Cost of Wind Energy Review: 2024 Edition

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New Report Naming Convention

- This year’s report uses a new naming convention—"2024 Edition"—to align with the Wind Energy Technologies Office's naming convention for the wind energy market reports (https://www.energy.gov/eere/wind/wind-market-reports-2024-edition).

- The data and results in this analysis are derived from the prior year’s 2023 commissioned plants, representative industry data, and state-of-the-art modeling capabilities used to inform Fiscal Year 2024 values in the report.

Acknowledgments

The authors would like to thank Patrick Gilman (U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office [WETO]) for supporting this research. Thanks also to Gage Reber (contractor to WETO) of Boston Government Services and Daniel Beals (contractor to WETO) of Lindahl Reed Inc. for reviewing prior versions of this presentation. Thank you to Ryan Wiser and Dev Millstein (Lawrence Berkeley National Laboratory) and Lindsay Sheridan (Pacific Northwest National Laboratory) for their analysis of wind project market data that informed this analysis. Thanks also to Amy Brice (National Renewable Energy Laboratory) for editing the presentation. Any remaining errors or omissions are the sole responsibility of the authors.

List of Acronyms and Abbreviations

AEP	annual energy production
APC	Applicable Project Components
ATB	Annual Technology Baseline
BOS	balance of system
CapEx	capital expenditures
COD	commercial operations date
CRF	capital recovery factor
DOE	U.S. Department of Energy
FCR	fixed charge rate
FY	fiscal year
GPRA	Government Performance and Results Act
HH	hub height
IEC	International Electrotechnical Commission
kW	kilowatt
LandBOSSE	Land-based Balance of System Systems Engineering
LCOE	levelized cost of energy
m	meter
m/s	meters per second
MACRS	Modified Accelerated Cost Recovery System
MW	megawatt
MWh	megawatt-hour
NPV	net present value
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
OpEx	operational expenditures
ORBIT	Offshore Renewables Balance of System and Installation Tool
ORCA	Offshore Wind Regional Cost Analyzer
RD	rotor diameter
USD	U.S. dollars
W	watt
WACC	weighted average cost of capital
WETO	Wind Energy Technologies Office
WISDEM®	Wind Plant Integrated Systems Design and Engineering Model
WOMBAT	Windfarm Operations & Maintenance cost-Benefit Analysis Tool
yr	year

Executive Summary

Executive Summary

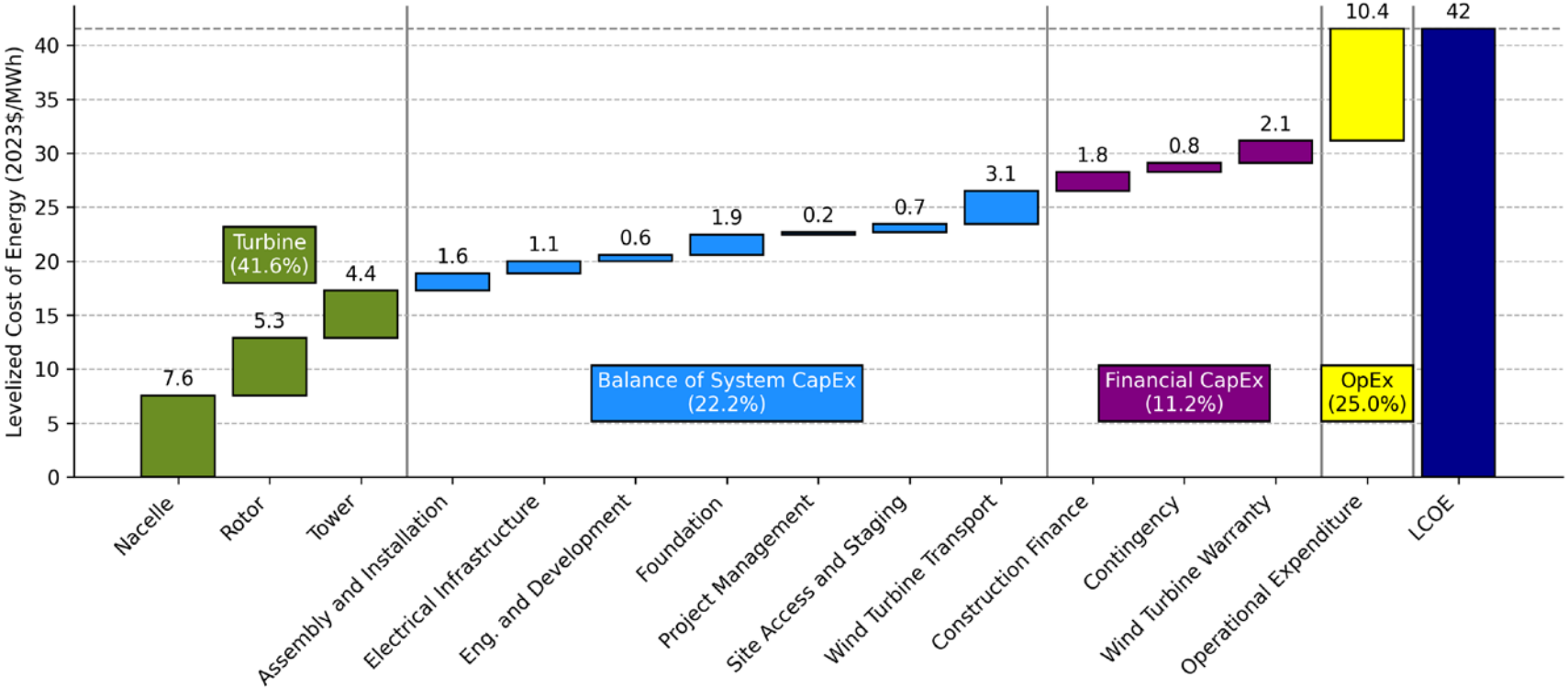
- The 13th annual *Cost of Wind Energy Review* uses representative utility-scale and distributed wind energy projects to estimate the levelized cost of energy (LCOE) for land-based and offshore wind power plants in the United States.
  - Data and results are derived from 2023 commissioned plants, representative industry data, and state-of-the-art modeling capabilities.
  - The goals of this analysis are to provide insight into current component-level costs and give a basis for understanding the impacts of market variability on wind energy LCOE in the United States.
    - Recent U.S. offshore wind industry strike prices exceed the LCOE estimates in this publication. Slide 43, titled "2023 Offshore Wind Reference Plant LCOE Estimates," outlines several factors contributing to these disparities.
- The primary elements of this 2023 analysis include:
  - Estimated LCOE for (1) a representative **land-based wind** energy project installed in a moderate wind resource in the United States, (2) a representative **fixed-bottom offshore wind** energy project installed in the U.S. North Atlantic, and (3) a representative **floating offshore wind** energy project installed off the U.S. Pacific coast
  - Updated LCOE estimates for representative residential-scale, commercial-scale, and large-scale **distributed wind** projects installed in a moderate wind resource in the United States
  - Sensitivity analyses showing the range of effects that basic LCOE variables could have on the cost of wind energy for land-based and offshore wind projects
  - Updated Fiscal Year 2024 values for land-based and offshore wind energy used for Government Performance and Results Act (GPRA) reporting and illustrated progress toward established GPRA targets.

Key Inputs and Levelized Cost of Energy Results

		Land-Based	Offshore		Distributed		
Parameter	Units	Utility Scale	Utility Scale (Fixed Bottom)	Utility Scale (Floating)	Single Turbine (Residential)	Single Turbine (Commercial)	Single Turbine (Large)
Wind turbine rating	MW	3.3	12	12	20 (kW)	100 (kW)	1.5
Capital expenditures (CapEx)	$/kW	1,968	5,411	7,349	8,665	6,800	3,362
Fixed charge rate (FCR) (real)	%	6.5	6.76	6.76	6.68	6.68	6.68
Operational expenditures (OpEx)	$/kW/yr	43	135	108	41	41	41
Net annual energy production	MWh/MW/yr	4,104	4,295	3,346	2,580	2,846	3,326
Levelized cost of energy (LCOE)	$/MWh	42	117	181	240	174	80

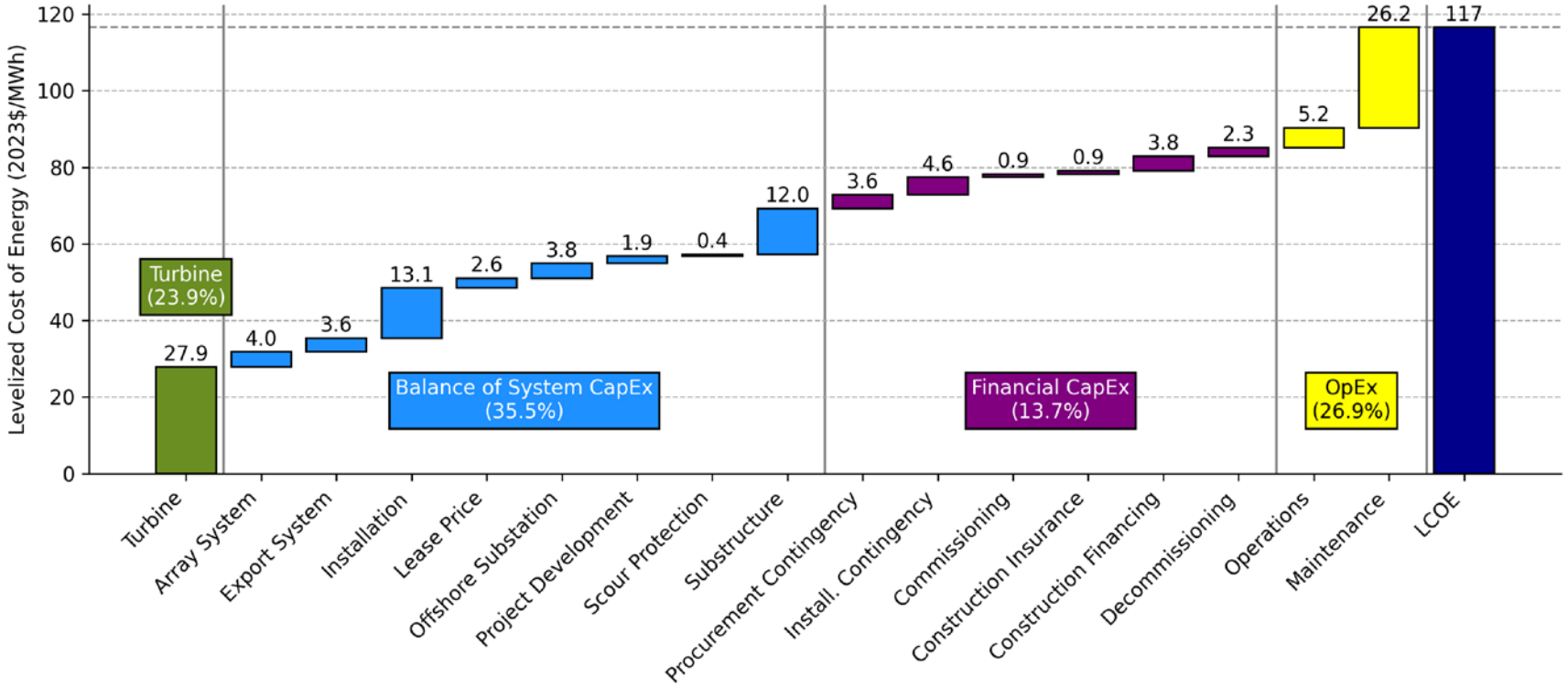
Note: Additional information on the sources of data are presented in the Appendix. Unless specifically stated, all cost data presented in this document are reported in 2023 U.S. dollars (USD).
kW = kilowatt; MW = megawatt; MWh = megawatt-hour

Levelized Cost Breakdown for Reference Land-Based Wind Plant



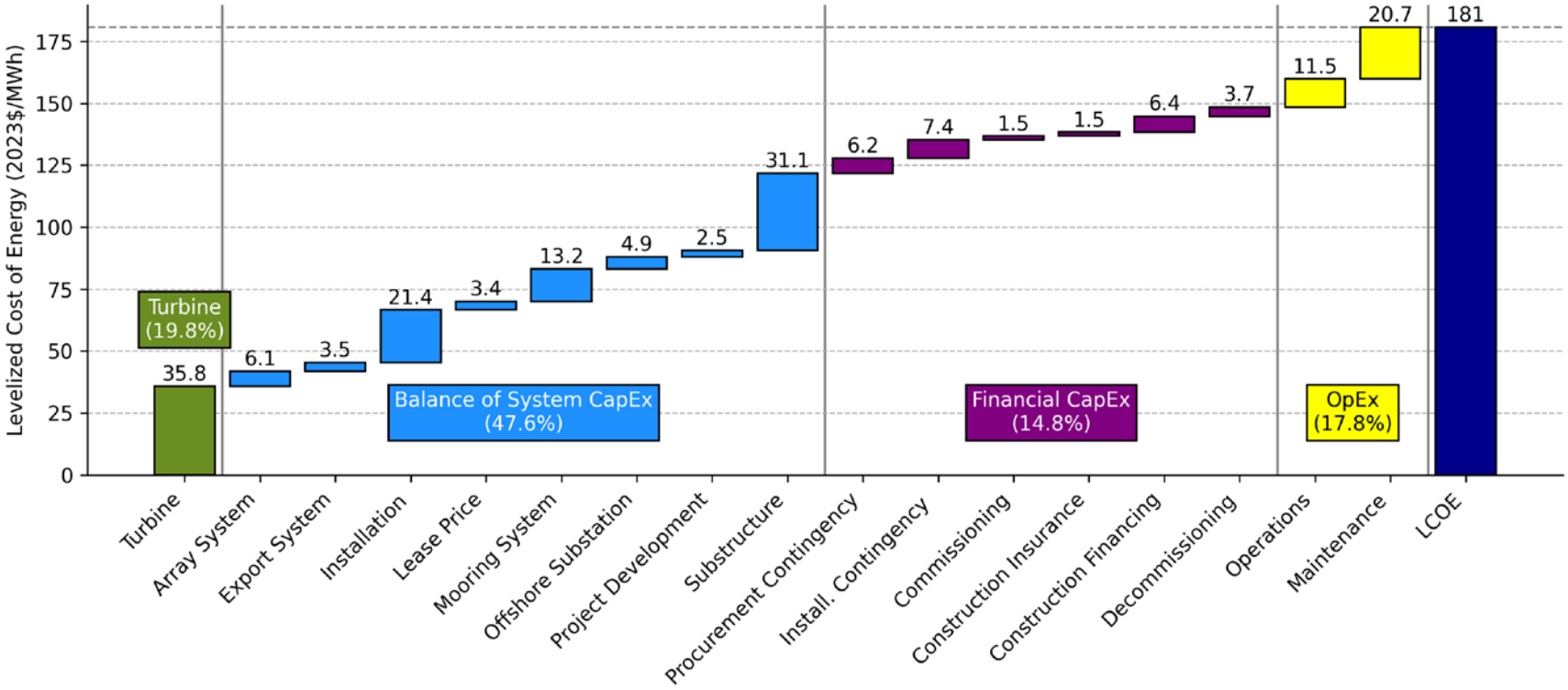
Note: The "Contingency" cost category also includes insurance, permitting, bonding, and markup estimates. The "Operational Expenditure" category includes maintenance cost. Eng. = Engineering.

Levelized Cost Breakdown for Reference Fixed-Bottom Offshore Wind Plant



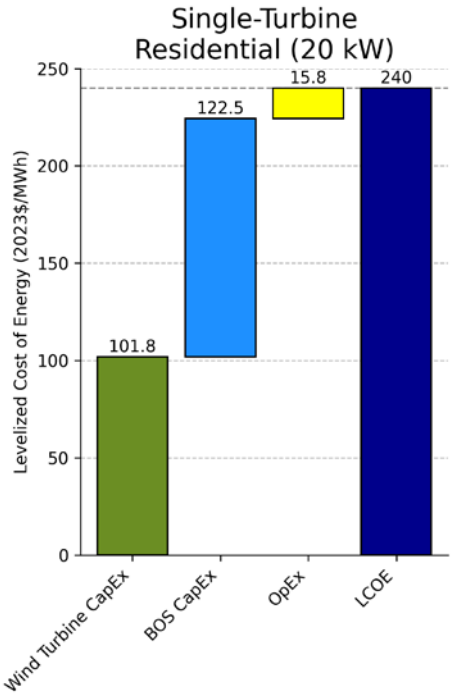
Note: The "Array System" cost includes costs associated with the procurement of the inter-array system cables of an offshore wind farm. Install. = Installation.

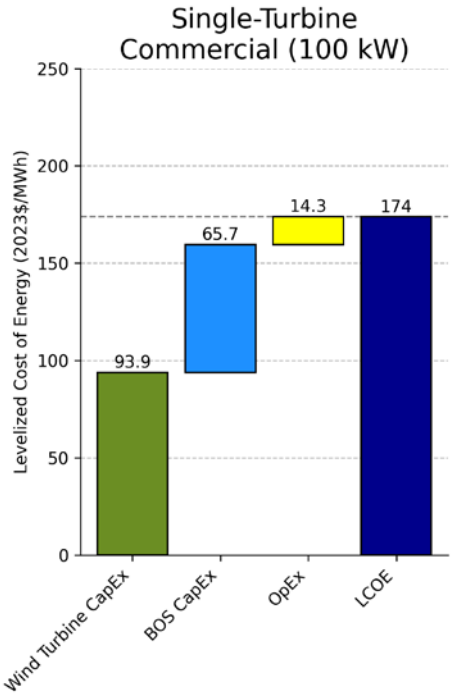
Levelized Cost Breakdown for Reference Floating Offshore Wind Plant

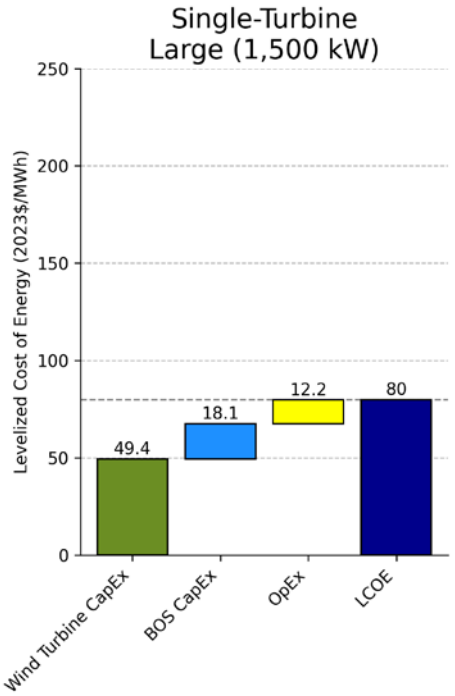


Note: The “Array System” cost includes costs associated with the procurement of the inter-array system cables of an offshore wind farm. Install. = Installation.

Levelized Cost Breakdown for Reference Distributed Wind Projects







BOS = balance of system

Key Conclusions

- The reference project LCOE for **land-based installations is $42/MWh**, with a range of land-based estimates from the single-variable sensitivity analysis covering $30–$61/MWh (see Slide 33).

- The **fixed-bottom offshore wind estimate is $117/MWh**, and the **floating substructure reference project estimate is $181/MWh**. These two reference projects give a single-variable sensitivity range of $76–$234/MWh (see Slides 46 and 47). This range is primarily caused by the large variation in CapEx ($3,000–$9,187/kW) and project design life.

- The **residential and commercial reference distributed wind** system LCOE are estimated at **$240/MWh and $174/MWh**, respectively. Single-variable sensitivity analysis for the representative systems is presented in the *2019 Cost of Wind Energy Review* (Stehly, Beiter, and Duffy 2020). Analysts included the LCOE estimate for a **large distributed wind energy** project in this year's analysis, estimated at **$80/MWh**.

Contents

1. Background

Background

- The *Cost of Wind Energy Review: 2024 Edition* estimates the levelized cost of energy (LCOE) for land-based, offshore, and distributed wind energy projects in the United States.
  - LCOE is a metric used to assess the cost of electricity generation and the total power-plant-level impact from technology design changes. It can be used to compare costs of all types of generation.
  - The specific LCOE method applied in this analysis is described in *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies* (Short, Packey, and Holt 1995):

$$LCOE = \frac{(CapEx * FCR) + OpEx}{\left(\frac{AEP_{net}}{1{,}000}\right)}$$

- LCOE = levelized cost of energy (dollars per megawatt-hour [$/MWh])
- FCR = fixed charge rate (%)
- CapEx = capital expenditures (dollars per kilowatt [$/kW])
- AEP_{net} = net average annual energy production (megawatt-hours per megawatt per year [MWh/MW/yr])
- OpEx = operational expenditures ($/kW/yr)

Background

- This review also provides an update to the *2022 Cost of Wind Energy Review* (Stehly, Duffy, and Mulas Hernando 2023) and examines wind turbine costs, financing, and market conditions. The analysis includes:
  - Estimated LCOE for a representative **land-based wind energy project** installed in a moderate wind resource (i.e., International Electrotechnical Commission [IEC] wind class IIb [IEC 2020]) in the United States
  - Estimated LCOE for representative **offshore (fixed-bottom and floating) wind energy projects** using National Renewable Energy Laboratory (NREL) models and databases of globally installed projects; the authors assessed representative sites on the U.S. North Atlantic coast (fixed bottom) and Pacific coast (floating) using current lease and call information, nominations data from the Bureau of Ocean Energy Management, and various geospatial datasets
  - LCOE estimates for representative **residential, commercial, and large distributed wind energy projects** in the United States
  - Sensitivity analyses showing the range of effects that basic LCOE variables could have on the cost of wind energy for land-based and offshore wind power plants
  - Updates to the national supply curves for land-based and offshore wind energy based on geographically specific wind resource conditions paired with approximate wind turbine size characteristics
  - Projected land-based and offshore wind cost trajectories from 2022 through 2035 used for U.S. Department of Energy (DOE) annual wind power LCOE reporting as required by the Government Performance and Results Act (GPRA).

2. U.S. Department of Energy Goals and Reporting Requirements

DOE Goals and Reporting Requirements

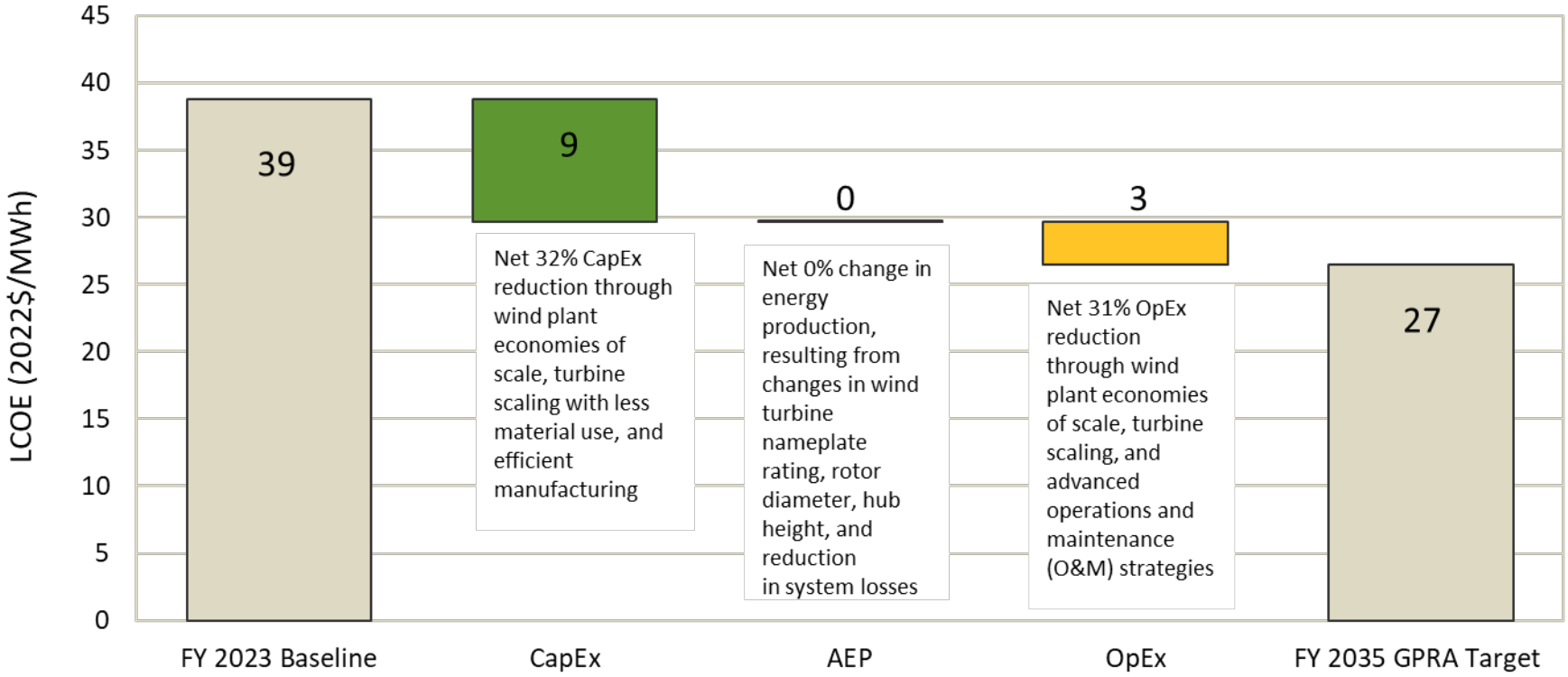
- Every year, the Wind Energy Technologies Office (WETO) reports the LCOE for land-based wind and fixed-bottom offshore wind to satisfy GPRA reporting requirements.
- This report provides the underlying market and cost data for WETO to fulfill the annual GPRA reporting requirements.
- Updates to the LCOE targets are periodically implemented to keep performance measures current with developments in the market, incorporate improved cost and performance estimating tools, and reset the dollar year to minimize inflationary pressures on LCOE.
- In Fiscal Year (FY) 2023, new GPRA LCOE baseline values, cost reduction trajectories, and end-point targets were established for land-based wind and fixed-bottom offshore wind.

GPRA Re-Baseline Efforts Then and Now

- The new baseline plant characteristics are a refinement of the previous values and were established using updated bottom-up engineering cost and performance tools, expert wind industry feedback, and analysis from the Annual Technology Baseline (ATB).
- The new GPRA end-point targets are based on cost reduction trajectories for land-based and fixed-bottom offshore wind projects that span FY 2023 to FY 2035, whereas the previous re-baseline analyses had a target year in FY 2030.
- The need for future re-baseline efforts will be assessed periodically, and re-baselining will be implemented as needed.
- The table summarizes the methods and assumptions of prior GPRA targets and the updated methods and assumptions for FY 2023 GPRA targets.

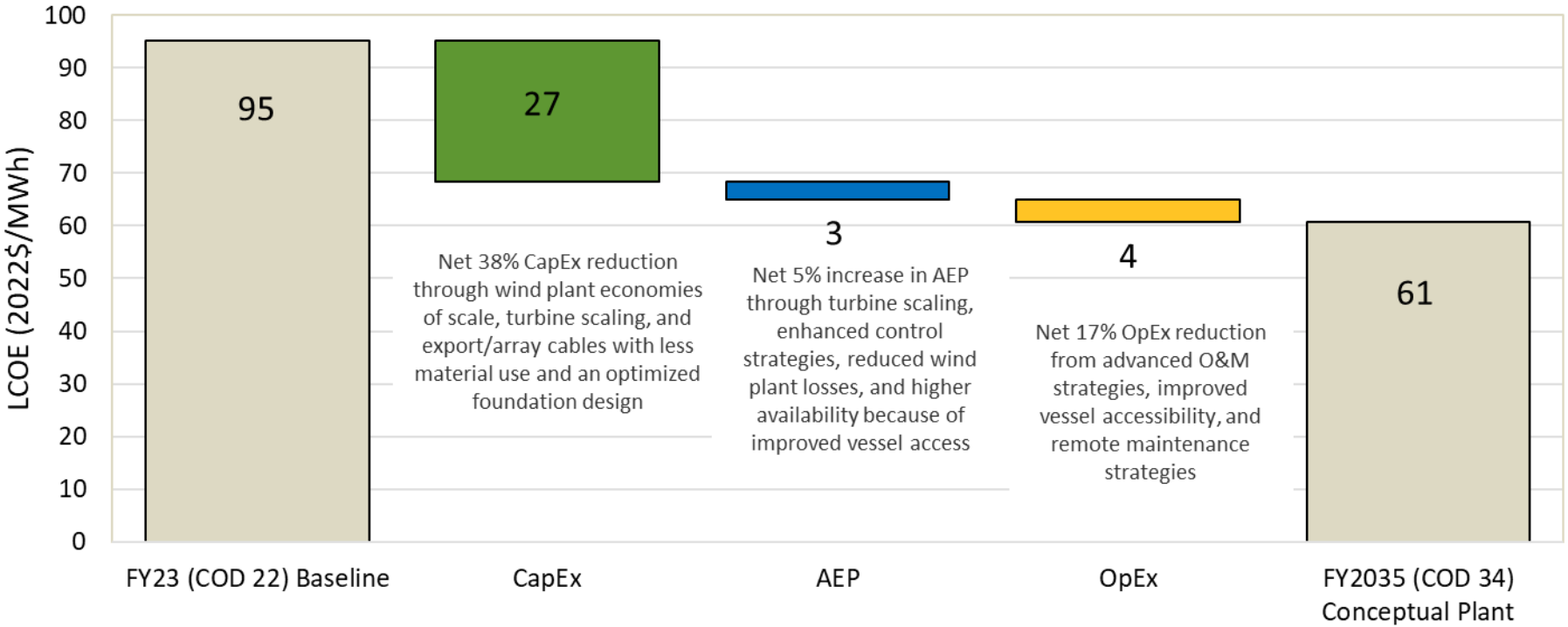
	Land-Based Wind		Fixed-Bottom Offshore Wind	
Effort	**Prior GPRA Baseline (Former)**	**Re-Baseline (Current)**	**Prior GPRA Baseline (Former)**	**Re-Baseline (Current)**
Commercial Operation Date	2015	2022	2018	2022
Technology	Market average turbine parameters	ATB Wind Turbine Technology 3 (3.3 MW, 148 m rotor diameter [RD], 100 m hub height [HH]) (atb.nrel.gov)	Market average turbine parameters	ATB Conservative Scenario (12 MW, 214 m RD, 136 m HH) (atb.nrel.gov)
Cost	Market capacity-weighted average (2015 USD)	ATB Conservative Scenario (atb.nrel.gov)	Bottom-up cost modeling + BVG Assoc. innovations reductions (Beiter et al. 2016; Valpy et al. 2017)	CapEx estimated using technology learning similar to ATB (atb.nrel.gov); OpEx and AEP trajectories informed by Wiser et al. (2021)
Finance	Finance model and market data	ATB finance assumptions in R&D case (atb.nrel.gov)	Fixed charge rate method with financing assumptions based on European conditions in 2018	Fixed charge rate method with financing assumptions based on North American conditions in 2022
Resource	7.25 m/s @ 50 m above the ground	7.25 m/s @ 50 m above the ground	8.43 m/s @ 50 m above the surface	8.43 m/s @ 50 m above the surface
Capacity Factor	40% (16.7% total losses)	46.8% (18.9% total losses)	48.6% (16.2% total losses)	48.7% (16.0% total losses)

GPRA Cost Reduction Pathway From 2023 to 2035 for Land-Based Wind



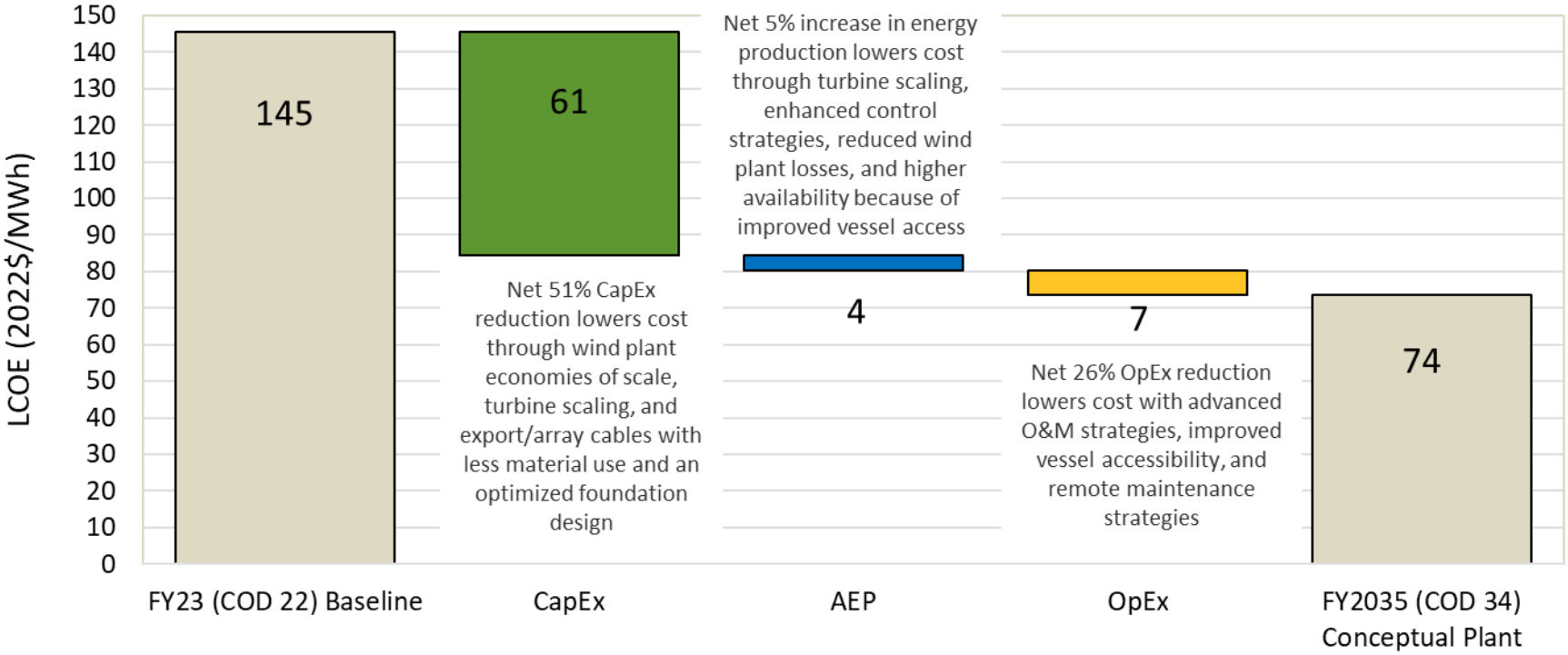
- The FY 2023 baseline assumes a representative wind turbine of 3.3 MW, 148 m (RD), 100 m (HH), and the FY 2035 target assumes a turbine of 6 MW, 170 m (RD), 115 m (HH).
- The land-based wind **GPRA baseline value starts at $39/MWh** (in 2022 USD) set in FY 2023, using the 2022 reference project data.
- The land-based wind **GPRA target is $27/MWh** by FY 2035 (in 2022 USD) and is derived from the analysis conducted in the 2023 Annual Technology Baseline: atb.nrel.gov.

GPRA Cost Reduction Pathway From 2023 to 2035 for Fixed-Bottom Offshore Wind



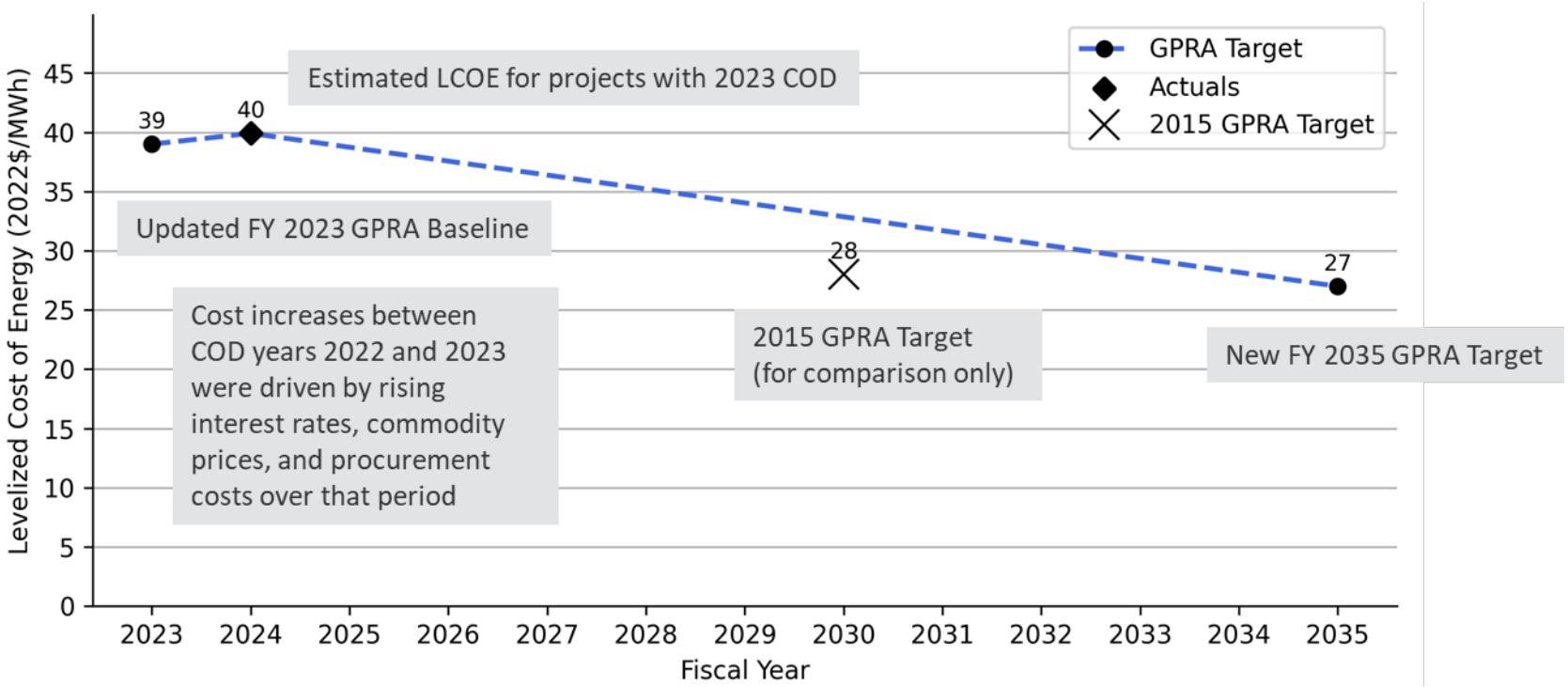
- The **GPRA baseline value starts at $95/MWh** (in 2022 USD) set in FY 2023 using 2022 reference project data.
- The **GPRA target is $61/MWh by FY 2035 (commercial operations date [COD] 2034)** (in 2022 USD) and is derived for a fixed-bottom wind plant at the reference site based on cost reductions informed by industry learning (Shields et al. 2022) and expert elicitation (Wiser et al. 2021). Note that values are rounded to the nearest dollar.

Modeled Cost Reduction Pathway From 2023 to 2035 for Floating Offshore Wind Energy



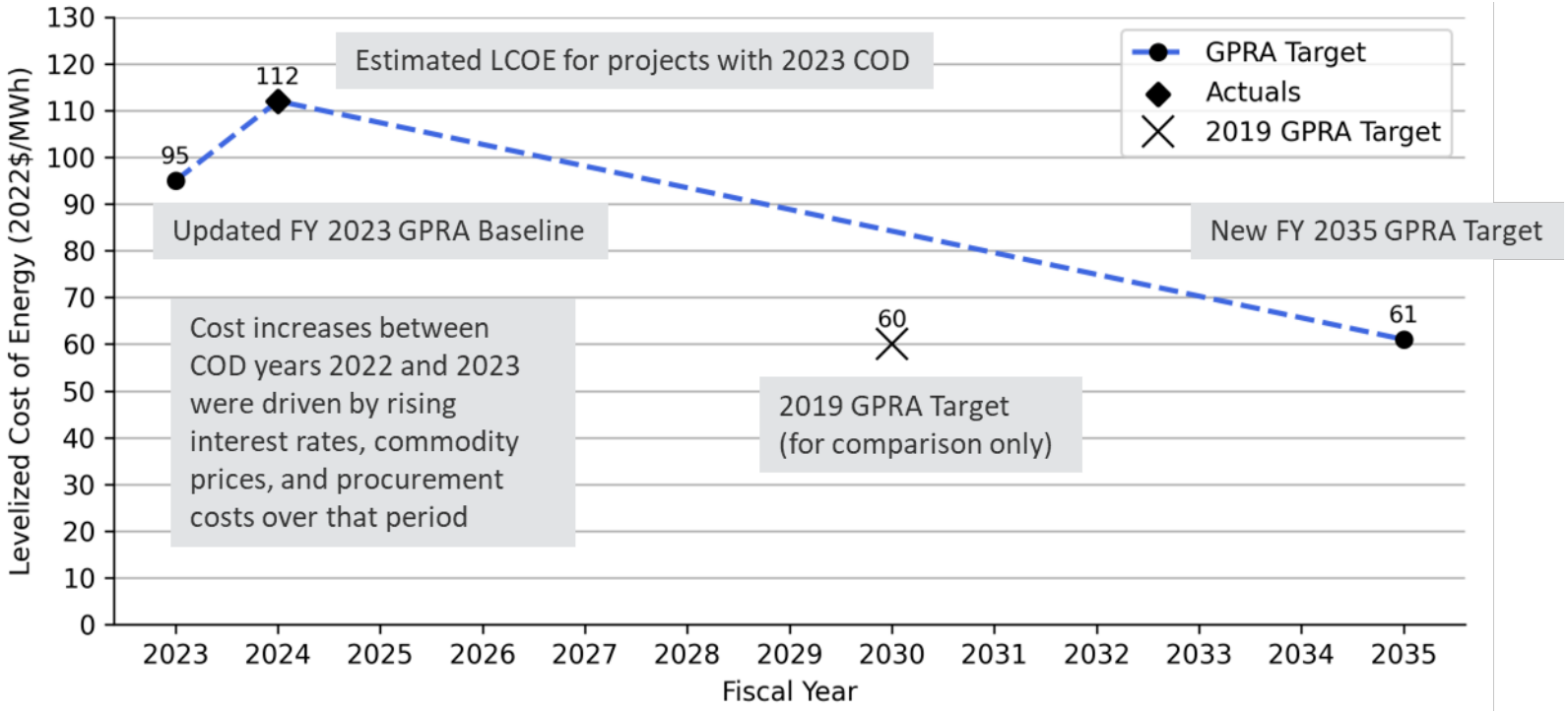
- **DOE has no official GPRA reporting requirement for floating offshore wind energy costs.**
- Projected floating offshore wind cost reductions are mapped to **$74/MWh in FY 2035** using similar methodology as fixed-bottom offshore wind.
- DOE established a Floating Offshore Wind Shot goal of $45/MWh (2020 USD) by 2035 for a different reference site using a different set of assumptions.
- Note that values are rounded to the nearest dollar.

Baseline and GPRA Cost Reduction Pathway From 2023 to 2035 for Land-Based Wind Energy



- Fiscal year estimates informed by projects with COD the prior year (FY = COD + 1).
- The FY 2023 baseline assumes a representative wind turbine of 3.3 MW, 148 m (RD), 100 m (HH), and the FY 2035 target assumes a turbine of 6 MW, 170 m (RD), 115 m (HH).
- For GPRA reporting, the FY 2024 $42/MWh LCOE was deflated from 2023 USD to 2022 USD using the Consumer Price Index from the Bureau of Labor and Statistics (undated).
- For comparison, the FY 2030 GPRA set in 2015 inflated from 2015 USD to 2022 USD using the Consumer Price Index from the Bureau of Labor and Statistics (undated).
- The FY 2023 and FY 2035 LCOE estimates are informed by the analysis conducted in the 2023 Annual Technology Baseline: atb.nrel.gov.

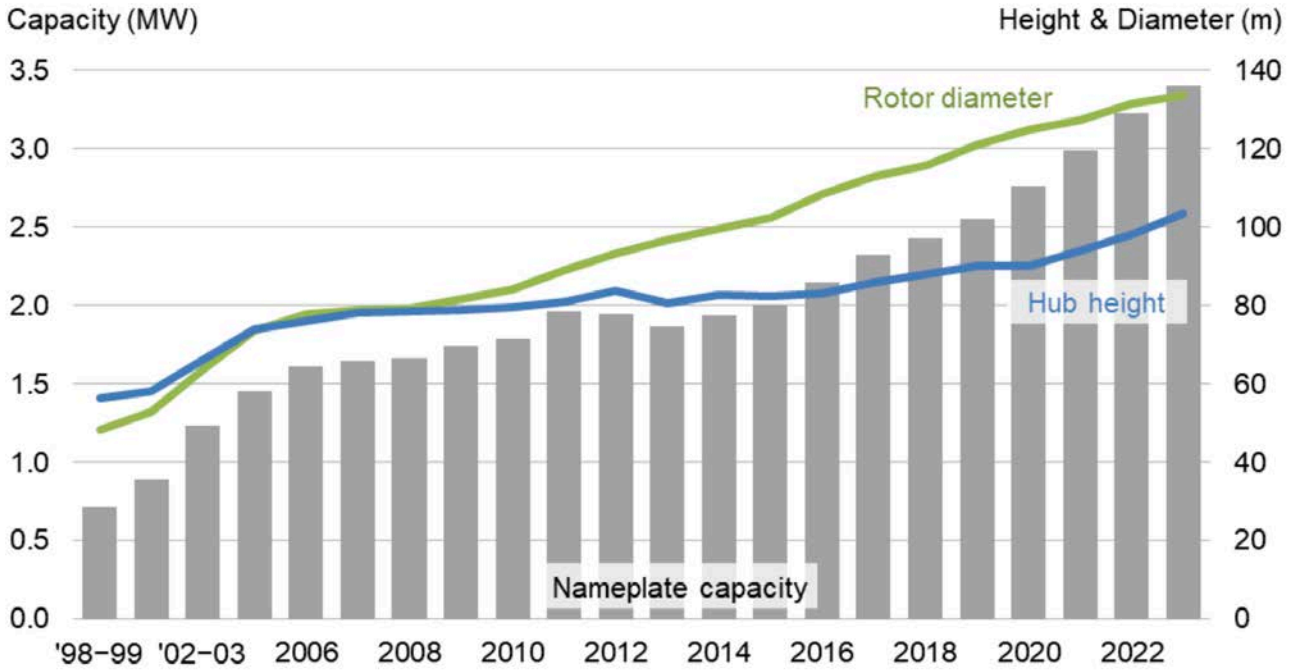
GPRA Cost Reduction Pathway From 2023 to 2035 for Fixed-Bottom Offshore Wind Energy



- The FY 2023 (COD 2022) LCOE is $95/MWh with an FY 2035 (COD 2034) GPRA target of $61/MWh.
- The FY 2035 target is informed by industry learning (Shields et al. 2022) and expert elicitation (Wiser et al. 2021).
- For GPRA reporting, the FY 2024 $117/MWh LCOE estimate was deflated from 2023 USD to 2022 USD using the Consumer Price Index from the Bureau of Labor and Statistics (undated).
- For comparison, the FY 2030 GPRA set in 2019 and inflated from 2018 USD to 2022 USD using the Consumer Price Index from the Bureau of Labor and Statistics (undated).

3. Land-Based Wind Energy

Land-Based Wind Turbine Average Nameplate Capacity, Hub Height, Rotor Diameter, and Assumed Representative Wind Plant



Average turbine nameplate capacity, hub height, and rotor diameter for land-based wind projects. Graphic is based on new installations each year.

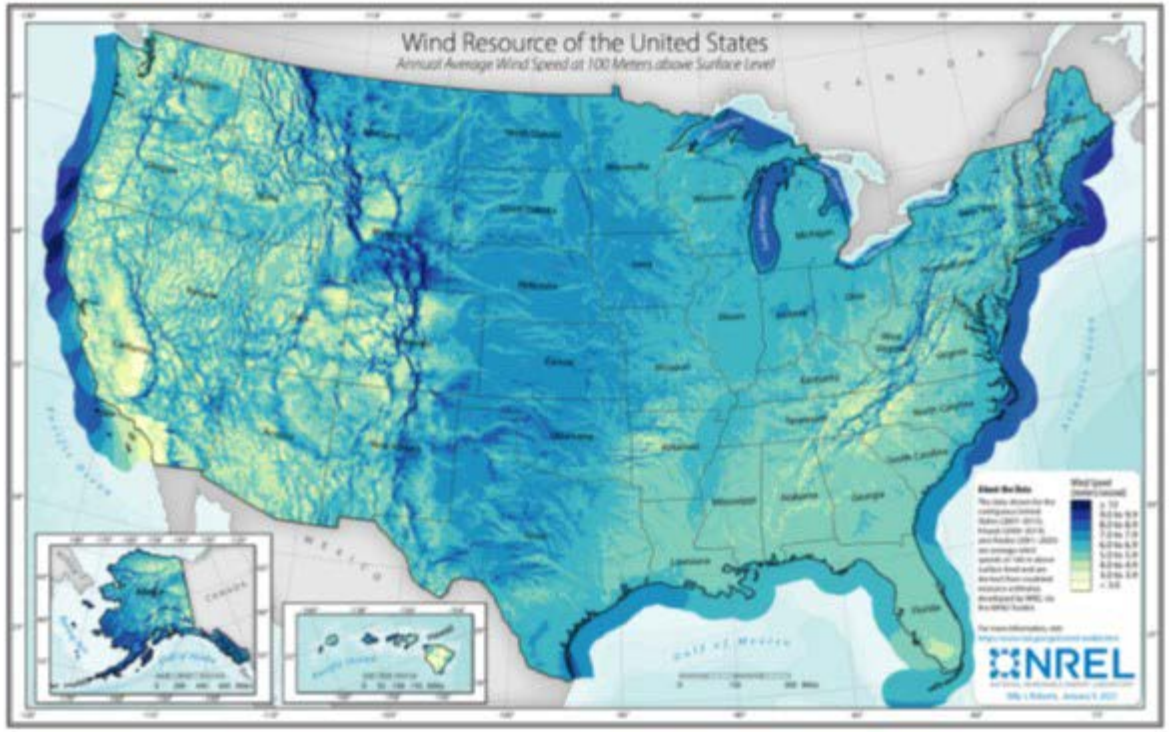
Source: Wiser and Millstein (2024)

Assumed wind turbine characteristics for project operating in 2023. atb.nrel.gov

Parameter	Value
Wind turbine rating	3.3 MW
Rotor diameter	148 m
Hub height	100 m
Wind plant capacity	200 MW
Number of turbines	61

Power curve data available on https://github.com/NREL/turbine-models.

Reference Land-Based Wind Site Characteristics and Performance

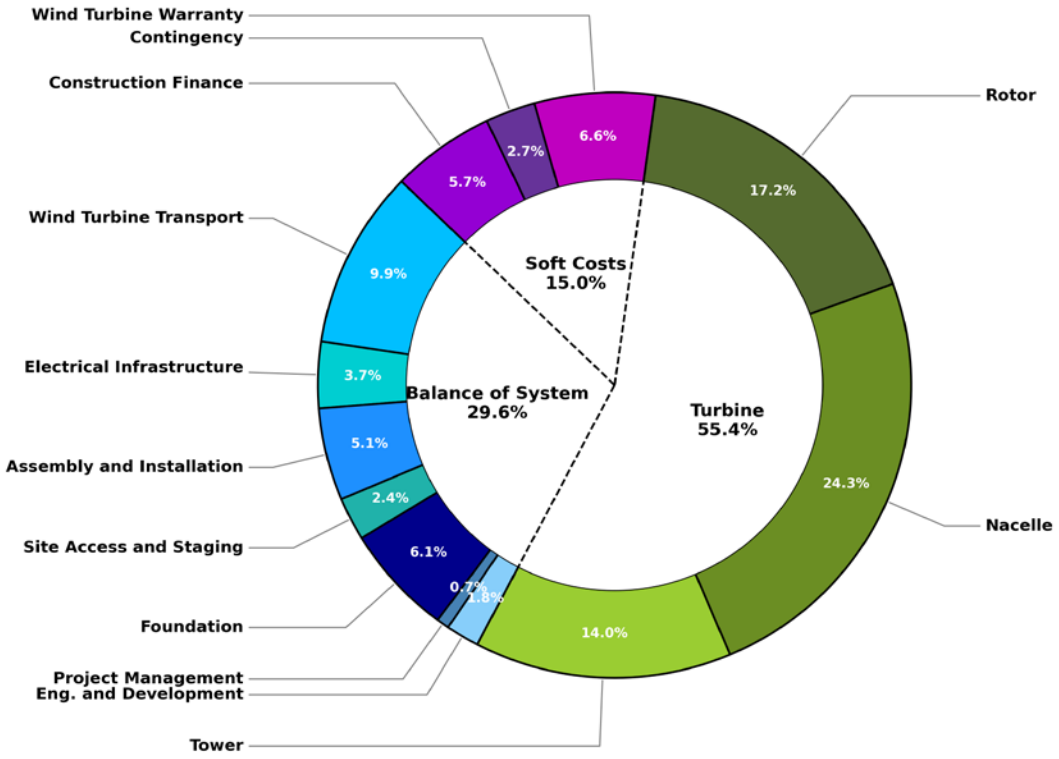


Parameter	Value
Annual average wind speed at 50 m above surface level	7.25 m/s
Annual average wind speed at hub height	8.01 m/s
Weibull k	2.0 (factor)
Shear exponent	0.14
Gross energy capture	5,055 MWh/MW/yr
Gross capacity factor	57.7%
Total losses	18.8%
Net energy capture	4,14 MWh/MW/yr
Net capacity factor	46.9%

Wind resource of the United States, annual average wind speed at 100 m above surface level.

Map by Billy J. Roberts, NREL; more information at https://windexchange.energy.gov/maps-data/324

Land-Based Wind Project Component Cost Breakdown

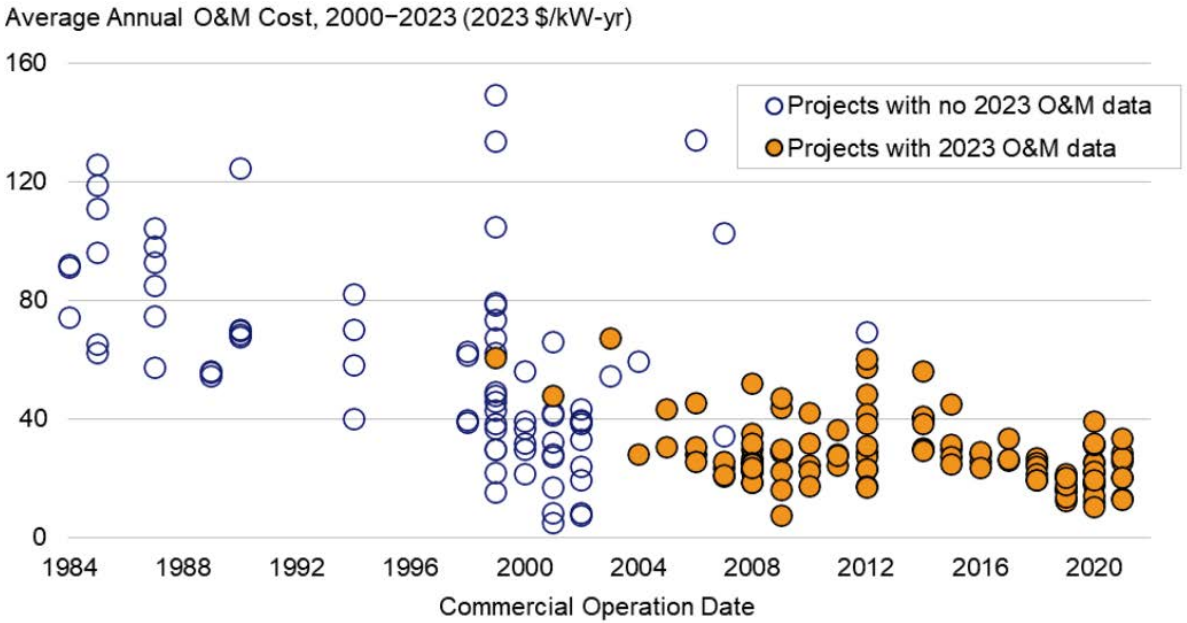


Parameter	Value (2023$/kW)
Wind Turbine CapEx	**1,091**
Rotor	337
Nacelle	477
Tower	276
BOS CapEx	**582**
Engineering and development	36
Project management	14
Foundation	120
Site access, staging, and facilities	47
Assembly and installation	100
Electrical infrastructure	72
Wind turbine transport	194
Soft Cost	**295**
Construction finance	111
Contingency*	54
Wind turbine warranty	130
Total CapEx	**1,968**

- Turbine component cost estimates are derived from recent updates to NREL's Wind Plant Integrated Systems Design and Engineering Model (WISDEM®) https://github.com/WISDEM/WISDEM.
- BOS component cost estimates are obtained from the Land-based Balance of System Systems Engineering (LandBOSSE) model (Eberle et al. 2019).
- Construction financing assumptions are from the 2024 Annual Technology Baseline atb.nrel.gov.

* Contingency category also includes insurance, permitting, bonding, and markup estimates

Land-Based Wind Plant Operational Expenditures Estimate and Historical Data



Parameter	Value
Estimated OpEx	$43/kW-yr

All-in project OpEx estimates informed by updated analysis conducted in the 2024 Annual Technology Baseline (atb.nrel.gov).

Average O&M costs for available data years from 2000 to 2023, by commercial operation date.

Source: Wiser and Millstein (2024)

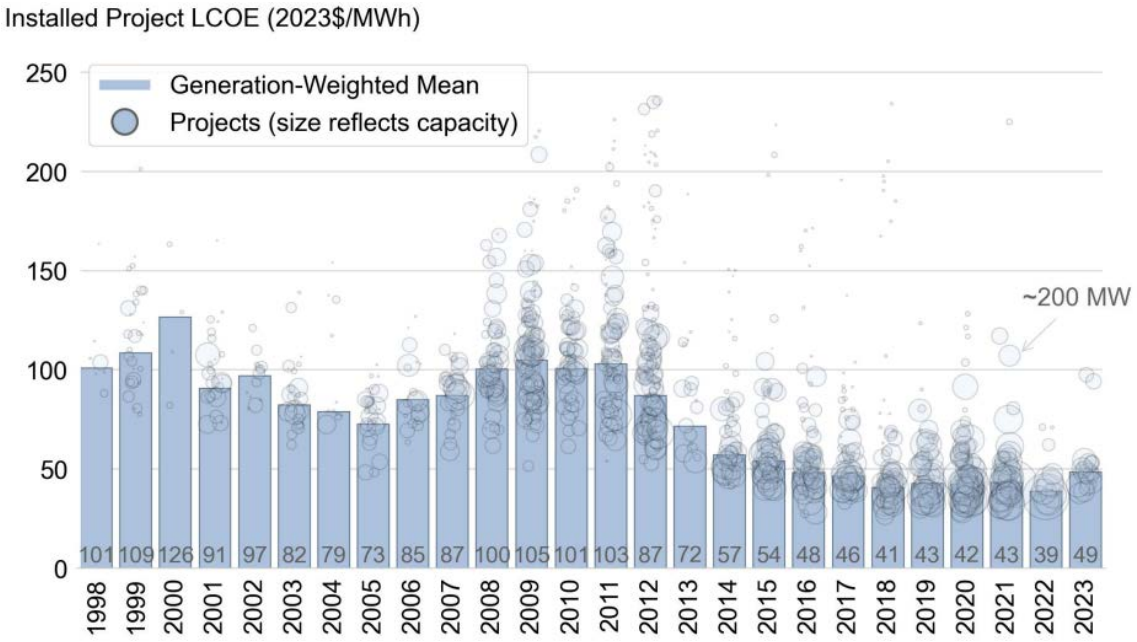
Note: O&M data reported in the chart do not include all operating costs.

Land-Based Wind Project Financial Assumptions

Parameter	Nominal Value	Real Value
Weighted average cost of capital	6.25%	3.66%
Capital recovery factor	8.01%	6.17%
Fixed charge rate (FCR)	8.43%	6.5%

- The economic evaluation of wind energy investments in this analysis uses the FCR method from NREL's Annual Technology Baseline and Standard Scenarios web page: atb.nrel.gov.
- The FCR represents the amount of annual revenue required to pay the carrying charge as applied to the CapEx on that investment during the expected project economic life and is based on the capital recovery factor (CRF) but also reflects corporate income taxes and depreciation.
- The analysis assumes the reference project operates for 25 years, a 5-year Modified Accelerated Cost Recovery System (MACRS) depreciation schedule, and an inflation rate of 2.5%.
- Additional financial assumption details are displayed in the Appendix.

LCOE for Representative Land-Based Wind Plant and Historical Data



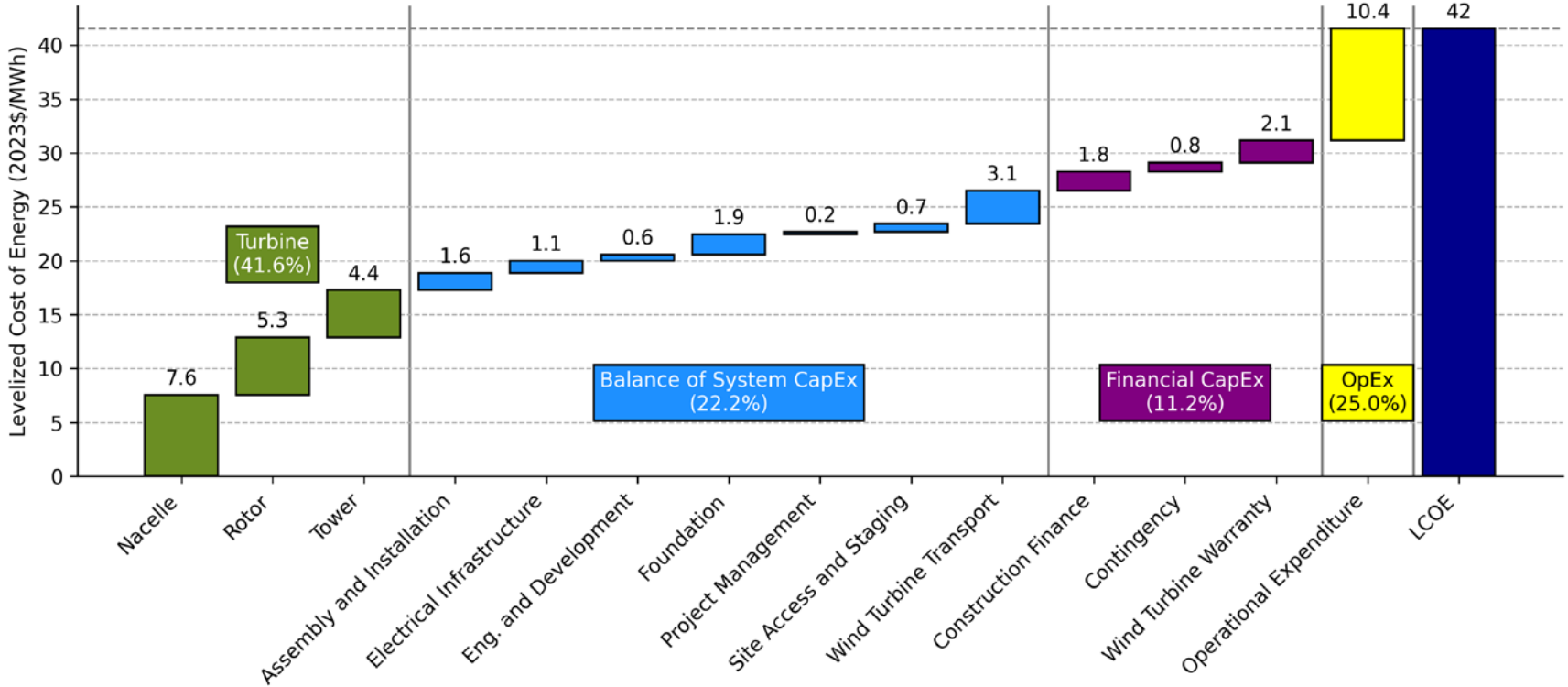
Estimated levelized cost of wind energy for actual wind projects by commercial operation date.

Source: Wiser and Millstein (2024)

Parameter	Value
Wind turbine rating	3.3 MW
Capital expenditures	$1,968/kW
Fixed charge rate (real)	6.5%
Operational expenditures	$43/kW/yr
Net annual energy production	4,104 MWh/MW/yr
Calculated levelized cost of energy	$42/MWh

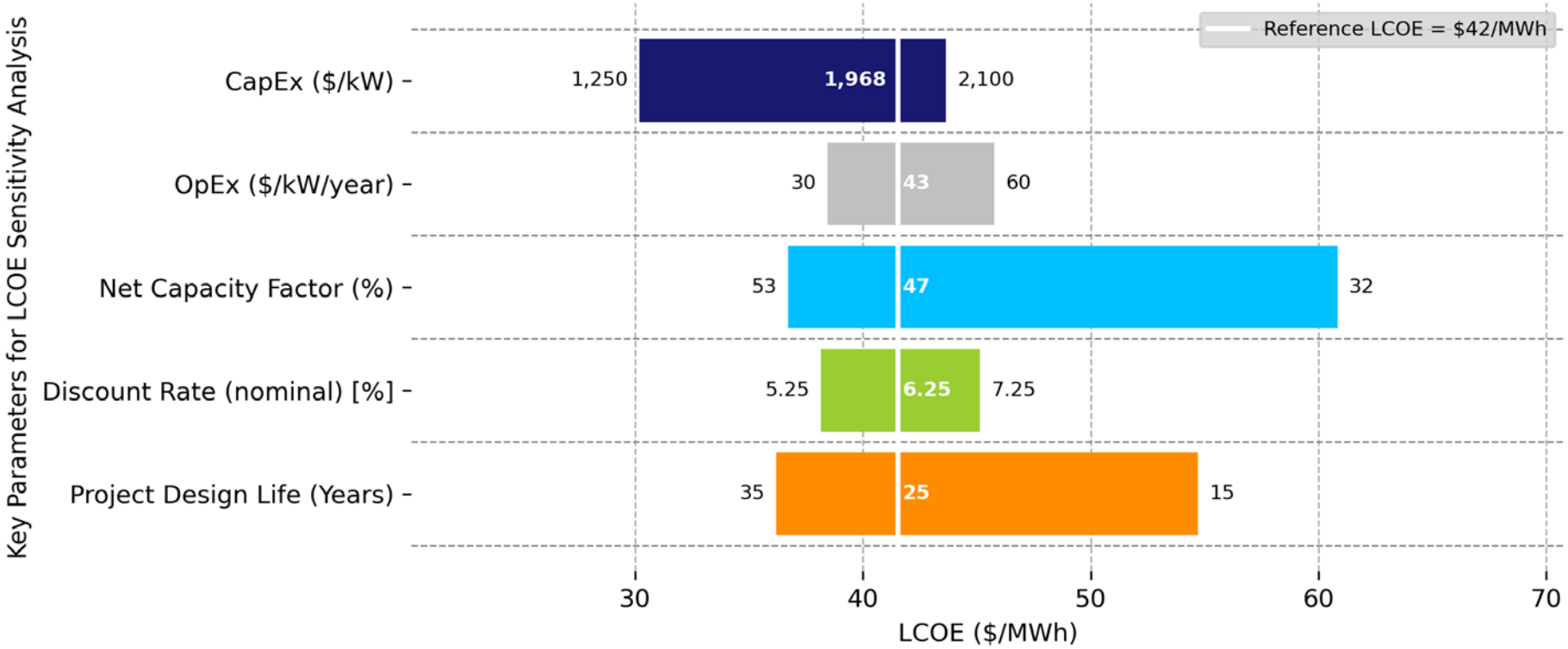
Modeled cost and performance data using the methods presented in the 2024 Annual Technology Baseline (atb.nrel.gov) to calculate LCOE.

LCOE Breakdown for Reference Land-Based Wind Plant



Note: The “Contingency” cost category also includes insurance, permitting, bonding, and markup estimates. “Operational Expenditure” includes maintenance cost.
Eng. = Engineering

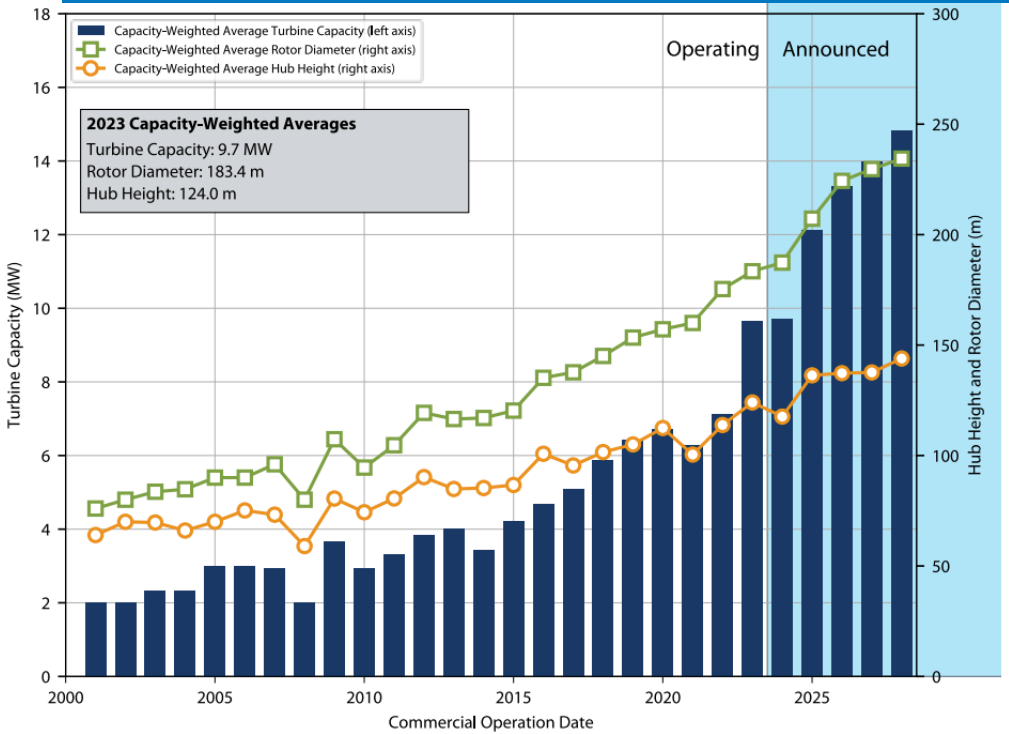
Range of LCOE Parameters for Land-Based Wind



Note: The reference LCOE reflects a representative industry LCOE. Changes in LCOE for a single variable can be understood by moving to the left or right along a specific variable. Values on the *x*-axis indicate how the LCOE will change as a given variable is altered and all others are assumed constant (i.e., remain reflective of the reference project).

4. Offshore Wind Energy

2023 Market Average Offshore Wind Turbine and Representative Wind Plant



Global capacity-weighted average turbine rating, hub height, and rotor diameter for offshore wind projects in 2023.

Source: *Offshore Wind Market Report: 2024 Edition* (McCoy et al. 2024)

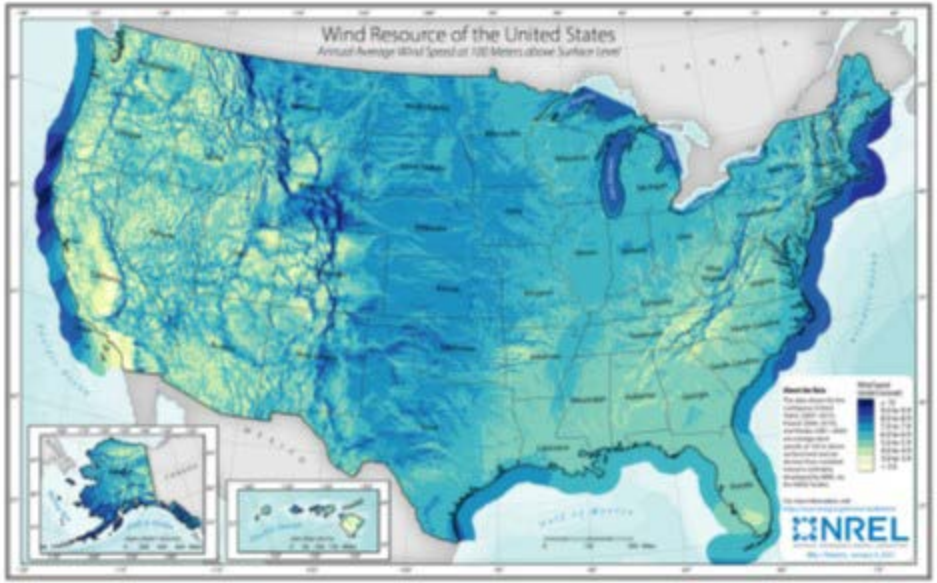
Parameter	Value
Wind turbine rating	12.0 MW
Rotor diameter	216 m
Hub height	137 m
Specific power	327 W/m^2
Wind plant capacity	600 MW
Number of turbines	50

Representative turbine parameters and power curves available on GitHub

- Global capacity-weighted average turbine rating in 2023 was 9.7 MW as the global market has begun adopting machines in the range of 12–15 MW (McCoy et al. 2024).
- The first commercial-scale offshore wind projects installed in the United States selected 11-MW (South Fork Wind and Revolution Wind) and 13-MW (Vineyard Wind I) turbines.

Offshore Wind Reference Wind Sites and Wind Plant Performance

- The fixed-bottom offshore wind reference project represents near-term development in the U.S. Northeast.
- The floating offshore wind reference site represents the first leases in California.

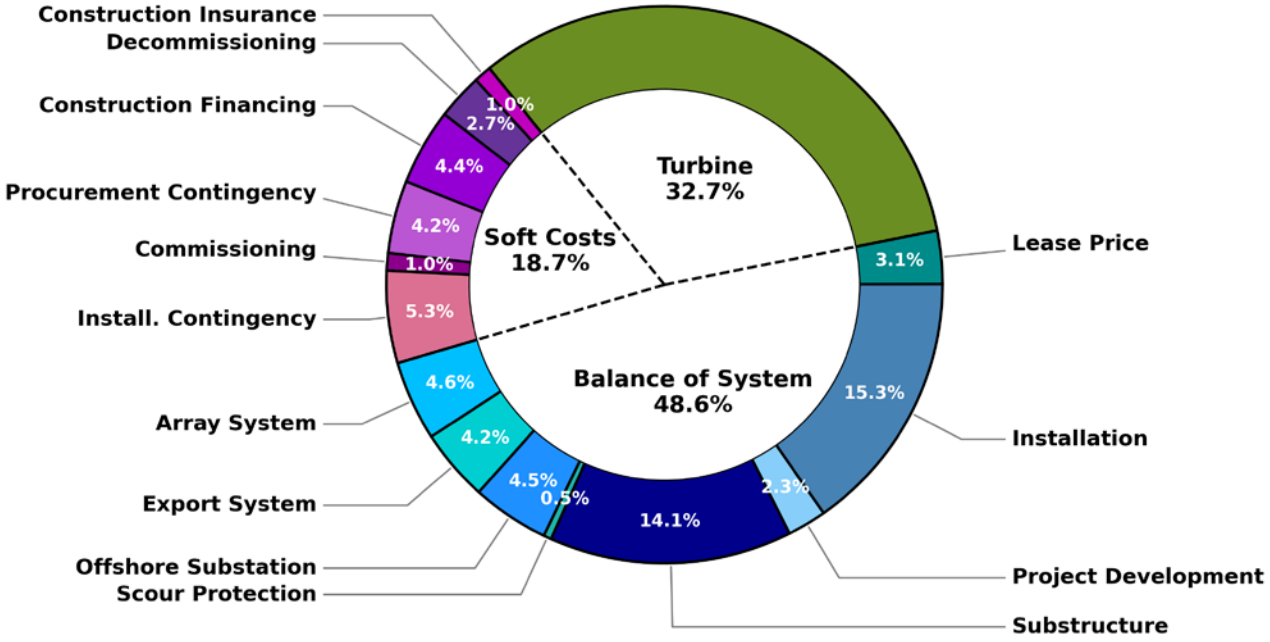


Wind resource of the United States, annual average wind speed at 100 m above surface level.

Map by Billy J. Roberts, NREL; more information at https://windexchange.energy.gov/maps-data/324

Parameter	Fixed-Bottom	Floating	Units
Water depth	34	739	m
Export cable length	50	36	km
Annual average wind speed at 50 m	8.43	7.67	m/s
Annual average wind speed at hub height	9.05	8.24	m/s
Weibull k	2.1	2.1	factor
Shear exponent	0.1	0.1	#
Gross energy capture	5,081	4,205	MWh/MW/yr
Gross capacity factor	58.0	48.0	%
Total losses	15.5	20.7	%
Net energy capture	4,295	3,346	MWh/MW/yr
Net capacity factor	49.0	38.2	%

Fixed-Bottom Offshore Wind System CapEx Component Cost Breakdown



Parameter	Value (2023$/kW)
Turbine	**1,770**
BOS	**2,629**
Array system	251
Export system	227
Offshore substation	243
Scour protection	25
Substructure	764
Project development	123
Installation	830
Lease price	167
Soft Costs	**1,012**
Construction insurance	55
Decommissioning	145
Construction financing	240
Procurement contingency	228
Commissioning	55
Install. contingency	289
Total CapEx	**5,411**

BOS and soft cost estimates are obtained with the Offshore Renewables Balance of System and Installation Tool (ORBIT) (Nunemaker et al. 2020). Refer to https://github.com/WISDEM/ORBIT.
Note: Values rounded to the nearest dollar, and "Install." indicates installation.

Relative Value of Manufactured Components for an Offshore Wind Project

- The U.S. Department of the Treasury (2023) issued guidance listing the Applicable Project Components (APC) for an offshore wind facility. The table on the next slide estimates the percent cost contribution of each APC for a representative offshore wind project. It also provides a more detailed list of major components under each APC and estimates the percent cost contribution of each major component in the representative offshore wind project.
- These relative costs are based on empirical data, NREL's Wind Plant Integrated Systems Design and Engineering Model (WISDEM®) (https://github.com/WISDEM/WISDEM) and the Offshore Renewables Balance of System and Installation Tool (ORBIT) (https://github.com/WISDEM/ORBIT).

Relative Value of Manufactured Components for an Offshore Wind Project

Applicable Project Component (APC)[1]	Percent Cost Contribution From Each APC (%)[2]	Major APC Components[2]	Percent Cost Contribution From Each Major Component (%)[2]
Turbine	51.4%	Nacelle	28.5%
		Blades	13.1%
		Hub	4.8%
		Power converter	2.4%
		Production	2.6%
Monopile	16.0%	Tubular monopile sections[3]	14.1%
		Production	1.9%
Transition piece	11.9%	Tubular transition piece section[3]	4.3%
		Personnel access system[4]	7.1%
		Production	0.5%
Export cable	7.9%	Armor	1.3%
		Insulated conductor	4.4%
		Sheathing	1.3%
		Production	0.9%
Array cable	2.6%	Armor	0.4%
		Insulated conductor	1.5%
		Sheathing	0.4%
		Production	0.3%
Offshore substation	9.4%	Electrical system[5]	3.3%
		Topside	5.6%
		Production	0.5%
Wind tower flange	0.8%	Preform	0.6%
		Production	0.2%

[1] The list of offshore wind APCs is provided in U.S. Department of the Treasury (2023).

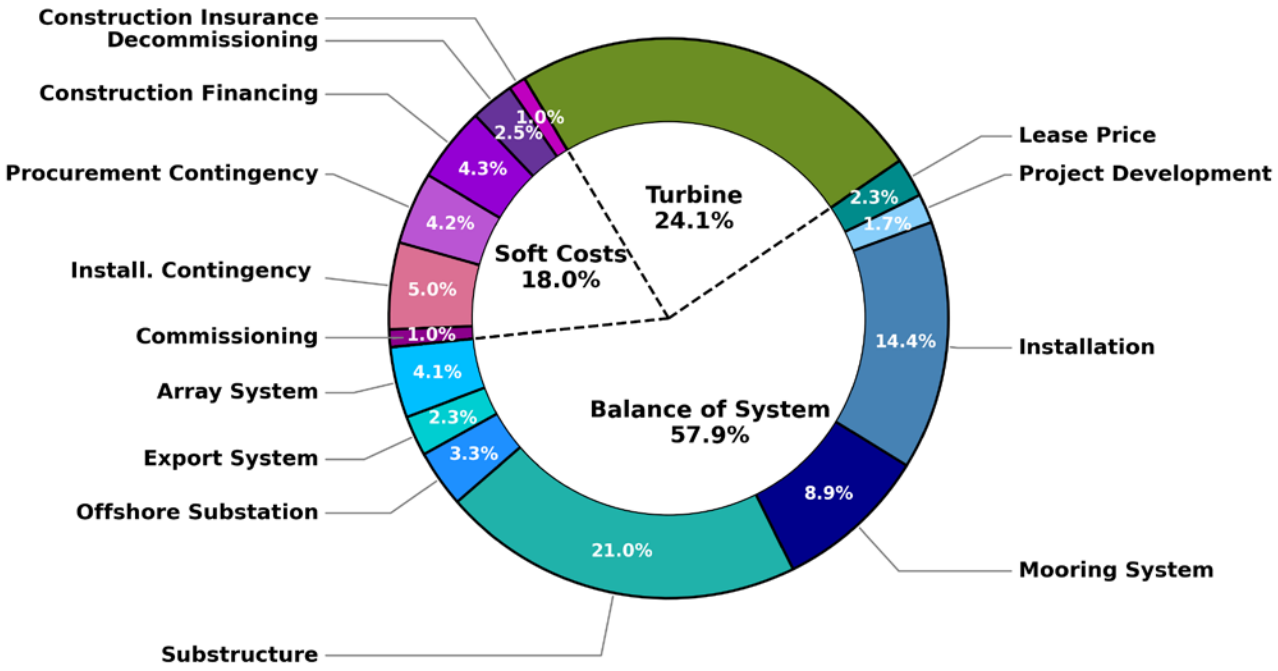
[2] The relative cost contributions and list of major components were developed by NREL.

[3] Monopiles and transition pieces comprise several tubular steel sections that are welded together, integrated, and then finished. Transition pieces are further outfitted with personnel access systems prior to installation. Some transition pieces may be integrated with a monopile in a single facility.

[4] A personnel access system includes internal platforms, external platforms, and boat landings.

[5] The electrical system includes transformers, switchgear, shunt reactors (high-voltage alternating current substations only), and converters (high-voltage direct current substations only).

Floating Offshore Wind System Component Cost Breakdown



Parameter	Value (2023$/kW)
Turbine	**1,770**
BOS	**4,254**
Array system	301
Export system	171
Offshore substation	243
Substructure	1,541
Mooring system	651
Installation	1,058
Project development	123
Lease price	167
Soft Costs	**1,325**
Construction insurance	74
Decommissioning	184
Construction financing	319
Procurement contingency	307
Install. contingency	368
Commissioning	74
Total CapEx	**7,349**

BOS and soft cost estimates are obtained with ORBIT (Nunemaker et al. 2020). Refer to https://github.com/WISDEM/ORBIT.

Note: Values rounded to the nearest dollar, and "Install." indicates installation.

Fixed-Bottom and Floating Offshore Wind OpEx Estimates

- Fixed-bottom and floating offshore wind plant OpEx estimates are calculated with NREL's Windfarm Operations & Maintenance cost-Benefit Analysis Tool (WOMBAT) (Hammond and Cooperman 2022).
- WOMBAT is a scenario-based tool* that uses a discrete event simulation framework to calculate the costs associated with component failures, scheduled maintenance tasks, and mobilization of equipment to carry out repairs.
- OpEx modeling assumptions:
  - 30 full-time technicians assumed per project in both sites
  - Three crew transfer vessels, one cable lay vessel, and one diving support vessel per project
  - Fixed-bottom site employs an in situ repair strategy
  - Floating case executes replacements through a tow-to-port strategy, which is assumed to be less expensive than in situ repairs
  - Failure rates and costs associated with repairs and replacements informed by COREWIND (2021).

Parameter	Fixed Value ($/kW-yr)	Floating Value ($/kW-yr)
Maintenance	**113**	**69**
Labor (technicians)	5	5
Materials	2	4
Equipment (vessels)	105	61
Operations	**22**	**38**
Management administration	2	2
Port fees	1	17
Insurance	19	19
Total OpEx	**135**	**108**

Values rounded to the nearest dollar.

*Access the WOMBAT model on GitHub.

Fixed-Bottom and Floating Offshore Wind Project Financial Assumptions

Parameter	Nominal Value	Real Value
Weighted average cost of capital	6.61%	4.01%
Capital recovery factor	8.28%	6.41%
Fixed charge rate	8.74%	6.76%

- The data used to calculate the weighted average cost of capital (WACC) are collected by NREL based on conversations with project developers and industry financiers and provides a basis for WACC assumptions for the representative wind project in 2022.
- The WACC, CRF, and FCR are given in nominal and real terms using the after-tax WACC discount rate of 6.61% and 4.01%, respectively, a project design lifetime of 25 years, and a net present value depreciation factor of 84.0% (assuming a 5-year MACRS depreciation schedule).
- Detailed financial assumptions are displayed in the Appendix.

Note: The WACC for land-based wind is higher than for offshore wind because it considers the influences of the production tax credit and assumes a lower debt fraction.

2023 Offshore Wind Reference Plant LCOE Estimates

- **The LCOE values for the 2023 representative fixed-bottom and floating offshore wind plants are estimated at $117/MWh and $181/MWh, respectively.***
- LCOE is calculated with the formulation presented in NREL's Annual Technology Baseline and presented on Slide 15.

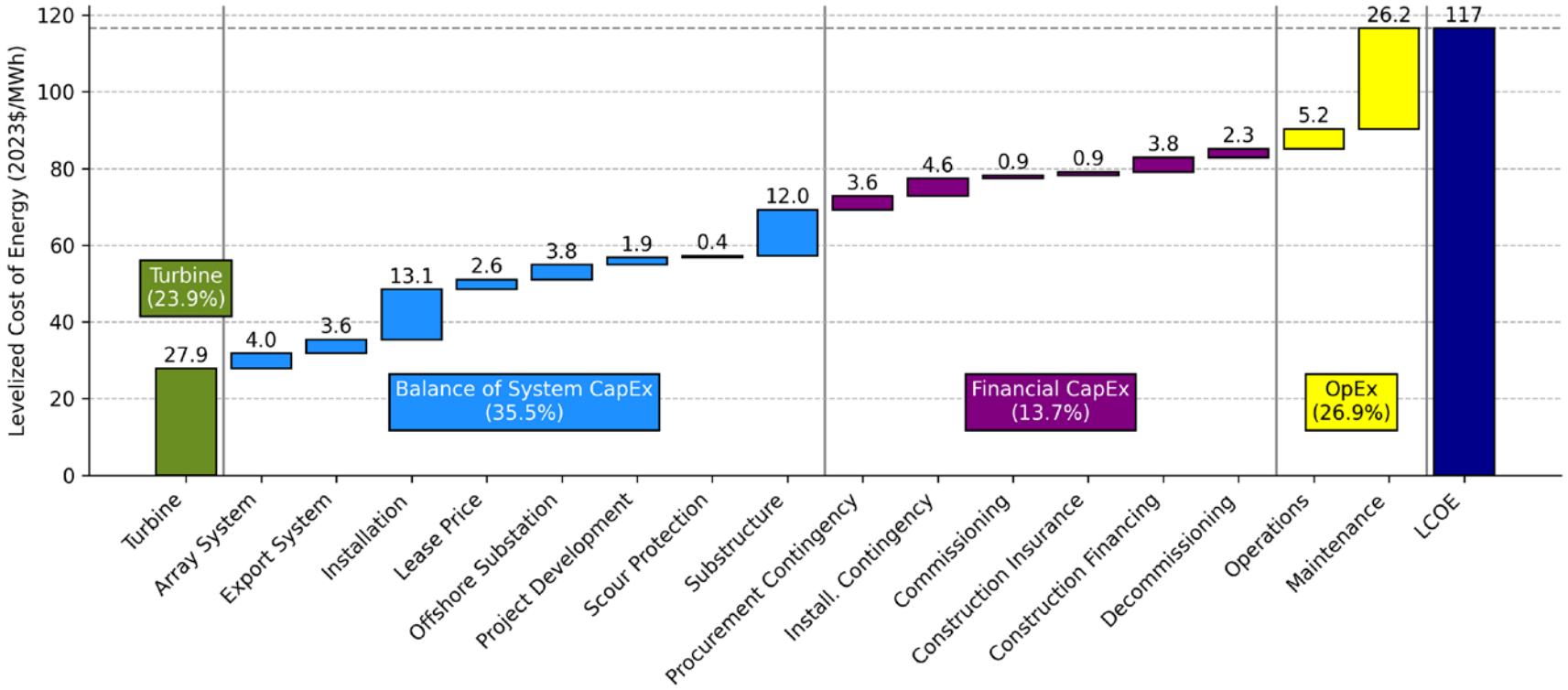
Parameter	Fixed-Bottom 12.0-MW Offshore Wind Turbine	Floating 12.0-MW Offshore Wind Turbine	Units
Capital expenditures	5,441	7,349	$/kW
Fixed charge rate (real)	6.76	6.76	%
Operational expenditures	135	108	$/kW/yr
Net annual energy production	4,295	3,346	MWh/MW/yr
Total LCOE	**117**	**181**	**$/MWh**

* The LCOE estimates given above rely on bottom-up cost modeling and assume mature supply chains for 600-MW projects with a 2023 COD. In 2023, several U.S. projects were under construction, but none of them were fully commissioned in that year (McCoy et al. 2024).

Readers should be cautious when comparing the above LCOE estimates with recent U.S. strike prices for the following reasons:

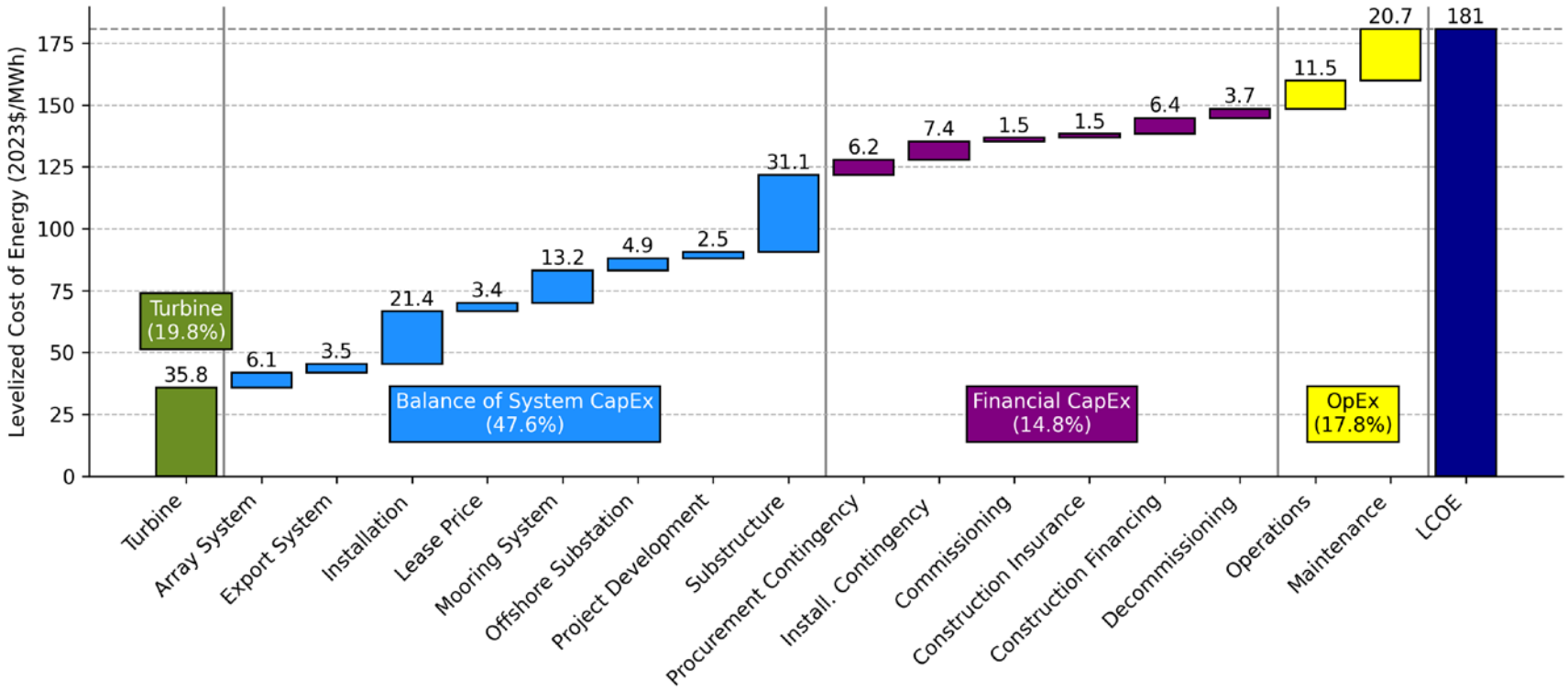
- LCOE and strike price are not the same thing. Developer profits and differences in the underlying technology, infrastructure, project structure, cost, performance, subsidy, and financing terms must be accounted when comparing LCOE and strike prices (Smart 2016; Beiter et al. 2021).
- Projects with different procurement timelines have varying levels of exposure to risks and inflationary pressures (DOE 2024). Expected CODs for recent solicitations range from 2026 to the early 2030s while the representative projects modeled in this report have an assumed COD in 2023.

Levelized Cost Breakdown for Reference Fixed-Bottom Offshore Wind Plant



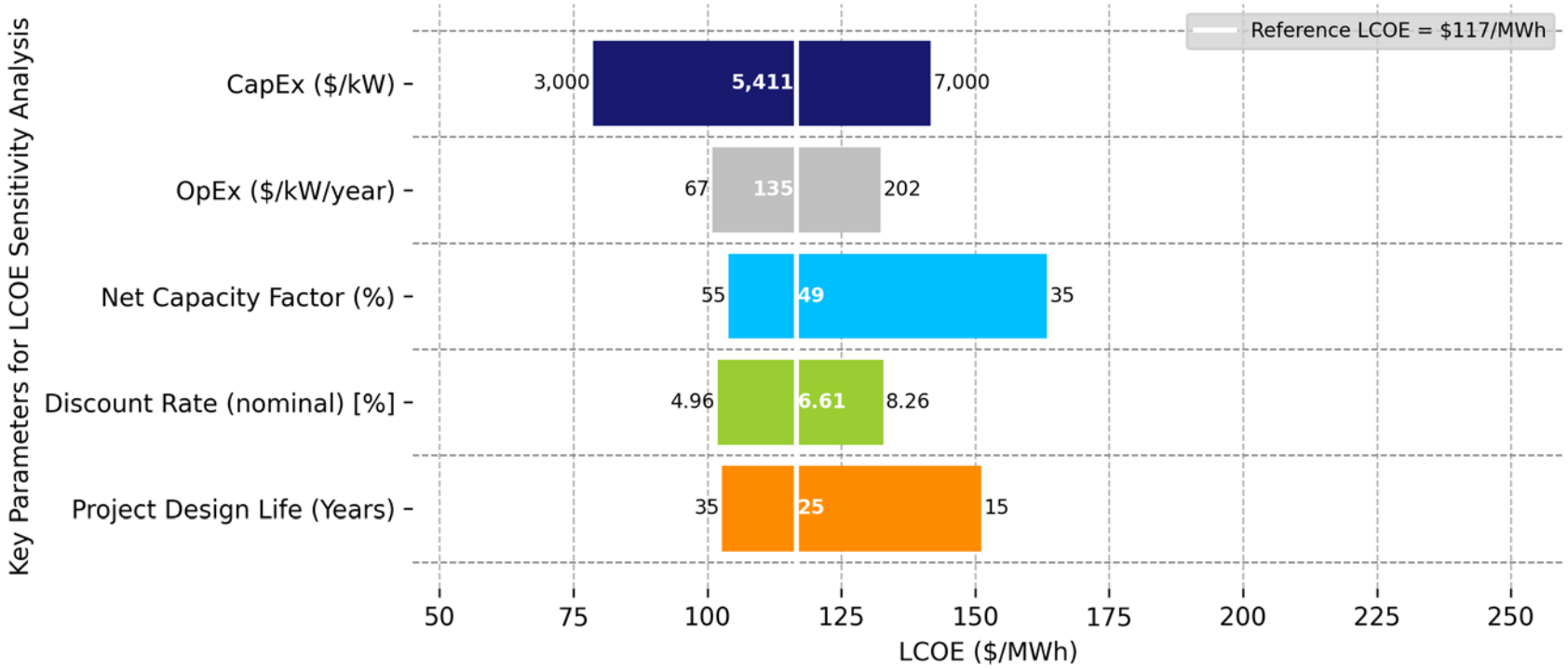
Note: The “Array System” cost includes costs associated with the procurement of the inter-array system cables of an offshore wind farm.

Levelized Cost Breakdown for Reference Floating Offshore Wind Plant



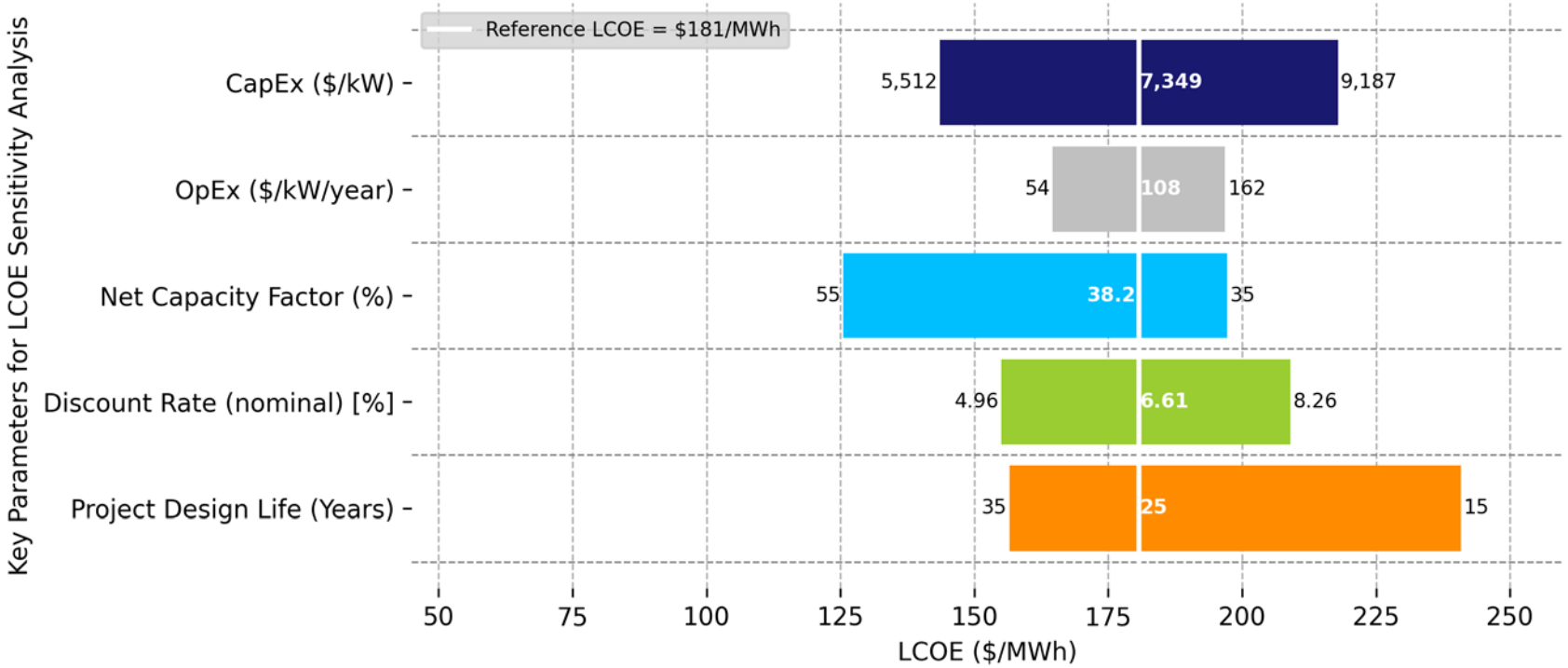
Note: The “Array System” cost includes costs associated with the procurement of the inter-array system cables of an offshore wind farm.

Range of LCOE Parameters for Fixed-Bottom Offshore Wind Platform



Note: The reference LCOE reflects a representative industry LCOE. Changes in LCOE for a single variable can be understood by moving to the left or right along a specific variable. Values on the *x*-axis indicate how the LCOE will change as a given variable is altered and all others are assumed constant (i.e., remain reflective of the reference project).

Range of LCOE Parameters for Floating Offshore Wind Platform



Note: The reference LCOE reflects a representative industry LCOE. Changes in LCOE for a single variable can be understood by moving to the left or right along a specific variable. Values on the *x*-axis indicate how the LCOE will change as a given variable is altered and all others are assumed constant (i.e., remain reflective of the reference project).

5. Distributed Wind Energy

Distributed Wind Turbine Characteristics for Residential, Commercial, and Large-Scale Projects

Parameter	Wind Turbine Class			Units
	Residential	Commercial	Large	
Wind turbine rating	20	100	1,500	kW
Rotor diameter	12.4	27.6	77	m
Hub height	30	40	80	m
Specific power	166	167	322	W/m^2
Number of wind turbines	1	1	1	-

Wind turbine classes are aligned with the *Distributed Wind Energy Futures Study* (McCabe et al. 2022).

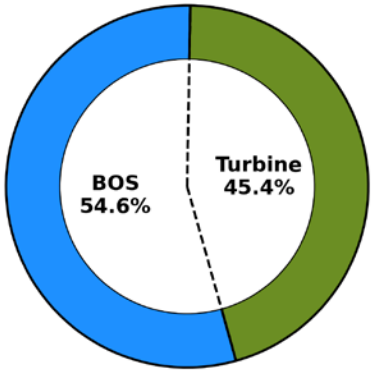
Distributed Wind Site Characteristics and Performance

Parameter	Wind Turbine Class			Units
	Residential	Commercial	Large	
Annual average wind speed at 50 m above surface level	6	6	6	m/s
Annual average wind speed at hub height	5.58	5.81	6.42	m/s
Weibull k	2	2	2	factor
Shear exponent	0.14	0.14	0.14	#
Gross energy capture	2,916	3,217	3,759	MWh/MW/yr
Gross capacity factor	33.3	36.7	42.9	%
Losses	6.86	6.86	6.86	%
Availability	95	95	95	%
Total losses	11.5	11.5	11.5	%
Net energy capture	2,580	2,846	3,326	MWh/MW/yr
Net capacity factor	29.5	32.5	38	%

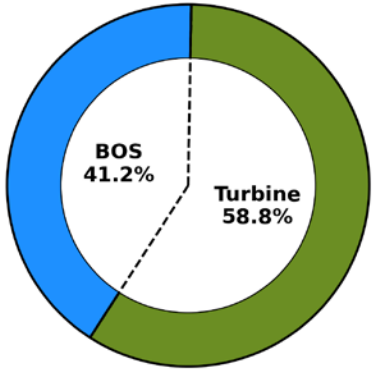
Residential and commercial wind turbines assume stall-regulated power curves; the large wind turbine assumes pitch-regulated power curve.
Power curve data available on https://github.com/NREL/turbine-models.

Distributed Wind Project Component Cost Breakdown and Estimated Operational Expenditures

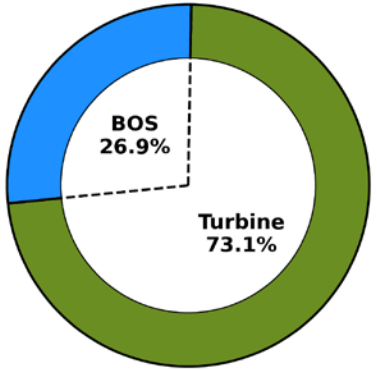
Residential (20 kW)



Commercial (100 kW)



Large (1,500 kW)



Parameter	Wind Turbine Class			Units
	Residential	Commercial	Large	
Wind turbine CapEx	3,932	4,001	2,459	$/kW
BOS CapEx	4,733	2,799	903	$/kW
Total CapEx	8,665	6,800	3,362	$/kW
OpEx	41	41	41	$/kW/yr

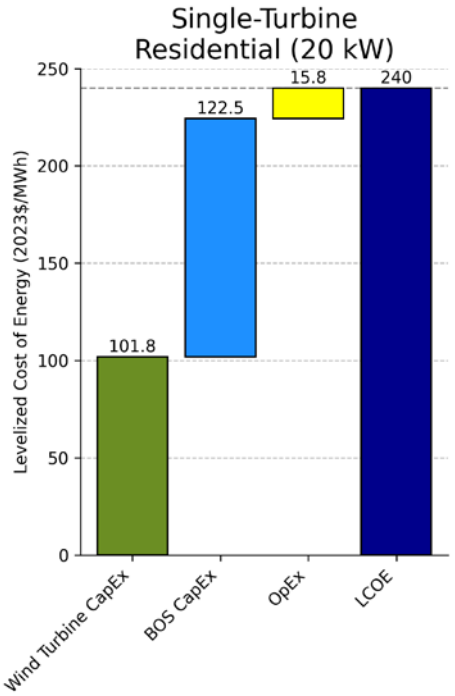
- BOS component cost estimates are obtained from the LandBOSSE model (Eberle et al. 2019).
- Because CapEx data are scarce for distributed wind projects, further cost details on the individual system components are not presented.
- OpEx market data are not widely available for distributed wind projects; therefore, $41/kW/yr is assumed for each wind class and is aligned with the 2024 ATB atb.nrel.gov.

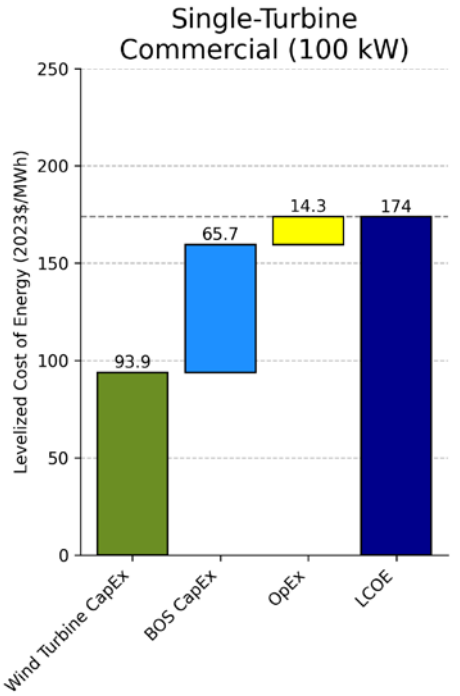
Distributed Wind Project Financial Assumptions

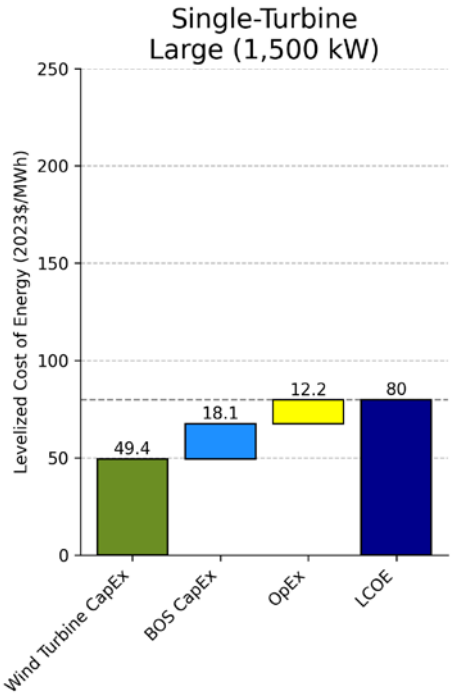
Parameter	Nominal	Real
Weighted average cost of capital (%)	6.5	3.9
Capital recovery factor (%)	8.2	6.33
Fixed charge rate (%)	8.64	6.68

- The economic evaluation of wind energy investments in this analysis uses the FCR method used in NREL's Annual Technology Baseline and Standard Scenarios web page: atb.nrel.gov.
- The FCR represents the amount of annual revenue required to pay the carrying charge as applied to the CapEx on that investment during the expected project economic life and is based on the CRF but also reflects corporate income taxes and depreciation.
- The analysis assumes the reference projects operate for 25 years and a 5-year MACRS depreciation schedule; for simplicity, financial assumptions are assumed to be the same for each wind class and are aligned with the assumptions in the 2024 Annual Technology Baseline atb.nrel.gov.
- Additional financial assumption details are displayed in the Appendix.

LCOE Breakdown for Reference Distributed Wind Projects







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7. Appendix

Methodology for Estimating the Percent Cost Contribution of Major Components in a Fixed-Bottom Offshore Wind Facility

- The U.S. Department of Treasury (2023) provides a list of Applicable Project Components (APCs) for an offshore wind facility.
- NREL developed what we believe to be a representative list of major components, including key subassemblies and systems, that contribute significantly to the cost of the APCs.
- We used NREL engineering and cost models (including WISDEM and ORBIT), coupled with empirical data, to estimate the cost of each major component for a range of turbine and plant configurations, and then reviewed these cost estimates with offshore wind manufacturers.
- Based on these results, we estimated the relative (or percentage) cost contribution of each manufactured component for the following reference offshore wind project. Note that this project definition differs from the project used in the majority of the report so that it can be more representative of upcoming offshore wind projects in the United States.

Parameter	Value
Plant capacity	1,200 MW
Turbine rating	15 MW
Water depth	40 m
Cable distance to landfall	70 km
Export cable voltage	220 kV (HVAC), OR 320 kV (HVDC)
Array cable voltage	66 kV

kV = kilovolt; HVAC = high-voltage alternating current; HVDC = high-voltage direct current

Land-Based Wind Reference Project Details

Parameter	Units	Value	Notes
Wind Plant and Reference Site Characteristics			
Wind plant capacity	MW	200	Representative of current commercial-scale projects atb.nrel.gov
Number of turbines	-	61	
Turbine rating	MW	3.3	
Rotor diameter	m	148	
Hub height	m	100	
Specific power	W/m^2	192	Calculation
Annual average wind speed at 50 m	m/s	7.25	Reference site wind speed
Annual average wind speed at hub height	m/s	8.01	Between IEC class III (7.5 m/s) and IEC class II (8.5 m/s)
Weibull k factor	-	2	
Shear exponent	-	0.143	Shear for neutral stability conditions
Total system losses	%	18.8	atb.nrel.gov
Net energy capture	MWh/MW/yr	4,104	System Advisor Model™ (SAM) calculation
Net capacity factor	%	46.9	

Land-Based Wind System CapEx Breakdown

Parameter	Value ($/kW)	Notes
CapEx		
Total CapEx	1,968	Calculation
Turbine	1,091	Wind Plant Integrated Systems Design and Engineering Model (WISDEM, https://github.com/WISDEM/WISDEM)
Rotor module	337	
Blades	282	
Pitch assembly	13	
Hub assembly	42	
Nacelle module	477	
Nacelle structural assembly	76	
Drivetrain assembly	236	
Nacelle electrical assembly	137	
Yaw assembly	28	
Tower module	276	

(Continued on next slide)

Land-Based Wind System CapEx Breakdown (continued)

Parameter	Value ($/kW)	Notes
CapEx		
Balance of system	582	Land-based Balance of System Systems Engineering [LandBOSSE] (Eberle et al. 2019)
Development	36	
Engineering and project management	14	
Foundation	120	
Site access and staging	47	
Assembly and installation	100	
Electrical infrastructure	72	
Wind turbine transport	194	
Soft costs	295	
Construction finance	111	atb.nrel.gov
Contingency	54	Includes insurance, permitting, bonding, and markup estimates
Wind turbine warranty	130	Assumes 2-year warranty

Land-Based Wind OpEx and Financing Terms

Parameter	Units	Value	Notes
OpEx			
Total OpEx	$/kW/year	43	atb.nrel.gov
Financials			
Project design life	Years	25	Project life assumption for Government Performance and Reporting Act (GPRA) reporting
Tax rate (combined state and federal)	%	25.7	atb.nrel.gov
Inflation rate	%	2.5	
Interest during construction (nominal)	%	7.0	
Construction finance factor	%	106.0	Calculation
Debt fraction	%	72.4	atb.nrel.gov
Debt interest rate (nominal)	%	7	
Return on equity (nominal)	%	9	
WACC (nominal; after-tax)	%	6.25	Calculation
WACC (real; after-tax)	%	3.66	
Capital recovery factor (nominal; after-tax)	%	8.01	
Capital recovery factor (real; after-tax)	%	6.17	
Depreciable basis	%	100	Simplified depreciation schedule
Depreciation schedule	-	5-year MACRS	Modified Accelerated Cost Recovery System (MACRS) is standard for U.S. wind projects
Depreciation adjustment (net present value [NPV])	%	84.7	Calculation
Project finance factor	%	105	
FCR (nominal)	%	8.43	
FCR (real)	%	6.50	
Levelized cost of energy	$/MWh	42	Calculation

Fixed-Bottom Offshore Wind Reference Project Details

Assumption	Units	Value	Notes
Wind plant characteristics			
Wind plant capacity	MW	600	Representative of commercial-scale projects
Number of turbines	-	50	Calculation
Turbine rating	MW	12	Informed by *Offshore Wind Market Report: 2024 Edition* (McCoy et al. 2024) and early U.S. fixed-bottom offshore wind projects
Rotor diameter	m	216	
Hub height	m	137.0	
Specific power	W/m^2	327	Calculation
Water depth	m	34	Representative fixed-bottom offshore site for COE Review
Substructure type	-	Monopile	
Distance from shore	km	50	
Cut-in wind speed	m/s	3	
Cut-out wind speed	m/s	25	
Average annual wind speed at 50 m	m/s	8.4	
Average annual wind speed at hub height	m/s	9.0	
Shear exponent	-	0.10	
Weibull k	-	2.1	
Total system losses	%	15.5	Offshore Regional Cost Analyzer (ORCA) (based on Beiter et al. 2016)
Gross energy capture	MWh/MW/year	5,081	Calculation
Net energy capture	MWh/MW/year	4,295	
Gross capacity factor	%	58.0	Computed with FLORIS
Net capacity factor	%	49.0	

Fixed-Bottom Offshore Wind System CapEx Breakdown

Assumption	Value ($/kW)	Notes
CapEx		
Total CapEx	5,411	
Turbine	1,770	Informed by collaborations with industry partners
Rotor-nacelle assembly	1,487	
Tower	283	
Balance of system	2,629	BOS Costs computed with ORBIT (Nunemaker et al. 2020)
Development	121	
Project management	2	
Substructure and foundation	788	
Substructure	232	
Foundation	556	
Electrical infrastructure	1,267	
Array cable system	477	
Export cable system	532	
Grid connection	258	
Assembly and installation	284	
Turbine installation	112	
Substructure and foundation installation	172	
Soft Costs	1,012	Soft Costs computed using same methodology as ORCA (Beiter et al. 2016)
Insurance during construction	55	
Decommissioning bond	145	
Construction finance	240	
Sponsor contingency	517	
Procurement contingency	228	
Installation contingency	289	
Project completion / commissioning	55	

Fixed-Bottom Offshore Wind OpEx and Financing Terms

Assumption	Units	Value	Notes
OpEx			
Total OpEx	$/kW/year	135	Calculated with WOMBAT
Operations (pretax)	$/kW/year	22	
Maintenance	$/kW/year	113	
Financials			
Project design life	Years	25	Offshore wind project life for GPRA reporting
Tax Rate (combined state and federal)	%	26	Updated based on conversations with industry partners
Inflation rate	%	2.5	
Debt fraction	%	73	
Debt interest rate (nominal)	%	7.0	
Return on equity (nominal)	%	10.5	
WACC (nominal; after-tax)	%	6.61	Calculation
WACC (real; after-tax)	%	4.01	
Capital recovery factor (nominal; after-tax)	%	8.28	
Capital recovery factor (real; after-tax)	%	6.41	
Depreciable basis	%	100	Simplified depreciation schedule
Depreciation schedule	-	5-year MACRS	Standard for U.S. wind projects
Depreciation adjustment (NPV)	%	84.0	Calculation
Project finance factor	%	106	
FCR (nominal)	%	8.74	
FCR (real)	%	6.76	
Levelized cost of energy	$/MWh	117	Calculation

Floating Offshore Wind Reference Project Details

Assumption	Units	Value	Notes
Wind plant characteristics			
Wind plant capacity	MW	600	Representative of commercial-scale projects
Number of turbines	-	50	Calculation
Turbine rating	MW	12	Informed by *Offshore Wind Market Report: 2024 Edition* (McCoy et al. 2024) and early U.S. fixed-bottom offshore wind projects
Rotor diameter	m	216	
Hub height	m	137.0	
Specific power	W/m^2	327	Calculation
Water depth	m	739	Representative floating site for Cost of Wind Energy Review
Substructure type	-	Semisubmersible	
Distance from shore	km	36	
Cut-in wind speed	m/s	3	
Cut-out wind speed	m/s	25	
Average annual wind speed at 50 m	m/s	7.7	
Average annual wind speed at hub height	m/s	8.5	
Shear exponent	-	0.10	
Weibull k	-	2.1	
Total system losses	%	20.7	Offshore Regional Cost Analyzer (ORCA) (based on Beiter et al. 2016)
Gross energy capture	MWh/MW/year	4,205	Calculation
Net energy capture	MWh/MW/year	3,346	
Gross capacity factor	%	48.0	Computed with FLORIS
Net capacity factor	%	38.2	

Floating Offshore Wind System CapEx Breakdown

Assumption	Value ($/kW)	Notes
	CapEx	
Total CapEx	7,349	
Turbine	1,770	Informed by collaborations with industry partners
Rotor-nacelle assembly	1,487	
Tower	283	
Balance of system	4,254	BOS Costs computed with ORBIT (Nunemaker et al. 2020)
Development	121	
Project management	2	
Substructure and foundation	2,192	
Substructure	1,541	
Foundation	651	
Electrical infrastructure	1,428	
Array cable system	654	
Export cable system	500	
Grid connection	274	
Assembly and installation	345	
Turbine installation	0	
Substructure and foundation installation	345	
Lease price	167	
Soft Costs	1,325	Soft Costs computed using same methodology as ORCA (Beiter et al. 2016)
Insurance during construction	74	
Decommissioning bond	184	
Construction finance	319	
Sponsor contingency	675	
Procurement contingency	307	
Installation contingency	368	
Project completion / commissioning	74	

Note: Floating turbine installation costs are included in the “Substructure and foundation installation” line item since the turbine is integrated with the substructure at the quayside before the assembly is towed out and installed at the project site.

Floating Offshore Wind OpEx and Financing Terms

Assumption	Units	Value	Notes
OpEx			
Total OpEx	$/kW/year	108	Calculated with WOMBAT
Operations (pretax)	$/kW/year	38	
Maintenance	$/kW/year	69	
Financials			
Project design life	Years	25	Offshore wind project life for GPRA reporting
Tax rate (combined state and federal)	%	26	Updated based on conversations with industry partners
Federal	%	21	
State	%	4.7	
Inflation rate	%	2.5	
Debt fraction	%	73	
Debt interest rate (nominal)	%	7.0	
Return on equity (nominal)	%	10.5	
WACC (nominal; after-tax)	%	6.61	Calculation
WACC (real; after-tax)	%	4.01	
Capital recovery factor (nominal; after-tax)	%	8.28	
Capital recovery factor (real; after-tax)	%	6.41	
Depreciable basis	%	100	Simplified depreciation schedule
Depreciation schedule	-	5-year MACRS	Standard for U.S. wind projects
Depreciation adjustment (NPV)	%	84.0	Calculation
Project finance factor	%	106	
FCR (nominal)	%	8.74	
FCR (real)	%	6.76	
Levelized cost of energy	$/MWh	181	Calculation

Distributed Wind Reference Project Details

Parameter	Units	20-kW Value	100-kW Value	1,500-kW Value	Notes
Wind Plant Characteristics					
Wind plant capacity	kW	20	100	1,500	Representative of residential distributed wind project
Number of turbines	-	1	1	1	
Turbine rating	kW	20	100	1,500	*Assessing the Future of Distributed Wind: Opportunities for Behind-the Meter Projects* (Lantz et al. 2016)
Rotor diameter	m	12.4	27.6	77	
Hub height	m	30	40	80	
Specific power	W/m^2	166	167	322	Calculation
Cut-in wind speed	m/s	3	3	3	Typical turbine characteristics
Cut-out wind speed	m/s	20	25	25	
Annual average wind speed at 50 m	m/s	6.00	6.00	6.00	Reference site wind speed
Annual average wind speed at hub height	m/s	5.58	5.81	6.42	IEC class IV
Weibull k factor	-	2.0	2.0	2.0	
Shear exponent	-	0.143	0.143	0.143	Shear for neutral stability conditions
Altitude above mean sea level	m	0	0	0	Altitude at turbine foundation
Losses	%	7	7	7	Informed by "Competitiveness Improvement Project" (https://www.nrel.gov/wind/competitiveness-improvement-project.html)
Availability	%	95	95	95	
Net energy capture	kWh/kW/yr	2,580	2,846	3,326	Calculation in Openwind (UL website: https://aws-dewi.ul.com/software/openwind/)
Net capacity factor	%	29.5	32.5	38.0	

Distributed Wind System CapEx, OpEx, and Financials Breakdown

Parameter	Units	20-kW Value	100-kW Value	1,500-kW Value	Notes
CapEx					
Total CapEx	$/kW	8,665	6,800	3,362	
Turbine	$/kW	3,932	4,001	2,459	atb.nrel.gov
Balance of system	$/kW	4,733	2,799	903	*NREL's Balance-of-System Cost Model for Land-Based Wind* (Eberle et. al., 2019)
OpEx					
Total OpEx	$/kW/year	41	41	41	*Assessing the Future of Distributed Wind: Opportunities for Behind-the Meter Projects* (Lantz et al. 2016)
Financials					
Project design life	Years	25	25	25	Project life for Government Performance and Reporting Act (GPRA) reporting
Tax Rate (combined state and federal)	%	25.7	25.7	25.7	atb.nrel.gov
Inflation rate	%	2.5	2.5	2.5	
Debt fraction	%	73	73	73	*Assessing the Future of Distributed Wind: Opportunities for Behind-the Meter Projects* (Lantz et al. 2016)
Debt interest rate (nominal)	%	7	7	7	Lawrence Berkeley National Laboratory 2021 financial analysis
Return on equity (nominal)	%	10	10	10	
WACC (nominal; after-tax)	%	6.5	6.5	6.5	Calculation
WACC (real; after-tax)	%	3.9	3.9	3.9	
Capital recovery factor (nominal; after-tax)	%	8.2	8.2	8.2	
Capital recovery factor (real; after-tax)	%	6.33	6.33	6.33	
Depreciable basis	%	100	100	100	Simplified depreciation schedule
Depreciation schedule	-	5-year MACRS	5-year MACRS	5-year MACRS	
Depreciation adjustment (NPV)	%	84.2	84.2	84.2	Calculation
Project finance factor	%	105	105	105	
FCR (nominal)	%	8.64	8.64	8.64	
FCR (real)	%	6.68	6.68	6.68	
Levelized cost of energy	$/MWh	240	174	80	Calculation

Thank You

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