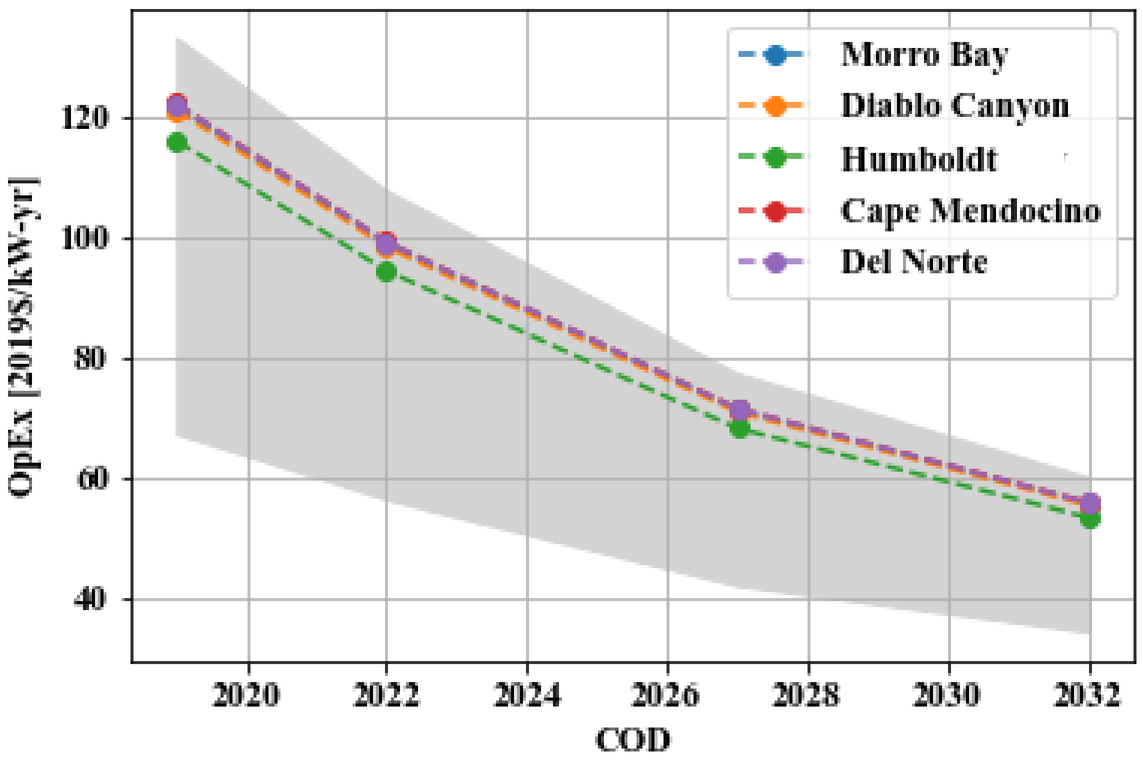
- CapEx differences between study areas is driven primarily by the variation in export cable length and installation costs (i.e., distance to construction port):

Study Area	Distance to Construction Port	Export Cable Length
Morro Bay	315 km	38 km
Diablo Canyon	249 km	50 km
Humboldt	55 km	40 km
Cape Mendocino	122 km	29 km
Del Norte	120 km	43 km

- Trajectory is estimated from:
  - Turbine upsizing (8 MW [2019 COD] to 15 MW [2032 COD])
  - Industry growth (50 MW [2019 COD] to 8,000 MW [2032 COD]) and technology innovation

Note: Mid-case scenario depicted.

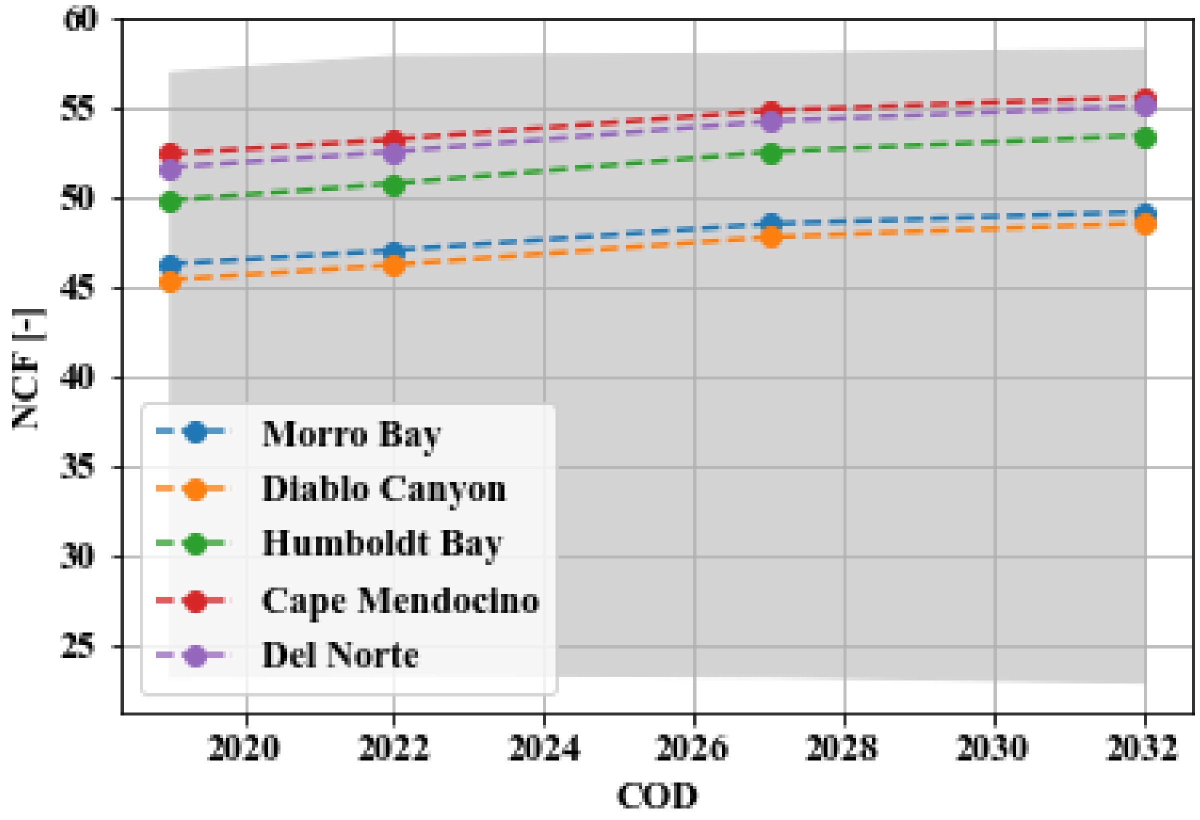
OpEx – CA Study Sites



- Difference in OpEx driven by distance from site to O&M port and wave regime

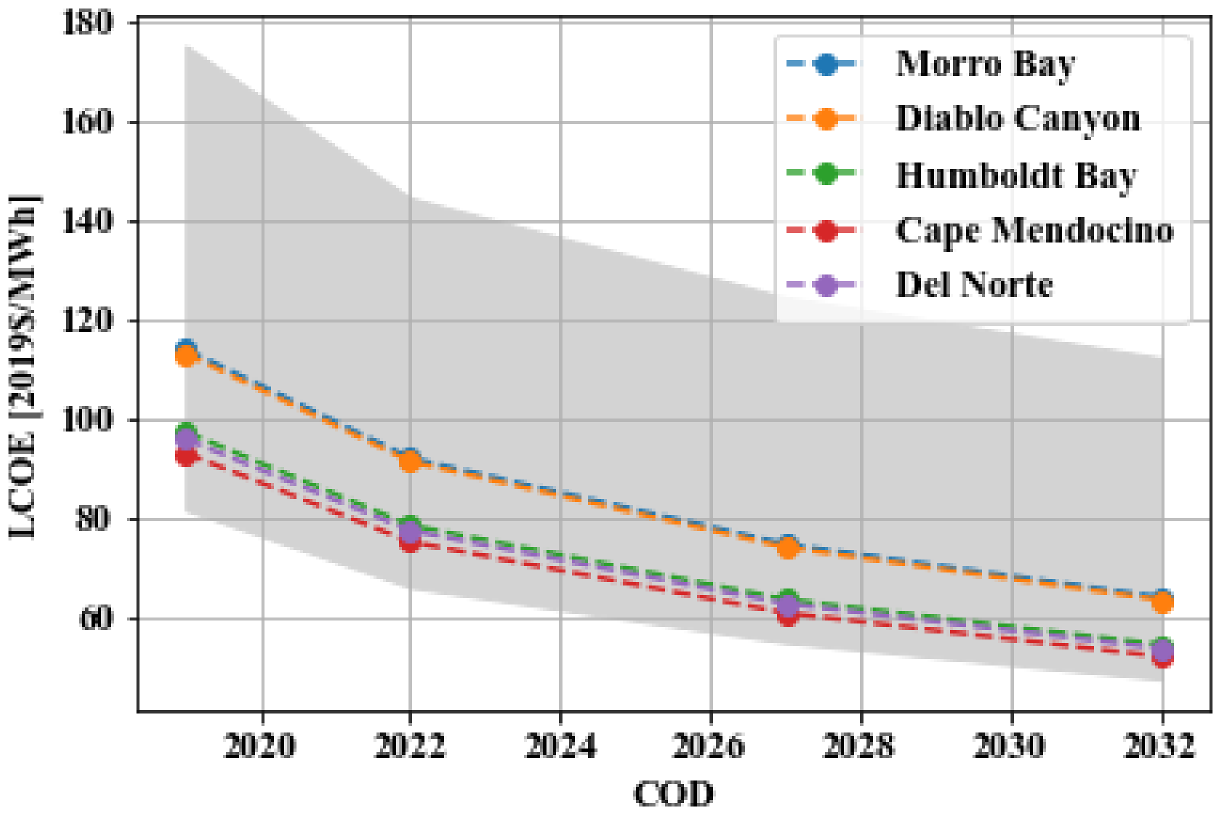
Study Area	Distance to O&M Port	Mean Significant Wave Height
Morro Bay	315 km	2.45 m
Diablo Canyon	249 km	2.48 m
Humboldt	55 km	2.58 m
Cape Mendocino	122 km	2.60 m
Del Norte	120 km	2.60 m

Net Capacity Factor (NCF) – CA Study Sites



- Estimated mean wind speeds @150m:
  - Morro Bay: 9.8 m/s
  - Diablo: 9.4 m/s
  - Humboldt: 10.8 m/s
  - Cape Mendocino: 11.6 m/s
  - Del Norte: 12.0 m/s
- Del Norte spends more time below the wind speed cut-in and above cut-out than Cape Mendocino
- Increase driven by vertical wind shear and assumed innovations in controls, conditions-based maintenance, improved weather forecasting, etc.

Levelized Cost of Energy (LCOE) – California Study Sites

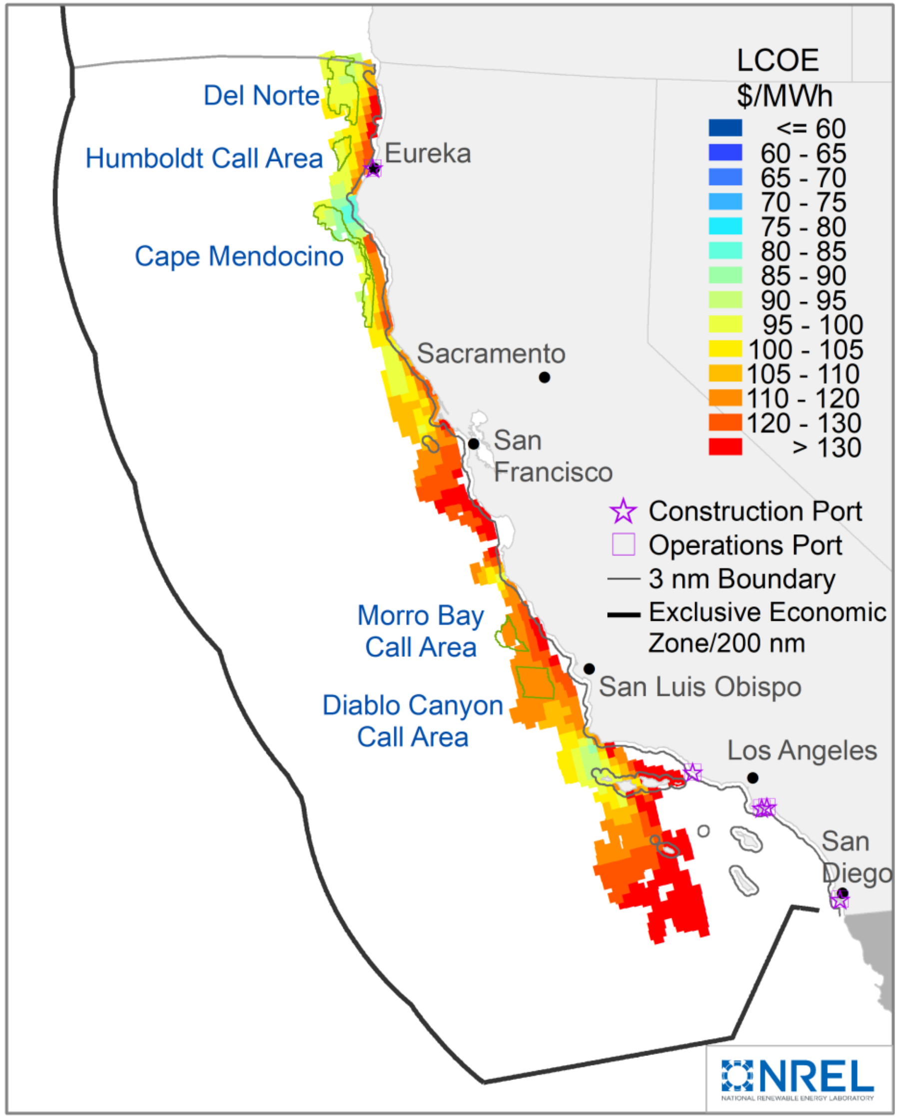


- LCOE differences driven primarily by variation in CapEx and AEP
- O&M costs relatively similar across sites
- Same financing, turbine technology and plant size assumptions made for the five study areas

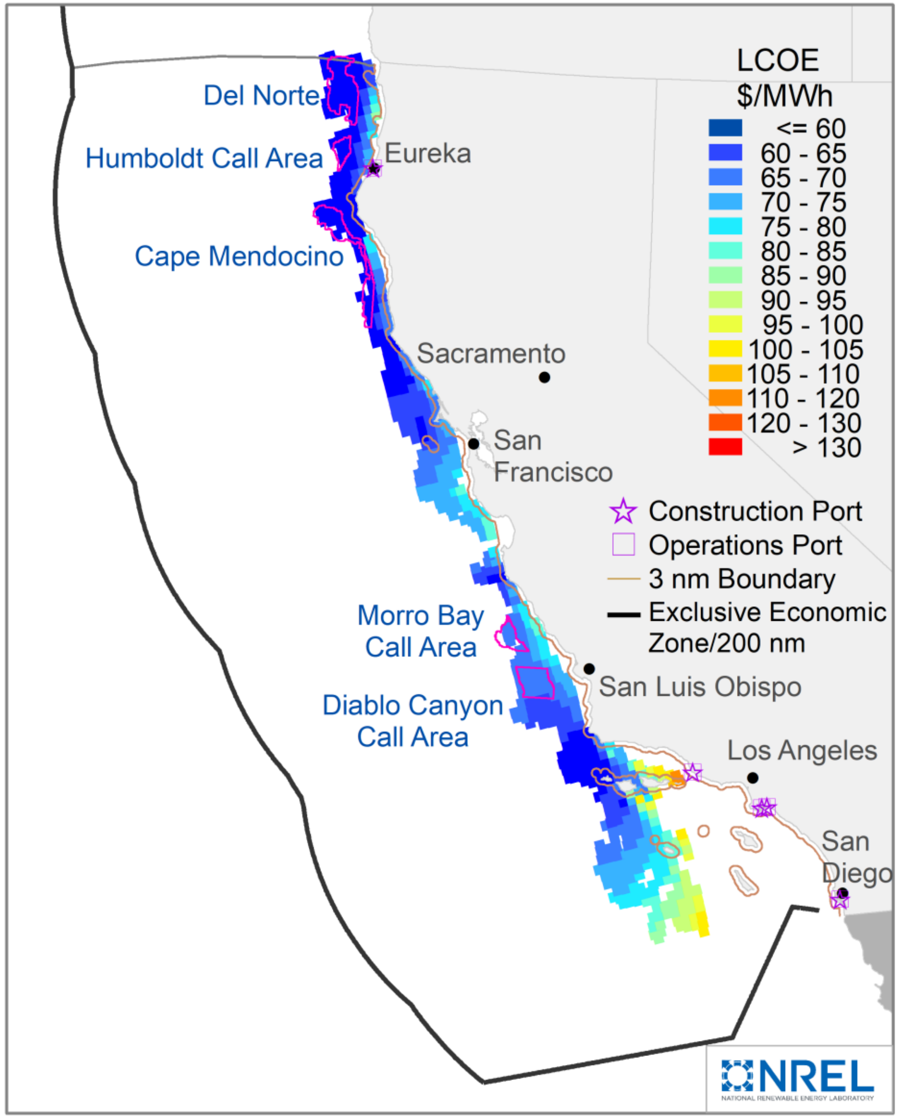
Note: Mid-case CapEx scenario depicted.

LCOE in the CA Analysis Domain

2019 COD



2032 COD



Note: Mid-case CapEx scenario depicted.

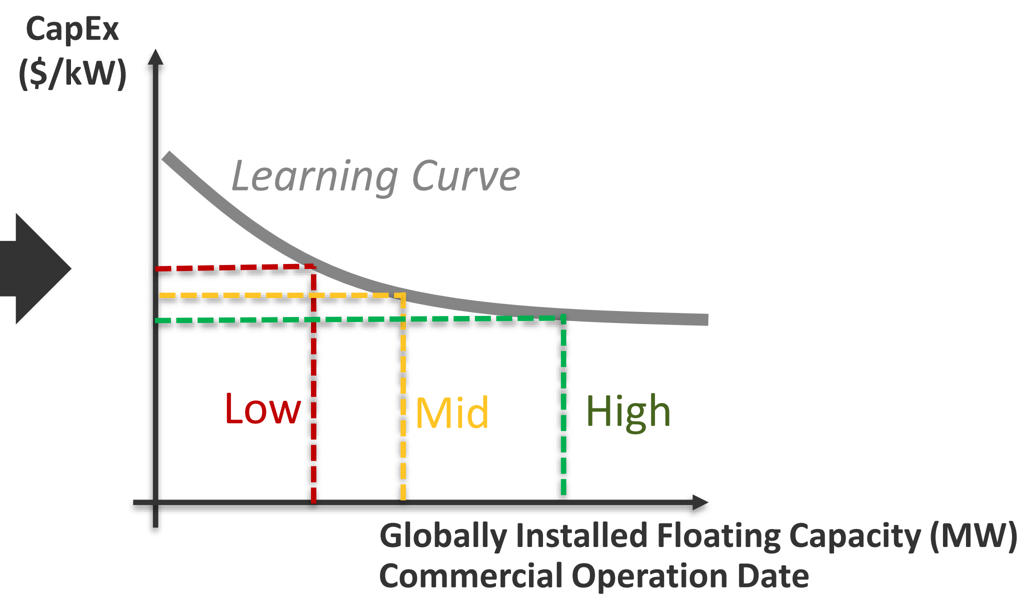
CapEx Scenarios

CapEx scenario definition

- CapEx scenarios reflect different levels of globally installed floating capacity by 2032
- Methodologically, these differences in the installed capacity levels by 2032 are captured through a CapEx learning curve that is derived from global fixed-bottom project data

Assumed Global Floating Capacity By 2032 (COD)

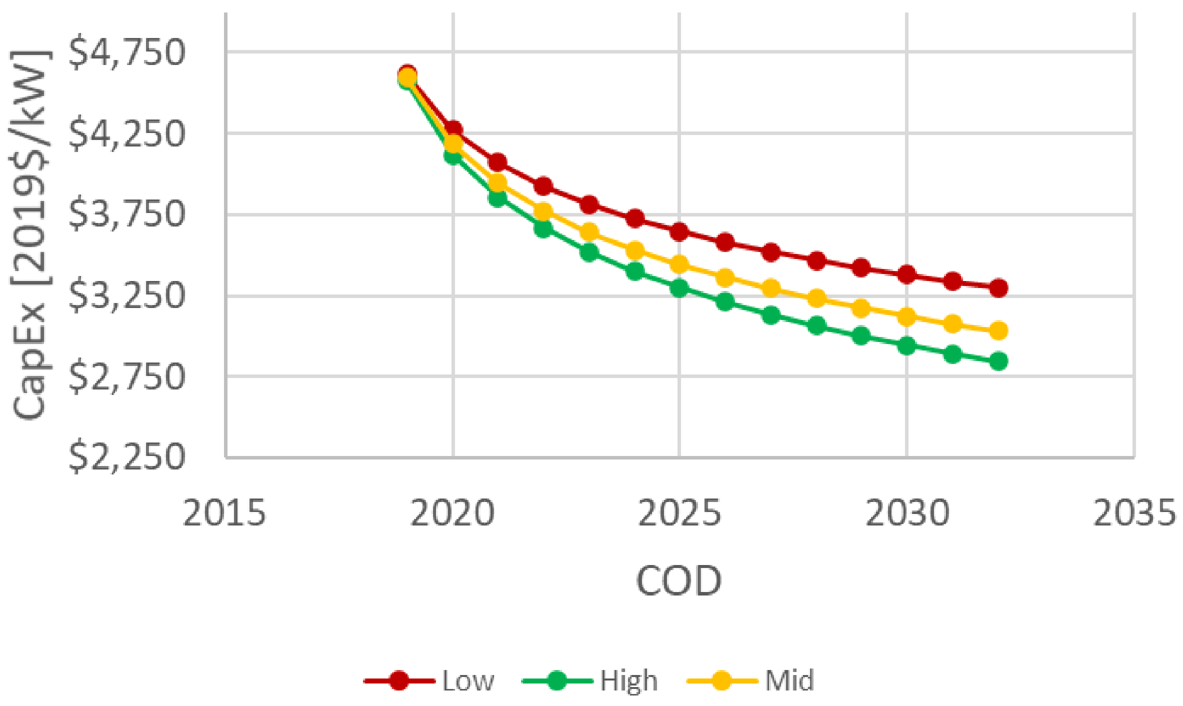
	Capacity (MW)			Source
4C Offshore	8,000			4COffshore 2020
University of Strathclyde/DNV GL	4,300			Hannon et al. 2019
Equinor	13,000			Buchsbaum 2018
WoodMacKenzie	4,200			Shreve and Kragelund 2020
NREL assumption for this study	***LOW*** 4,000	***MID*** 8,000	***HIGH*** 13,000	



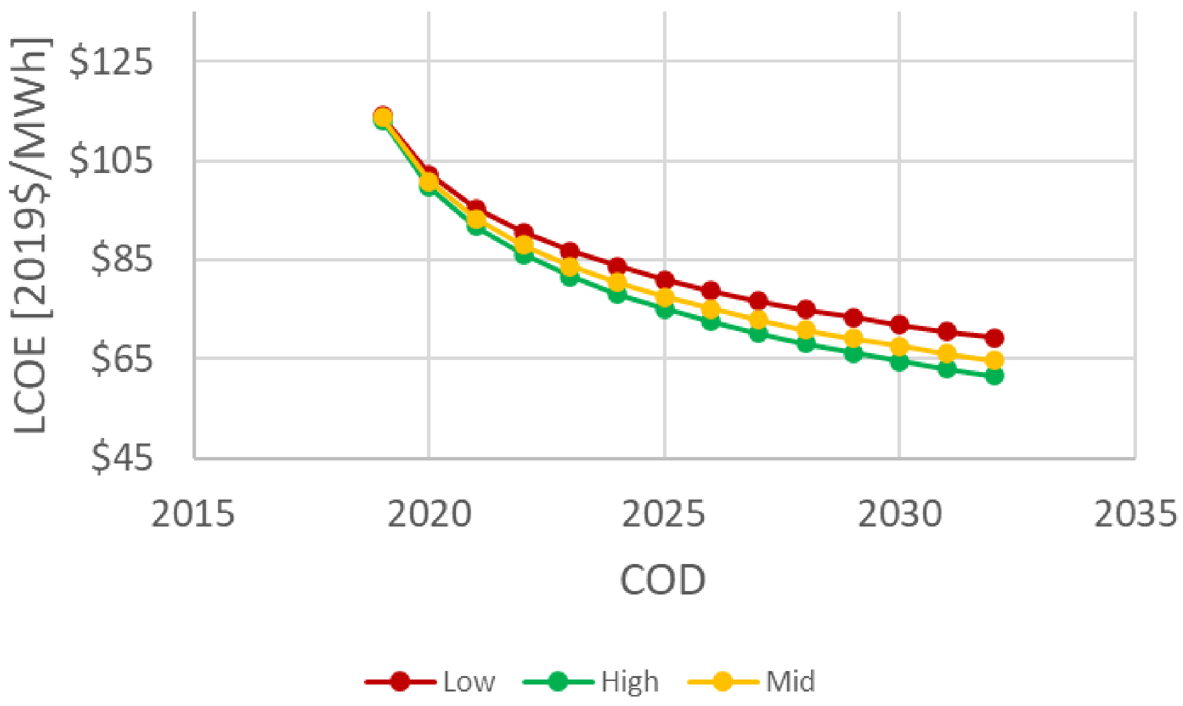
Learning curve shown for Illustration only

Cost Trajectories to 2032

CapEx – Diablo Canyon



LCOE – Diablo Canyon



Low = 4 GW
Mid = 8 GW
High = 13 GW of floating capacity by 2032

Note: Diablo Canyon chosen for illustration; scenarios were also estimated for the four other study areas.

Comparison to Prior Studies

Key Differences to Prior Floating Cost Analyses for CA

- In the 2019–2020 IRP process, floating cost estimates from NREL's 2018 Annual Technology Baseline (NREL 2019) were used
- These assessments, all published in different years, reflect varying sets of assumptions
- The floating (and fixed-bottom) offshore wind industry has progressed rapidly over the last few years in terms of commercial and technological status
- In this current study, modeling assumptions are updated to reflect these advances

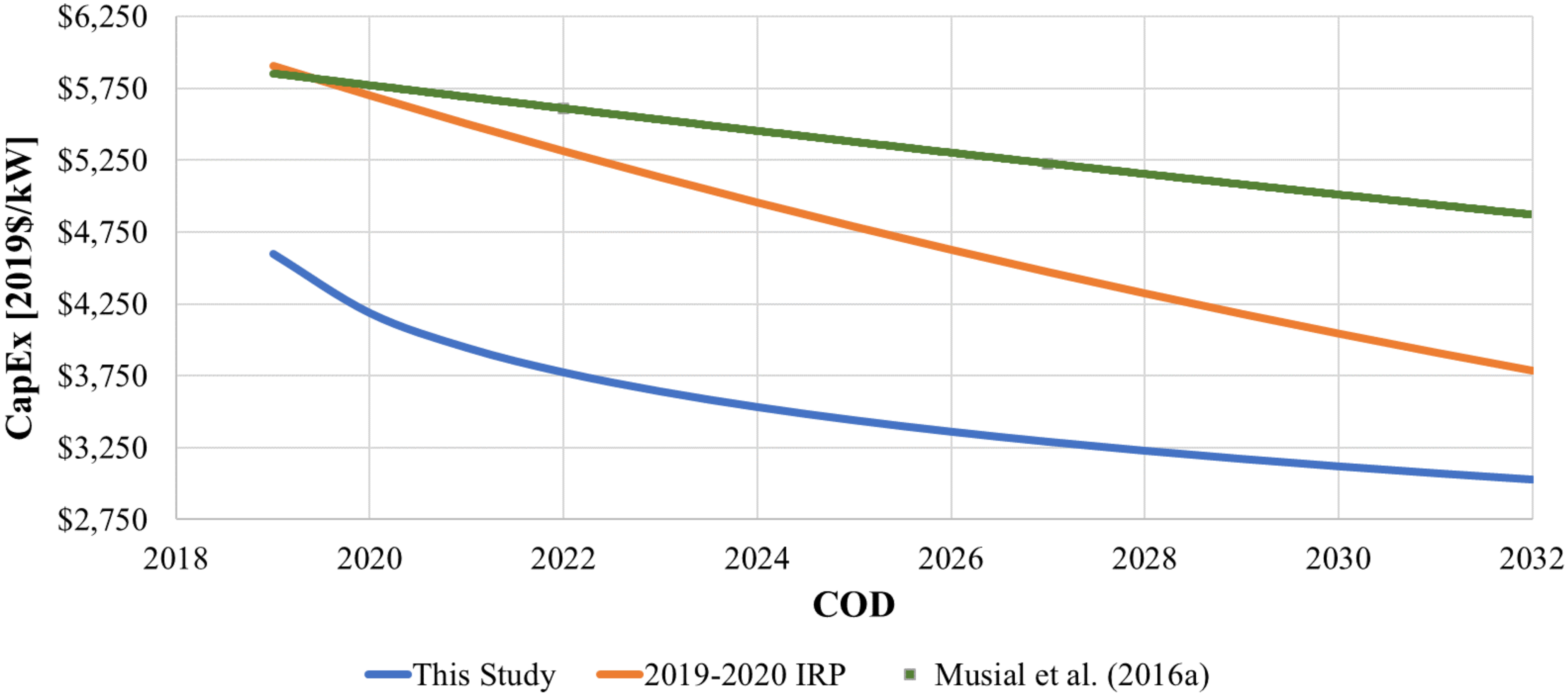
	This Study	Musial et al. 2016a	NREL 2019a[1]
Turbine size, 2019/2032 (MW)	8–15	6–10	3.4–10
Plant size (MW)	1,000	600	600
Fixed charge rate (%)	7.2%	10.5%	9.5%
Wind speed data	CA20 resource data set	17-yr AWS Truepower / MERRA[1] data set	Wind Toolkit data[3]
Aggregation	Site-specific	Site-specific	Average (TRG)

Key Differences to Prior Floating Cost Analyses for CA

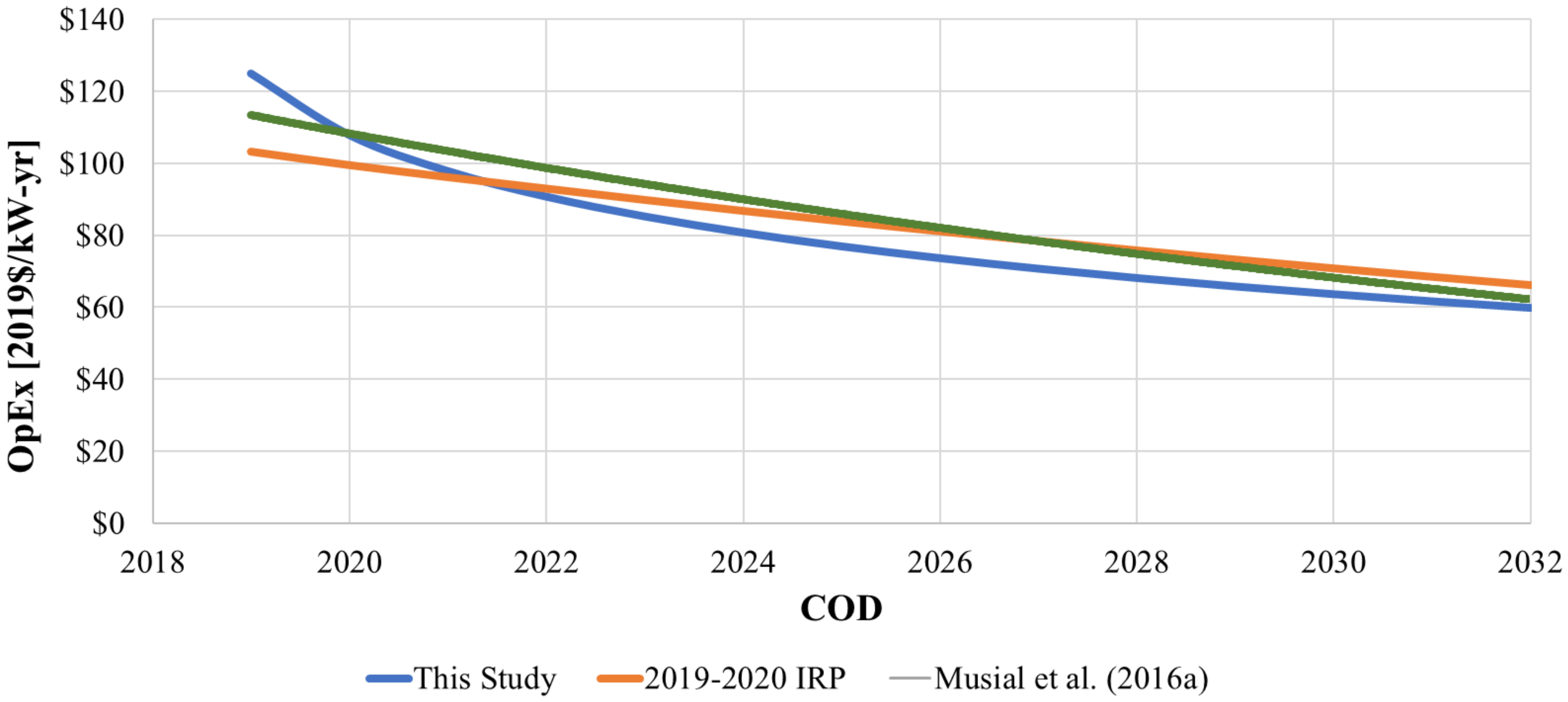
Results of this Study in Comparison with Earlier Assessment
All Values in 2019$ for 2030 COD

	Capacity Factor		CapEx ($/kW)		OpEx ($/kW-yr)		LCOE ($/MWh)	
	2019-2020 IRP	NREL 2020 (current)	2019-2020 IRP	NREL 2020 (current)	2019-2020 IRP	NREL 2020 (current)	2019-2020 IRP	NREL 2020 (current)
Morro Bay	55%	49%	3,791	3,209	71	64	76	72
Diablo Canyon	46%	48%	4,042	3,122	71	64	96	68
Humboldt	52%	53%	3,791	2,929	71	61	81	58
Cape Mendocino	53%	55%	3,791	2,877	71	64	79	56
Del Norte	52%	55%	3,791	2,956	71	64	81	58

CapEx


$6,250
$5,750
$5,250
$4,750
$4,250
$3,750
$3,250
$2,750
CapEx [2019$/kW]
2018
2020
2022
2024
2026
2028
2030
2032
COD
This Study
2019-2020 IRP
Musial et al. (2016a)

OpEx


$140
$120
$100
$80
$60
$40
$20
$0
OpEx [2019$/kW-yr]
2018
2020
2022
2024
2026
2028
2030
2032
COD
This Study
2019-2020 IRP
Musial et al. (2016a)

Next steps

Next steps

- August 28 – September 16 — *Peer review*
- Late October 2020 — *Publication of report*
- Q4 2020 – Q4 2021 — *Integration with IRP process*

Next steps

Invited Peer Reviewers

Avangrid
AWEA
BOEM
CAISO
California Coastal Commission
California Energy Commission
California Ocean Protection Council
California Public Utilities Commission
CalWEA
Castle Wind
Department of Energy
E3 - Energy and Environmental Economics
EDPR
Equinor
Governor’s Office of Planning and Research
Humboldt State University

Magellan Wind
Mainstream Renewable Power
Monterey Bay Community Power
North Coast Tribe
Offshore Wind Association
Orsted
Pacific Ocean Energy Trust
PG&E
Principle Power
Redwood Coast Energy Authority
RWE
Shell
Southern California Edison
State Lands Commission Executive Office
UC Berkeley Labor Center

Q&A

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NREL Transforming ENERGY

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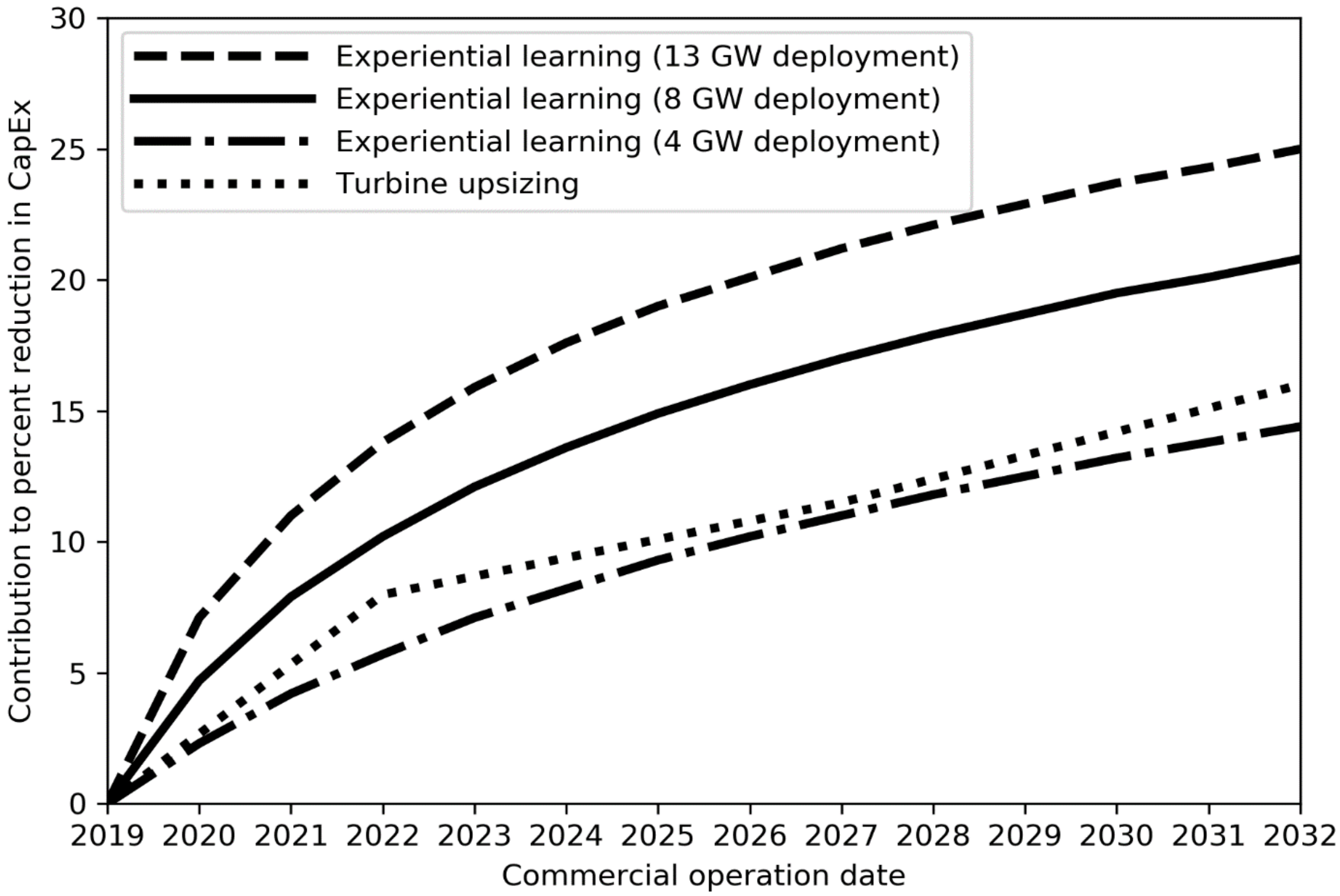
Back-up slides

Modeling Approach

1. Develop key technology assumptions about current and future floating technology
   - Turbine size and properties
   - Substructure choice
   - Plant size and turbine spacing
   - Array and export cable
2. Identify the nearest port and grid interconnection infrastructure
3. Collect spatial (Beiter et al. 2016) and floating cost data
   - Wind speed
   - Distance to grid features
   - Distance to construction and operations ports
   - Metocean conditions
   - Bathymetry
4. Calculate gross energy production and losses (wake, electrical, environmental, availability)
5. Develop financial assumptions for floating offshore wind project
6. Run ORCA to estimate baseline (2019) LCOE
7. Develop estimates of global floating offshore wind deployment by 2032 and run learning curve module
8. Calculate future LCOE by applying learning-induced effects (as a function of global floating offshore wind deployment) and impact from turbine upsizing to baseline costs and performance
9. Extrapolate costs and performance for 2033–2050 from modeled data between 2019 and 2032 (logarithmic fit)

Cost projections



- Learning rate: “Fractional reduction in cost for each doubling of cumulative [offshore wind] capacity”[1]
- In this study, the learning rate is derived through a regression analysis of empirical offshore wind data
- In our formulation of the learning rate, the combined effects on capital expenditures (CapEx) are captured from:
  - “learning-by-doing” (e.g., efficiencies, scale of production, standardization, “knowing your supply chain”)[2]
  - “learning-by-researching” (e.g., innovation, technology advancement)[2]
  - But not: CapEx effects from turbine upsizing; these are modeled separately in NREL’s ORBIT model

Source: [1] Rubin, E., I. Azevedo, P. Jaramillo, S. Yeh. 2015. “A review of learning rates for electricity supply technologies” Energy Policy, 86: 198-218;
[2] Junginger, M., A. Louwen. 2020. “Technological Learning in the Transition to a Low-Carbon Energy System” London (U.K.): Academic Press / Elsevier. ISBN: 978-0-12-818762-3.

Turbine Rating and Substructure Assumptions