# 2022 Cost of Wind Energy Review

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December 2023

*Photo from iStock-627281636*

# 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) and Daniel Beals of Allegheny Science and Technology (contractor to WETO) for reviewing prior versions of this presentation. Thank you to Ryan Wiser and Mark Bolinger (Lawrence Berkeley National Laboratory) and Alice Orrell (Pacific Northwest National Laboratory) for their analysis of wind project market data that informed this analysis. Thanks also to Philipp Beiter, Eric Lantz, Rob Hammond, Aubryn Cooperman, Matt Shields, Owen Roberts, and Annika Eberle (National Renewable Energy Laboratory) for their technical guidance and 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

| | |
|---|---|
| AEP | annual energy production |
| ATB | Annual Technology Baseline |
| BOS | balance of system |
| CapEx | capital expenditures |
| COD | commercial operations date |
| CRF | capital recovery factor |
| CSM | Cost and Scaling Model |
| DOE | U.S. Department of Energy |
| DW | distributed wind |
| FCR | fixed charge rate |
| FY | fiscal year |
| GPRA | Government Performance and Results Act |
| GW | gigawatt |
| 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 |
| NCF | net capacity factor |
| NP | name plate |
| NREL | National Renewable Energy Laboratory |
| O&M | operations and maintenance |
| OpEx | operational expenditures |
| ORCA | Offshore Wind Regional Cost Analyzer |
| PTC | production tax credit |
| RD | rotor diameter |
| USD | U.S. dollars |
| WACC | weighted average cost of capital |
| WETO | Wind Energy Technologies Office |
| yr | year |

# Executive Summary

# Executive Summary

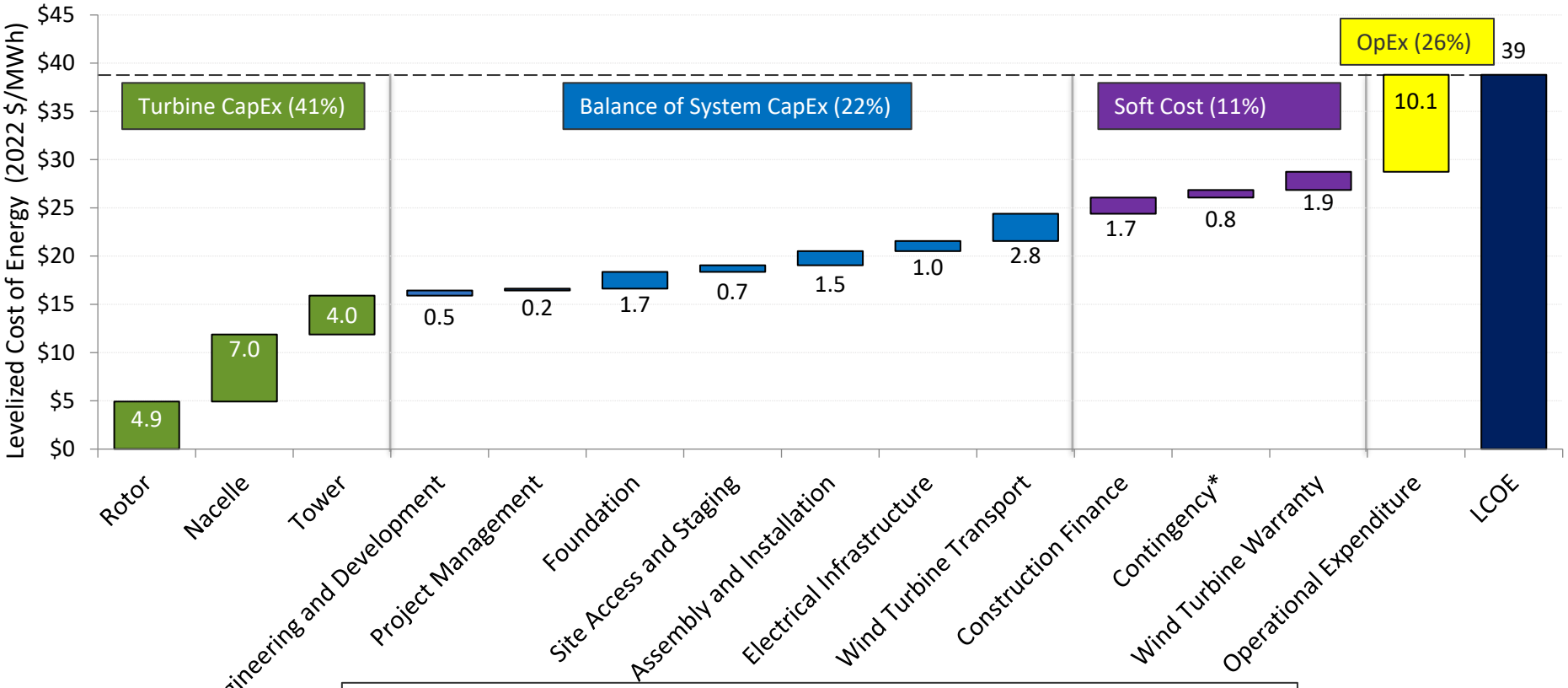
- The 12th annual *Cost of Wind Energy Review*, now presented as a slide deck, uses representative utility-scale and distributed wind energy projects to estimate the levelized cost of energy (LCOE) for land-based and offshore wind power plants in the United States.
  - Data and results are derived from 2022 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 variability in wind energy LCOE across the country.
- The primary elements of this 2022 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-, commercial-, 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 2023 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 | 1,750 | 4,640 | 6,169 | 8,425 | 6,327 | 3,270 |
| Fixed charge rate (FCR) (real) | % | 6.73 | 6.48 | 6.48 | 6.73 | 6.73 | 6.73 |
| Operational expenditures (OpEx) | $/kW/yr | 41 | 108 | 87 | 39 | 39 | 39 |
| Net annual energy production | MWh/MW/yr | 4,100 | 4,295 | 3,346 | 2,580 | 2,846 | 3,326 |
| Levelized cost of energy (LCOE) | $/MWh | 39 | 95 | 145 | 235 | 163 | 78 |

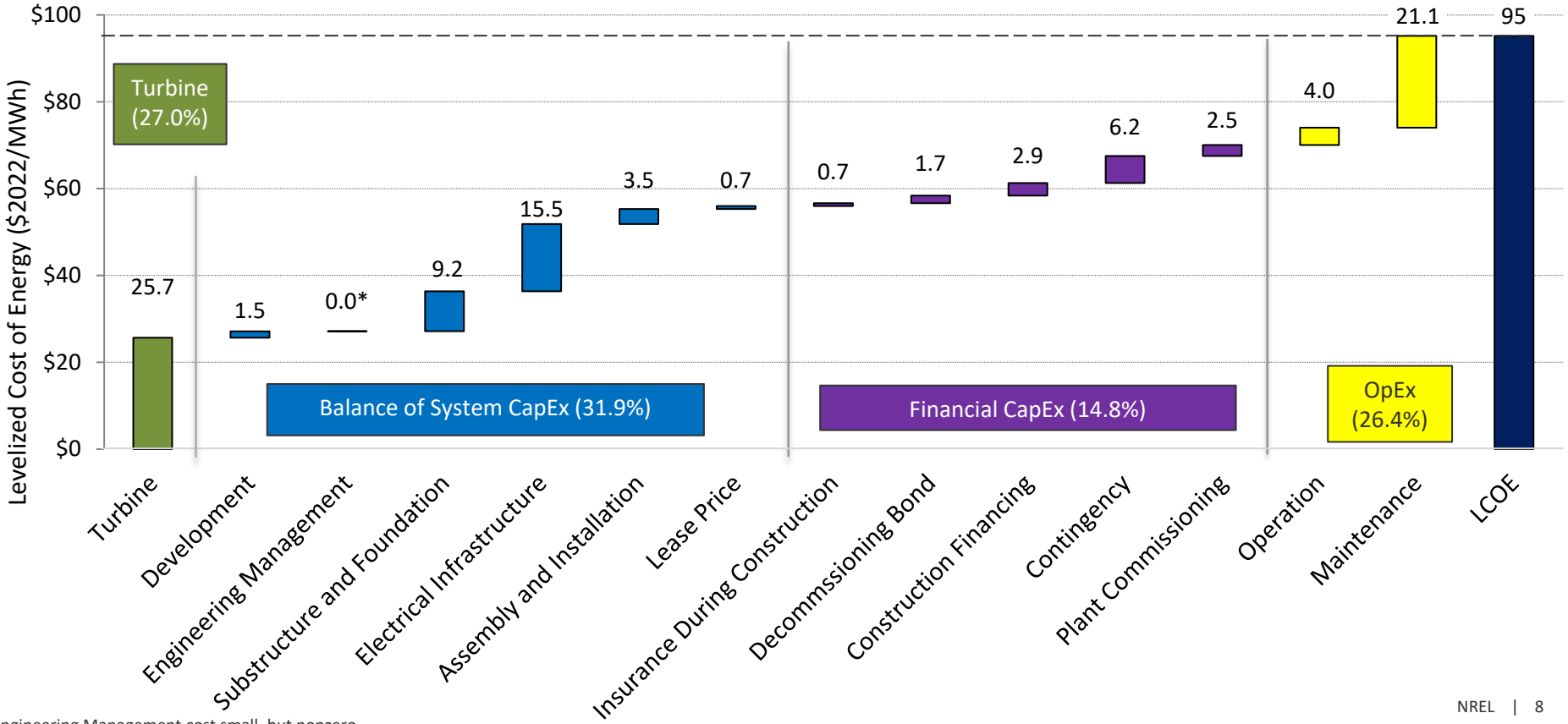
Note: Additional information on the sources of data are presented in the Appendix section. Unless specifically stated, all cost data are reported in 2022 U.S. dollars (USD).
kW = kilowatt; MW = megawatt; MWh = megawatt-hour

# Levelized Cost Breakdown for Reference Land-Based Wind Plant



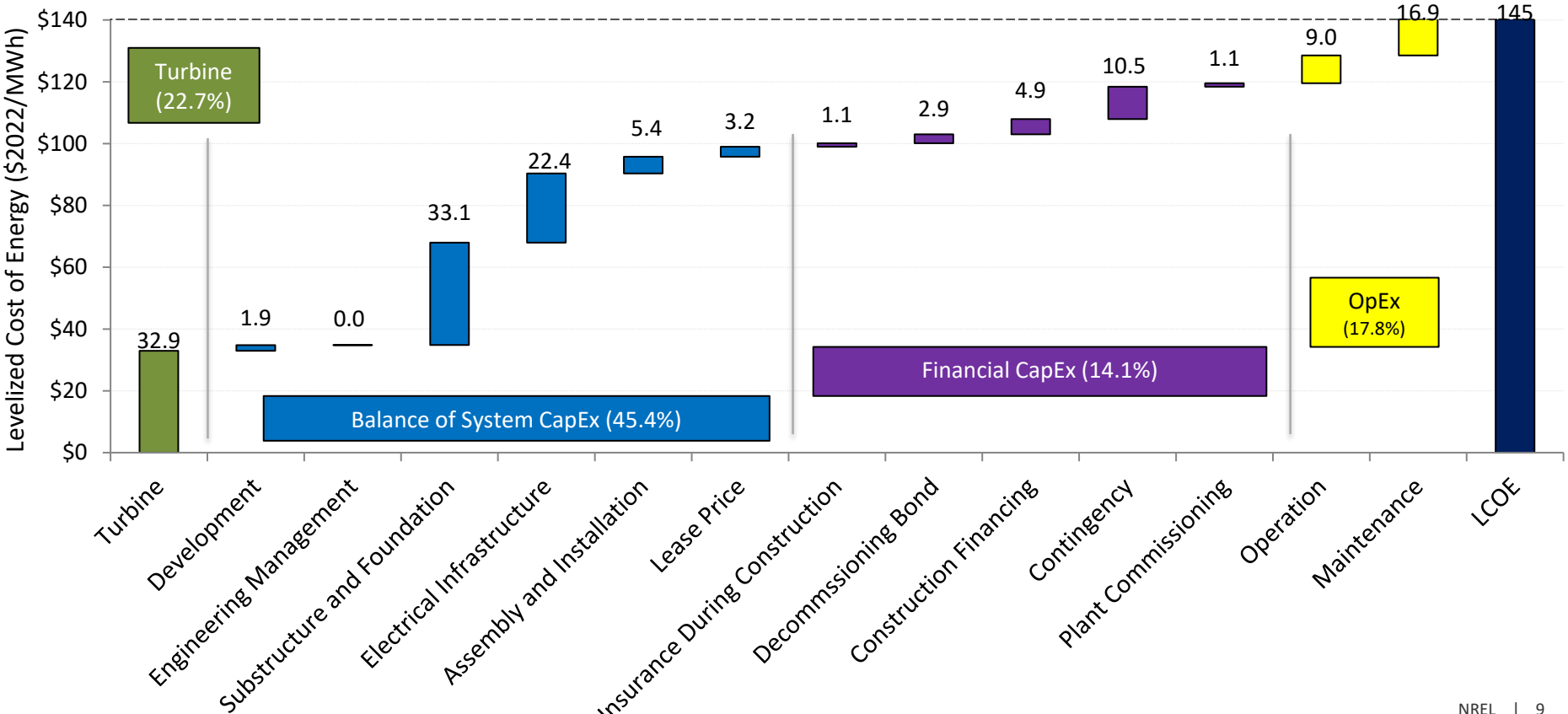

*Cost category also includes insurance, permitting, bonding, and markup estimates

# Levelized Cost Breakdown for Reference Fixed-Bottom Offshore Wind Plant




* Engineering Management cost small, but nonzero

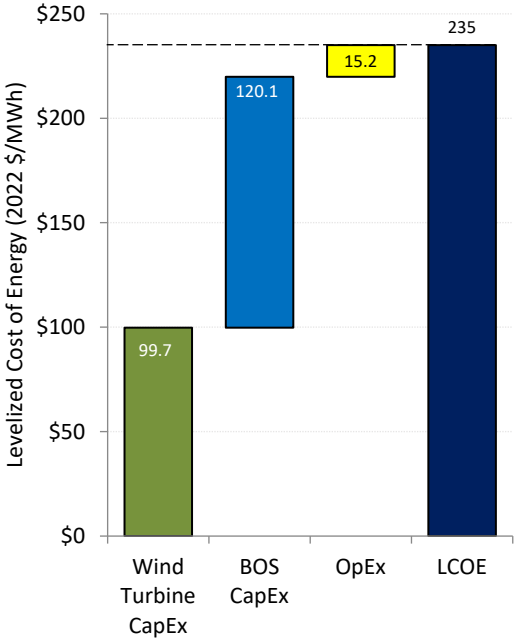
# Levelized Cost Breakdown for Reference Floating Offshore Wind Plant



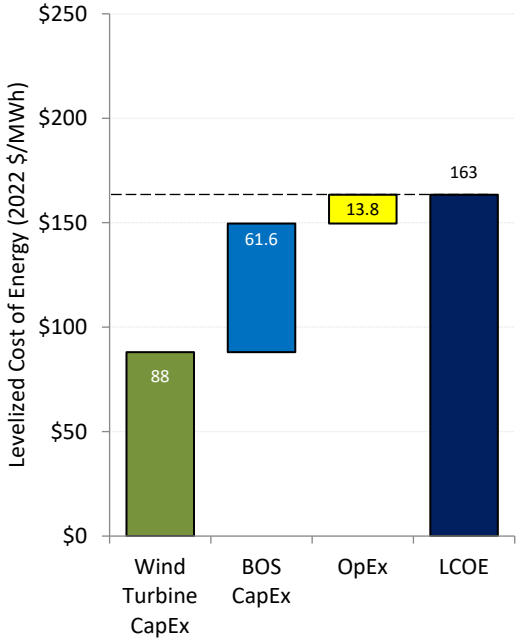

* Engineering Management cost small, but nonzero

# Levelized Cost Breakdown for Reference Distributed Wind Projects

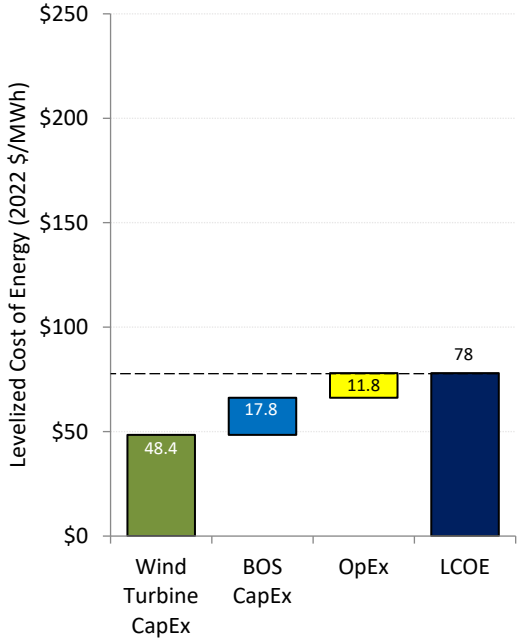
## Single-Turbine Residential (20 kW)




## Single-Turbine Commercial (100 kW)




## Single-Turbine Large (1,500 kW)




BOS = balance of system

# Key Conclusions

- The reference project LCOE for **land-based installations is $39/MWh**, with a range of land-based estimates from the single-variable sensitivity analysis covering $30–$57/MWh.

- The **fixed-bottom offshore wind estimate is $95/MWh**, and the **floating substructure reference project estimate is $145/MWh**. These two reference projects give a single-variable sensitivity range of $52–$184/MWh. This range is primarily caused by the large variation in CapEx ($1,800–$7,711/kW) and project design life.

- The **residential and commercial reference distributed wind** system LCOE are estimated at **$235/MWh and $163/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 **$78/MWh**.

# 1. Background

# Background

- The *2022 Cost of Wind Energy Review* 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 and 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 *2021 Cost of Wind Energy Review* (Stehly and Duffy 2022) 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 data sets
  - 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

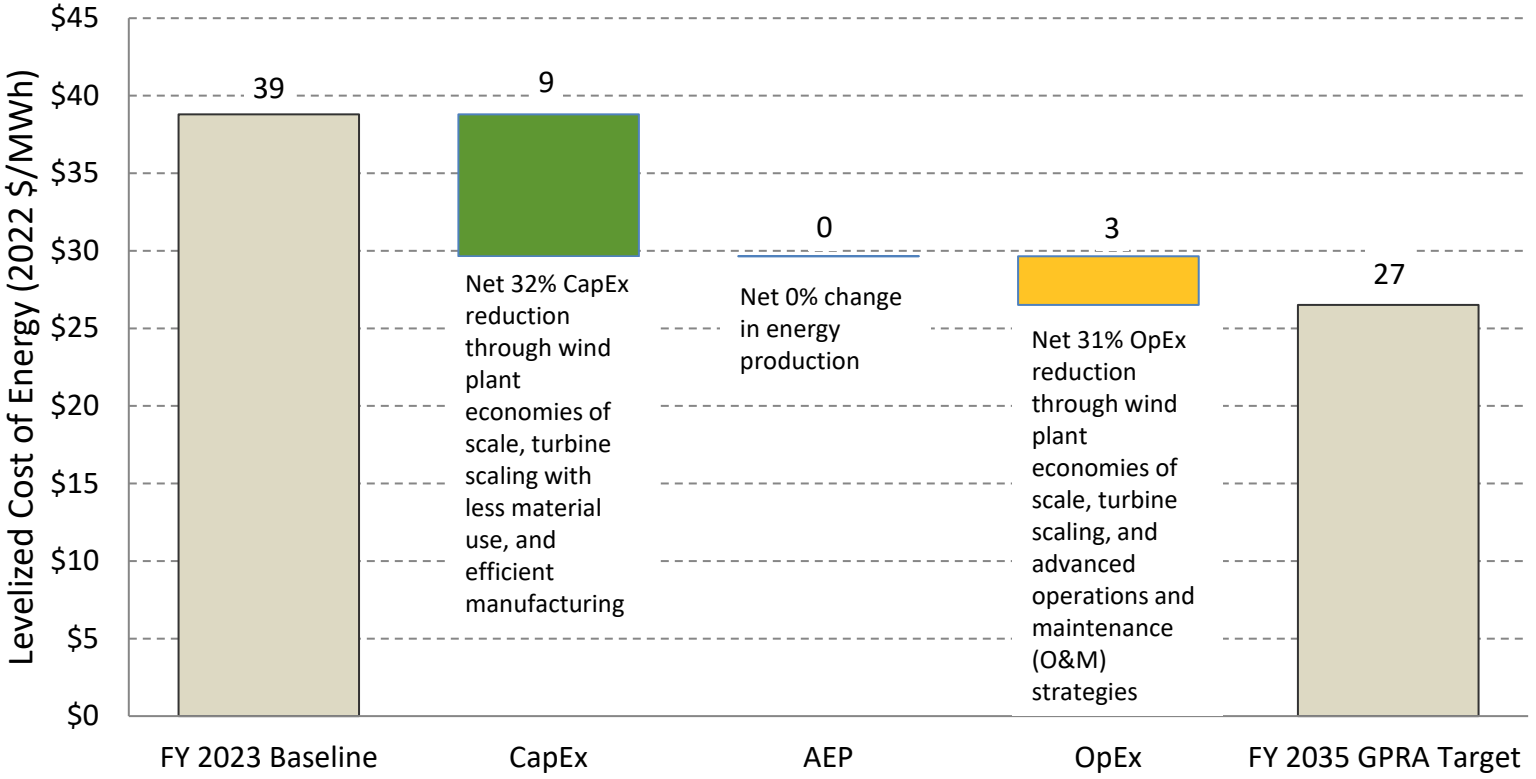
- Every year, the Wind Energy Technologies Office (WETO) reports the LCOE for land-based wind and fixed-bottom offshore wind to satisfy GPRA reporting requirements.
- This report provides the underlying market and cost data for WETO to inform the annual GPRA reporting requirements.
- Updates to the LCOE 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.
- 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.
- Future re-baseline efforts will be assessed periodically and will be implemented as needed.
- The table summarizes the methods and assumptions of the prior GPRA targets and the updated methods and assumptions for the FY 2023 GPRA targets.

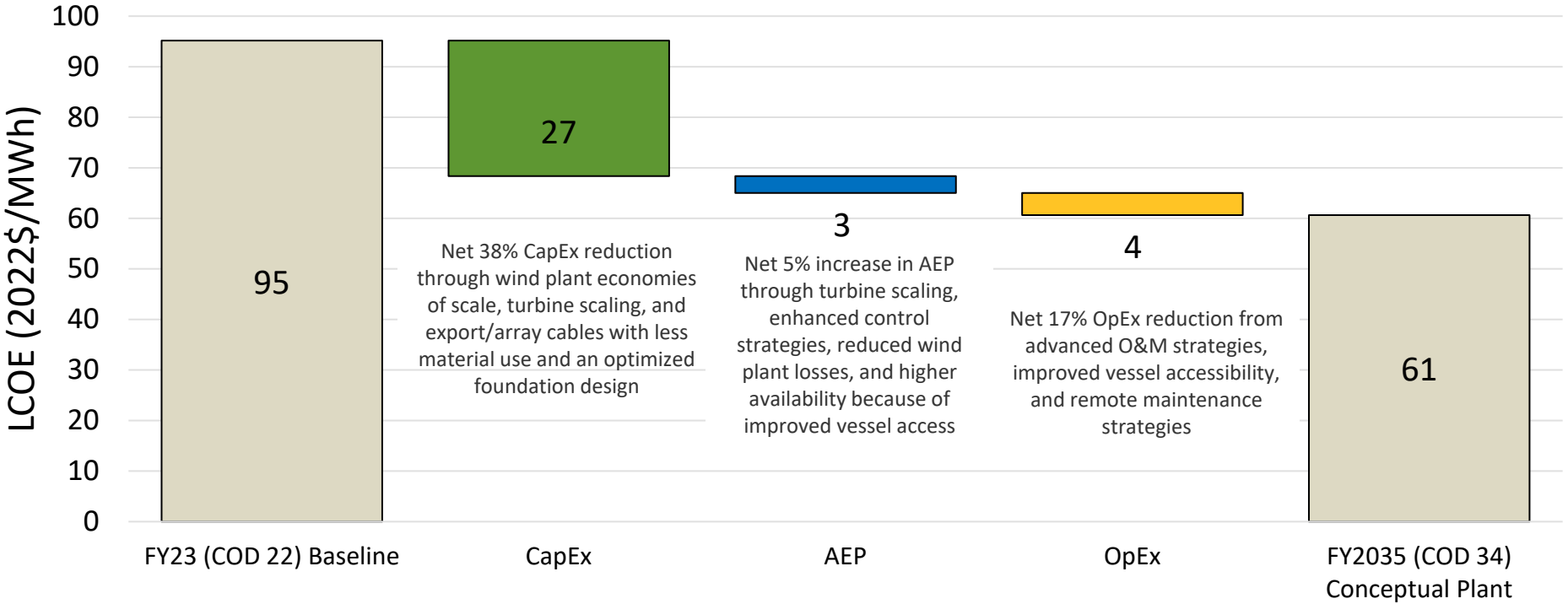
| | Land-Based Wind | | Fixed-Bottom Offshore Wind | |
|---|---|---|---|---|
| **Effort** | **Prior GPRA Baseline (Then)** | **Re-Baseline (Now)** | **Prior GPRA Baseline (Then)** | **Re-Baseline (Now)** |
| Commercial Operation Date | 2015 | 2022 | 2018 | 2022 |
| Technology | Market average turbine 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 rotor diameter, 136 m hub height) (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 |
| Performance | 40% (16.7% total losses) | 46.8% (18.9% total losses) | 48.6% (16.2% total losses) | 48.7% (16.0% total losses) |

# Government Performance and Results Act Cost Reduction Pathway From 2023 to 2035 for Land-Based Wind



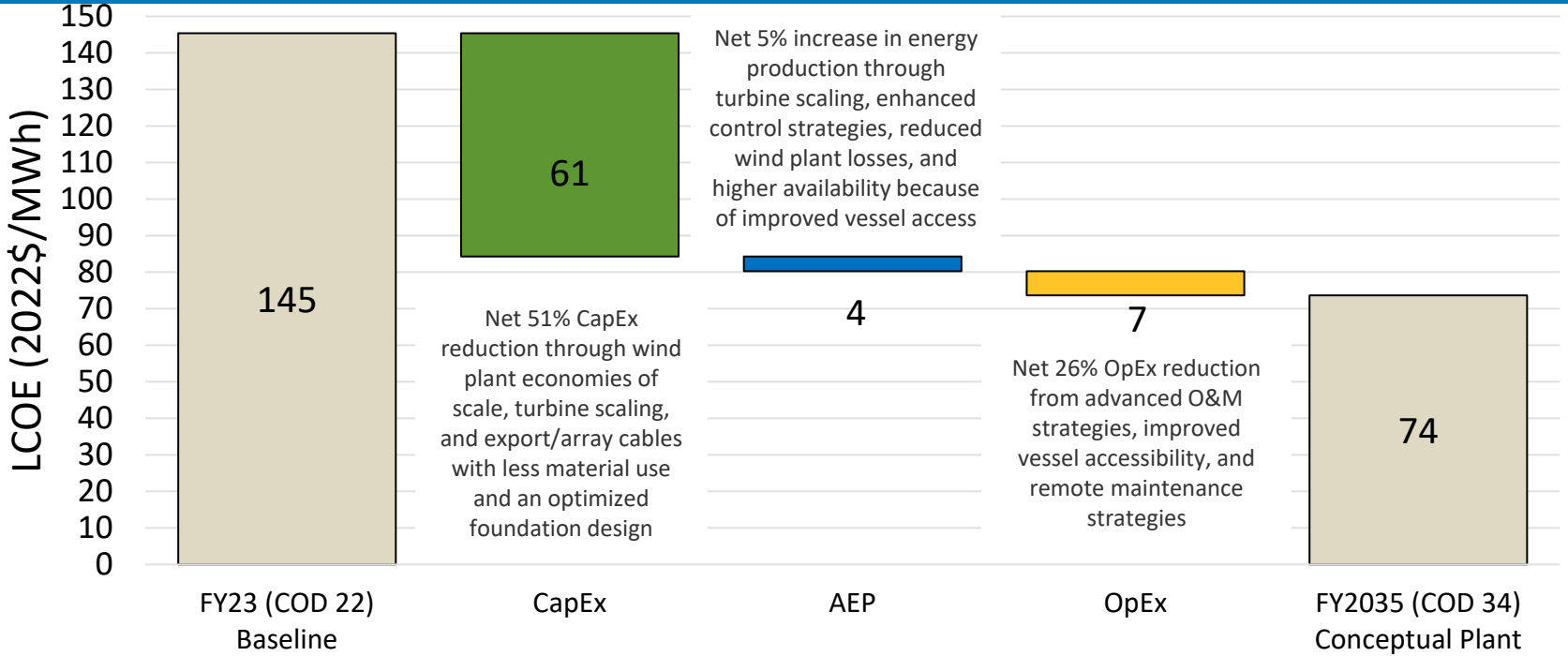

- The FY 2023 baseline assumes a representative 3.3 MW–148 m (RD)–100 m (HH) wind turbine and the FY 2035 target assumes a 6 MW–170 m (RD)–115 m (HH) wind turbine.
- The land-based wind **GPRA baseline value starts at $39/MWh** (in 2022 USD) set in FY 2023, using the 2022 reference project data.
- The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

# Government Performance and Results Act Cost Reduction Pathway From 2023 to 2030 for Fixed-Bottom Offshore Wind



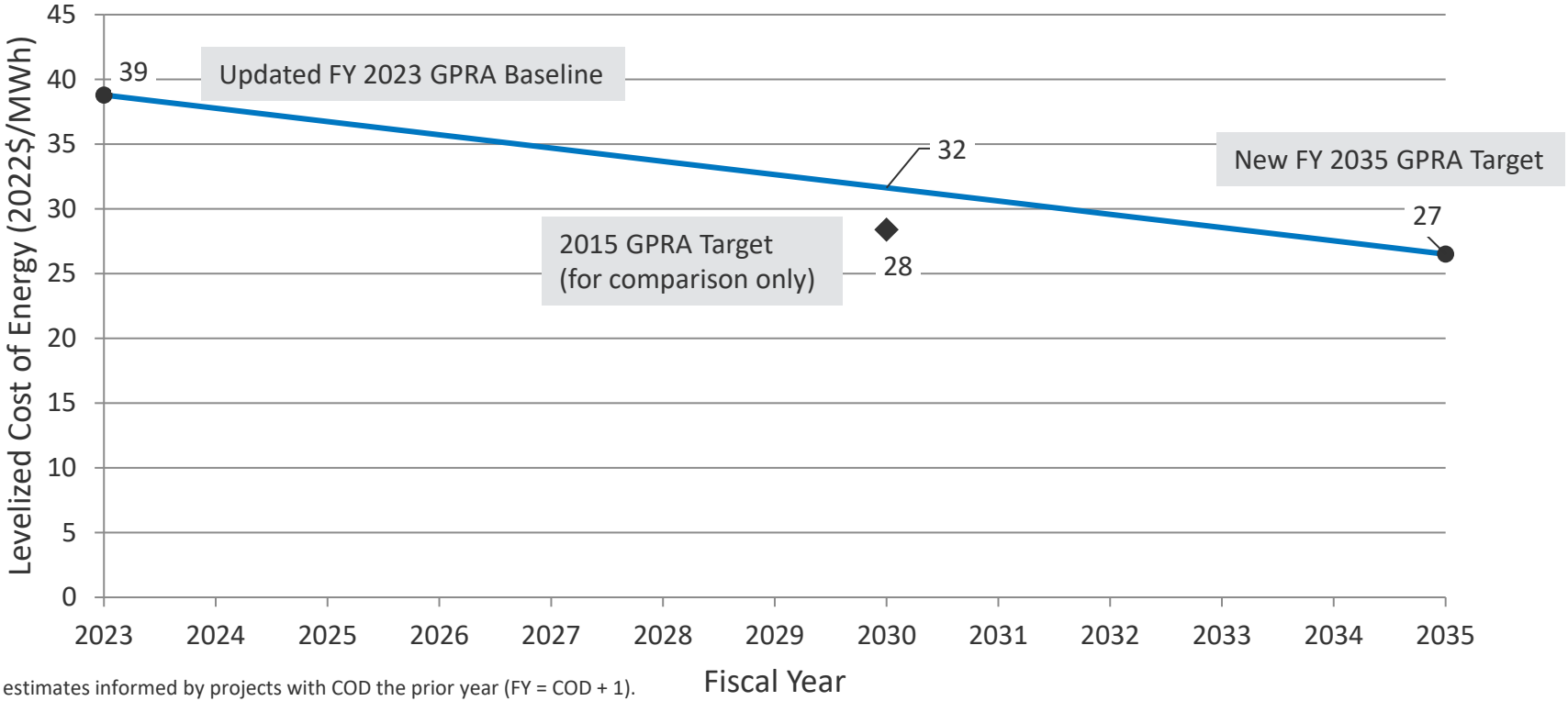

- The **GPRA baseline value starts at $95/MWh** (in 2022 USD) set in FY 2023 using 2022 reference project data.
- The **GPRA target is $61/MWh by FY 2035 (commercial operations date [COD] 2034)** (in 2022 USD) and is derived for a fixed-bottom wind plant at the reference site based on cost reductions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

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



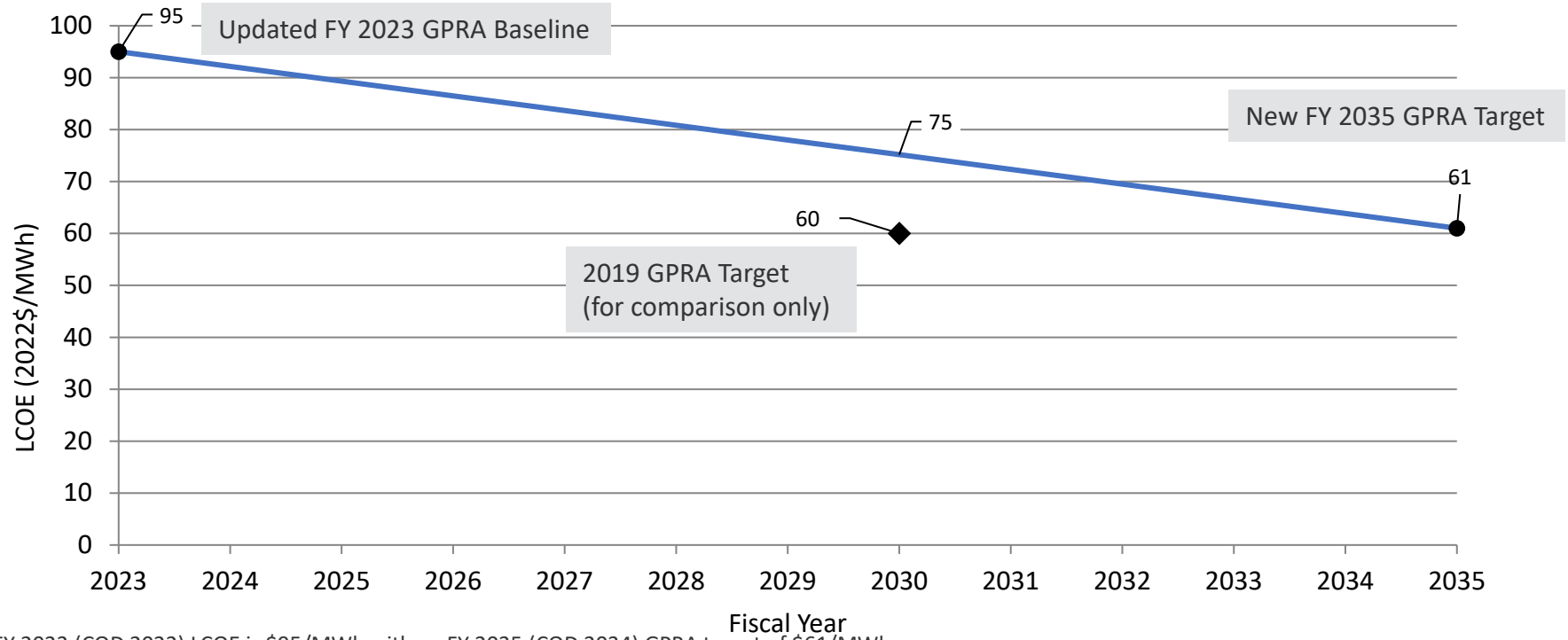

- **DOE has no official GPRA reporting requirement for floating offshore wind energy costs.**
- Projected floating offshore wind cost reductions are mapped to **$74/MWh in FY 2030** using similar methodology as fixed-bottom offshore wind.
- DOE established a Floating Offshore Wind Shot goal of $45/MWh (2020 USD) by 2035 for a different reference site using a different set of assumptions.

# 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 3.3 MW–148 m (RD)–100 m (HH) wind turbine and the FY 2035 target assumes a 6 MW–170 m (RD)–115 m (HH) wind turbine.
- For comparison, the FY 2030 GPRA set in 2015 inflated from 2015 USD to 2022 USD assuming a 23.5% cumulative rate of inflation 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.

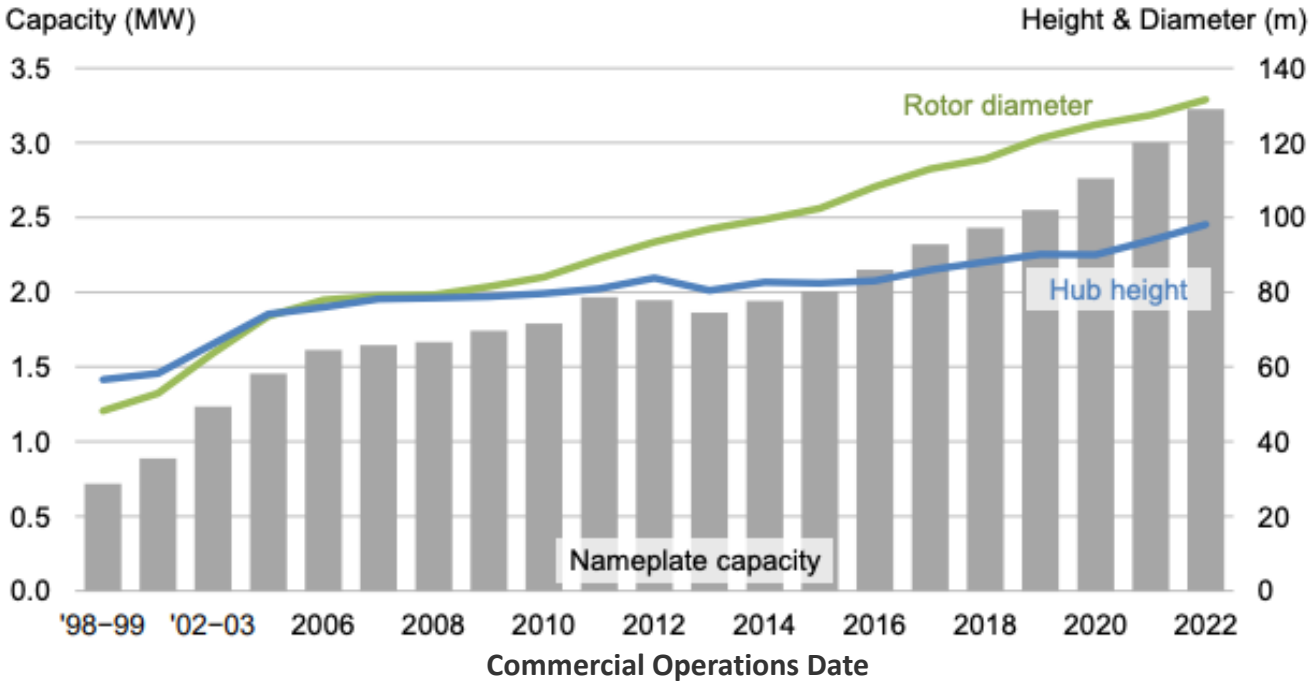
# GPRA Cost Reduction Pathway From 2023 to 2035 for Fixed-Bottom Offshore Wind Energy




- The FY 2023 (COD 2022) LCOE is $95/MWh with an FY 2035 (COD 2034) GPRA target of $61/MWh.
- The FY 2030 target is informed by industry learning (Shields et al. 2022) and expert elicitation (Wiser et al. 2021).
- 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

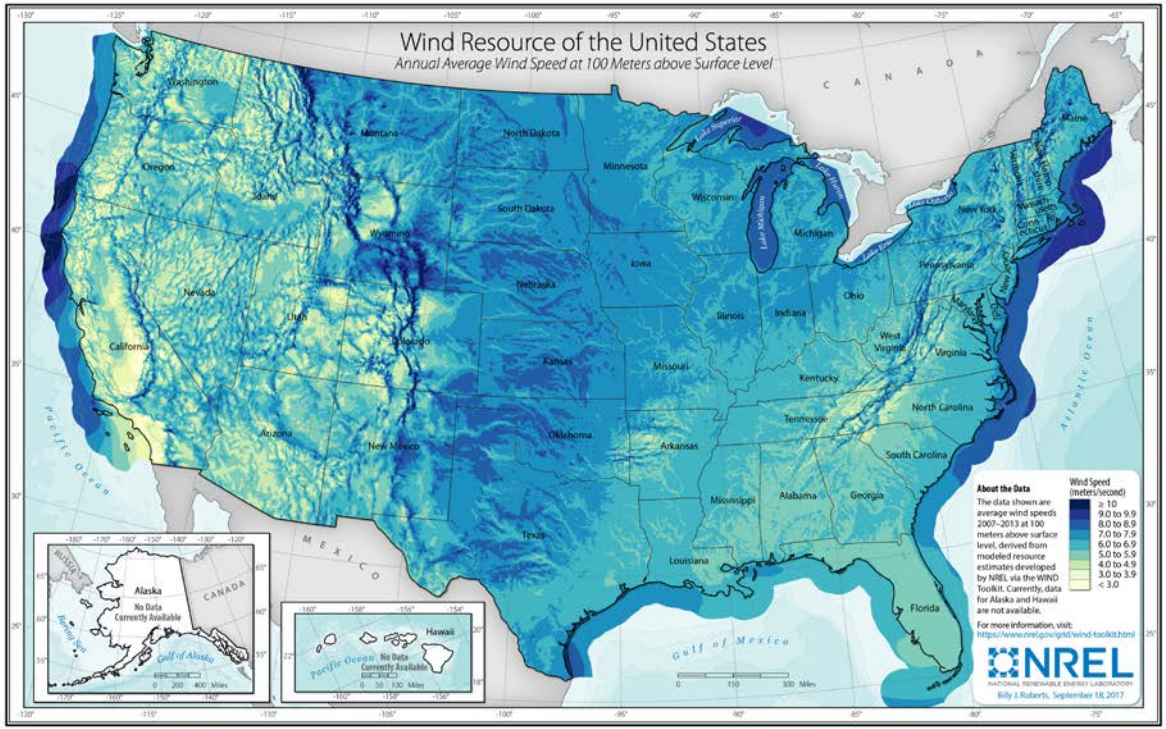
Chart source: Wiser and Bolinger (2023)

Assumed wind turbine characteristics in 2022 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

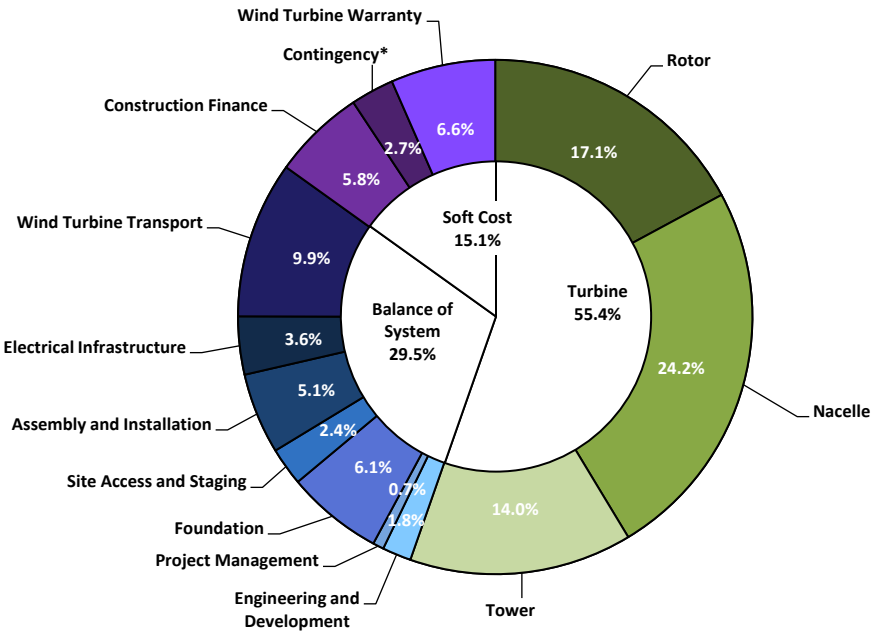



Wind resource of the United States, annual average wind speed at 100 m above surface level

Source: NREL (2017)

| Parameter | Value |
|---|---|
| Annual average wind speed at 50 m above surface level | 7.25 m/s |
| Annual average wind speed at hub height | 8 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 | 18.9% |
| Net energy capture | 4,100 MWh/MW/yr |
| Net capacity factor | 46.8% |

# Land-Based Wind Project Component Cost Breakdown




- Turbine component cost estimates are derived from recent updates to NREL's Cost and Scaling Model 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 2023 Annual Technology Baseline atb.nrel.gov.

| Parameter | Value ($/kW) |
|---|---|
| **Wind Turbine CapEx** | **969** |
| Rotor | 300 |
| Nacelle | 424 |
| Tower | 245 |
| **BOS CapEx** | **517** |
| Engineering and development | 32 |
| Project management | 12 |
| Foundation | 106 |
| Site access, staging, and facilities | 42 |
| Assembly and installation | 89 |
| Electrical infrastructure | 64 |
| Wind turbine transport | 172 |
| **Soft Cost** | **264** |
| Construction finance | 102 |
| Contingency* | 48 |
| Wind turbine warranty | 115 |
| **Total CapEx** | **1,750** |

All costs reported in 2022 USD

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

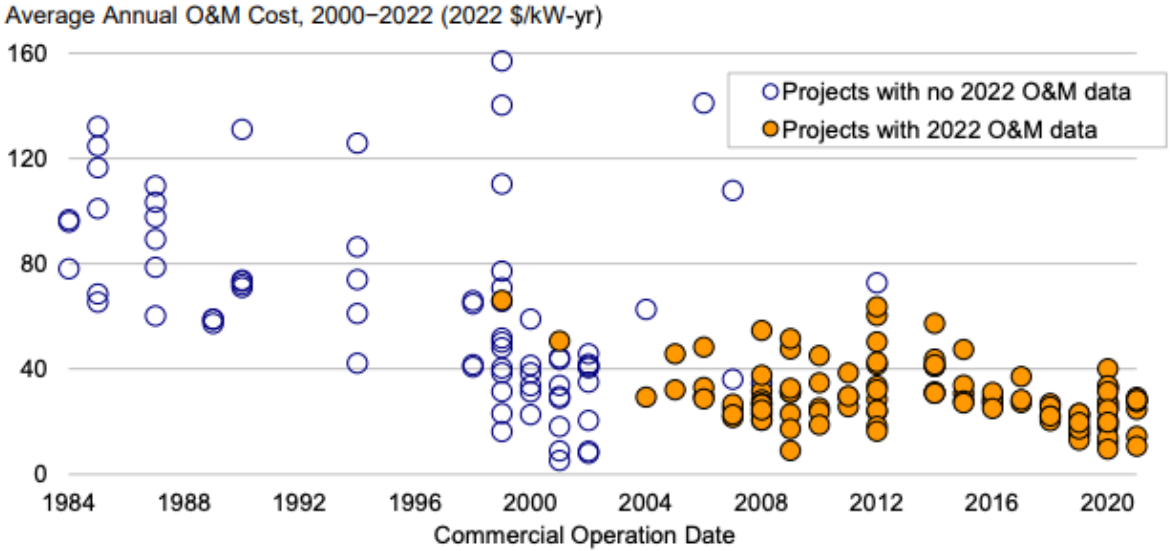
# Relative Value of Manufactured Product Components for the Land-Based Wind Project

| Cost of Wind Energy Review Cost Parameter | Manufactured Product Component (U.S. Department of the Treasury 2023) | Contribution to Total Manufactured Product Value for an Industry-Standard Wind Turbine (%) |
|---|---|---|
| **Wind Turbine CapEx** | | |
| Rotor | Blades | 31.2 (+3.5% / -4.5%) |
| | Rotor hub | 9.9 (+2.1% / -0.5%) |
| Nacelle | Nacelle (excluding power converter) | 47.5 (+4.5% / -2.5%) |
| | Power converter | 8.9 (+1.1% / -2.1%) |
| Tower | Wind tower flanges | 1.6 (+0.6% / -0.5%) |
| **BOS CapEx** | | |
| Turbine incorporation and installation | Final onsite manufacturing and installation of wind turbine (excluding tower)* | 0.9 (+0.9%) |

- In May 2023, the U.S. Department of the Treasury (2023b) released guidance that indicates for a project to qualify for the domestic content bonus under the Inflation Reduction Act, "all manufacturing processes with respect to any steel or iron items that are Applicable Project Components take place in the United States," and a minimum percentage of the costs of manufactured products and components "are attributable to manufactured products (including components) which are mined, produced, or manufactured in the United States."
- This table breaks down relevant land-based wind project components to show the applicable manufactured product components identified by the U.S. Department of the Treasury (2023a) and provides their relative contribution to the total manufactured product cost.
- Manufactured product component cost estimates were developed for a range of wind turbine ratings using empirical data and NREL's Cost and Scaling Model (https://github.com/WISDEM/WISDEM). As a result, the relative contributions are not specific to the 3.3-MW wind turbine used in this report but are broadly applicable to industry-standard wind turbines. Additional information describing the methodology for developing the manufactured product component data is presented in the Appendix.

* The U.S. Department of the Treasury (2023a) guidance allows direct material and direct labor costs to produce a U.S. manufactured product (here, the wind turbine, excluding the tower) within the total manufactured product cost if all the manufactured product components (e.g., the blades, rotor hub, nacelle, power converter, and tower flanges) are produced in the United States.

# Land-Based Wind Plant Operational Expenditures Estimate and Historical Data




Average O&M costs for available data years from 2000 to 2022, by commercial operation date

Chart source: Wiser and Bolinger (2023)

| Parameter | Value |
|---|---|
| Estimated OpEx | $41/kW-yr |

All-in project OpEx estimates informed by updated analysis conducted in the 2023 Annual Technology Baseline (atb.nrel.gov).

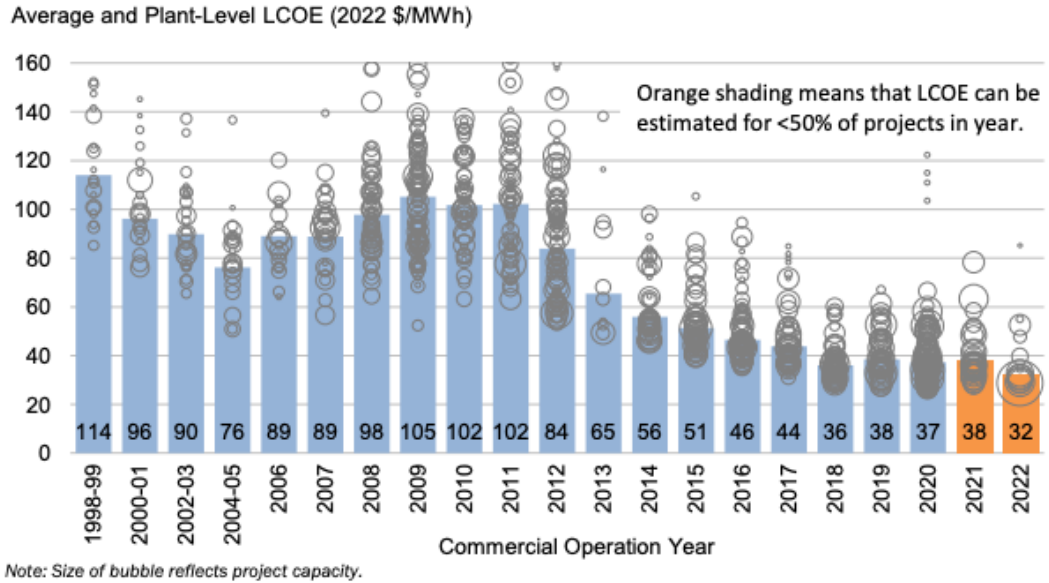
Note: O&M data reported in the chart do not include all operating costs.

# Land-Based Wind Project Financial Assumptions

| Parameter | Nominal Value | Real Value |
|---|---|---|
| Weighted average cost of capital | 6.57% | 3.97% |
| Capital recovery factor | 8.25% | 6.38% |
| Fixed charge rate | 8.7% | 6.73% |

- The economic evaluation of wind energy investments in this analysis uses the fixed charge rate (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



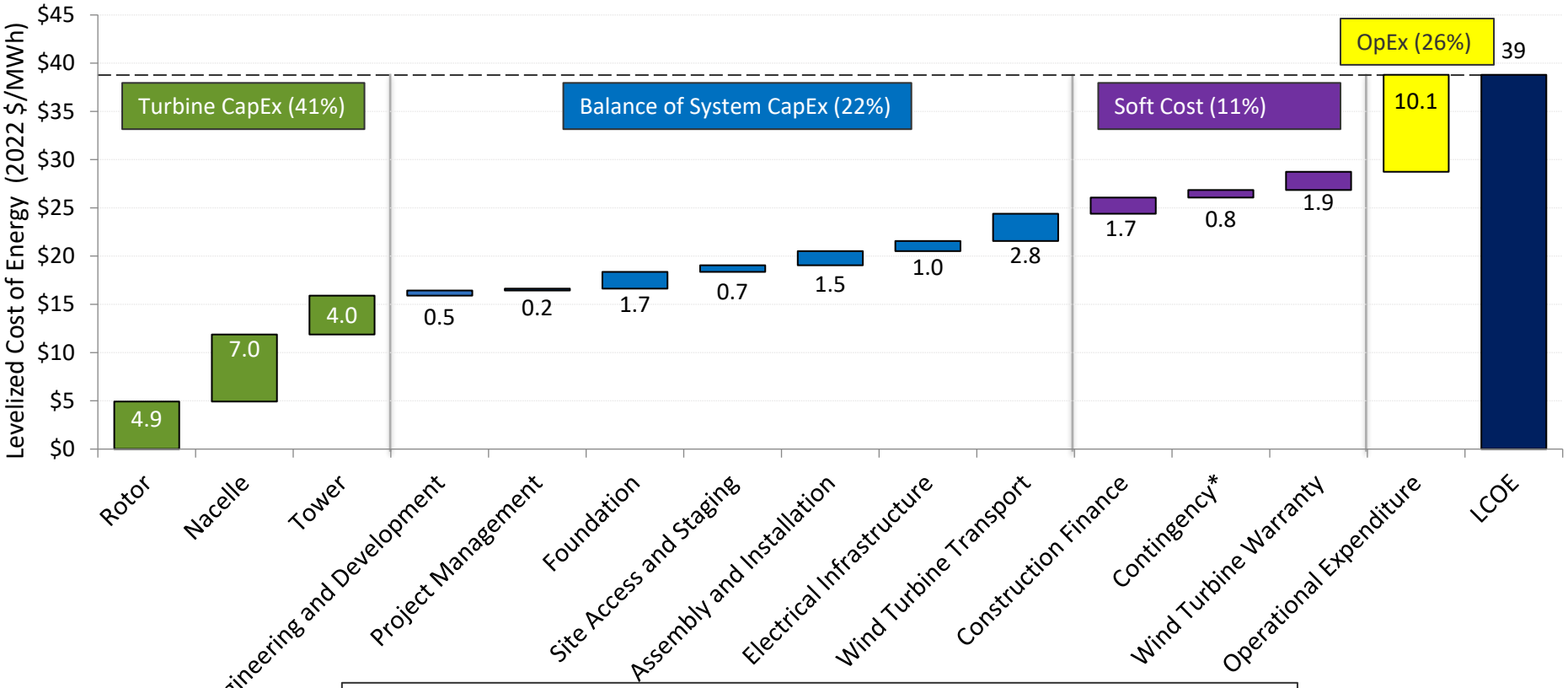

Estimated levelized cost of wind energy for actual wind projects by commercial operation date

Chart source: Wiser and Bolinger (2023)

| Parameter | Value |
|---|---|
| Wind turbine rating | 3.3 MW |
| Capital expenditures | $1,750/kW |
| Fixed charge rate (real) | 6.73% |
| Operational expenditures | $41/kW/yr |
| Net annual energy production | 4,100 MWh/MW/yr |
| Calculated levelized cost of energy | $39/MWh |

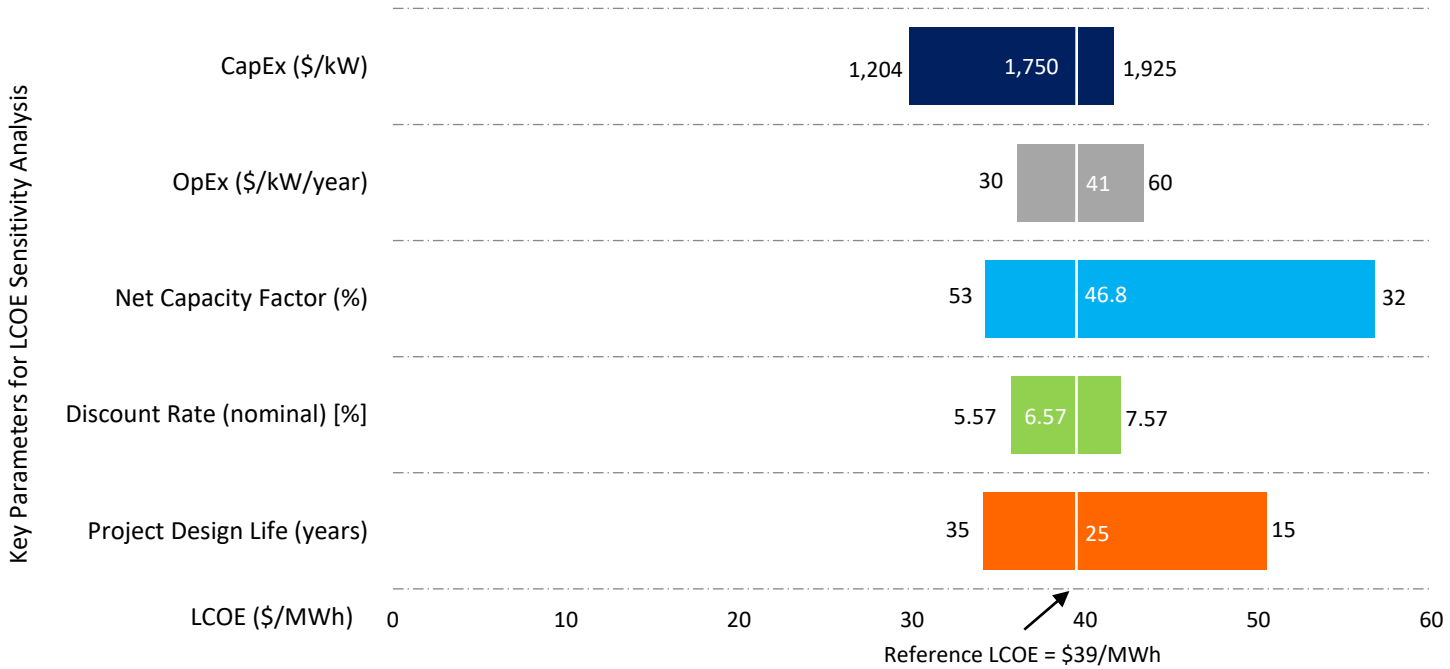
Modeled cost and performance data using the methods presented in the 2023 Annual Technology Baseline (atb.nrel.gov) to calculate LCOE.

# LCOE Breakdown for Reference Land-Based Wind Plant




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

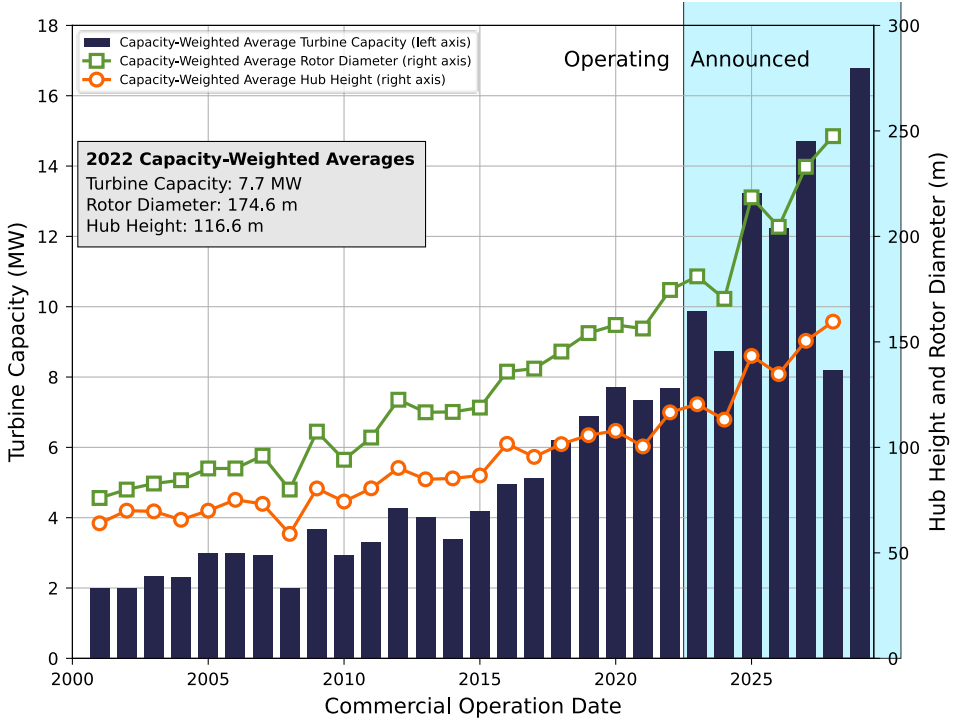
# Range of LCOE Parameters for Land-Based Wind




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

# 2022 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 2022.

Source: *Offshore Wind Market Report: 2023 Edition* (Musial et al. 2023)

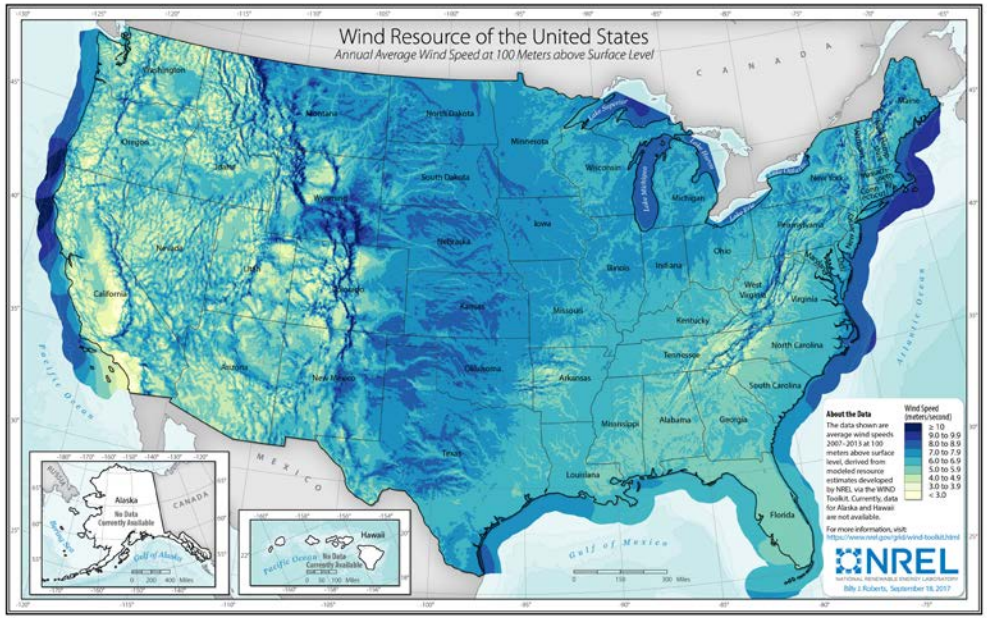
| Parameter | Value |
|---|---|
| Wind turbine rating | 12.0 MW |
| Rotor diameter | 216 m |
| Hub height | 137 m |
| Specific power | 327 W/m$^2$ |
| Wind plant capacity | 600 MW |
| Number of turbines | 50 |

Representative turbine parameters and power curves available on GitHub

- Global capacity-weighted average turbine rating in 2022 was 7.7 MW, up from 7.4 MW in 2021 (Musial et al. 2023).
- The first commercial-scale offshore wind projects installed in the United States selected 11-MW (South Fork Wind) and 13-MW (Vineyard Wind I) turbines.

# Offshore Wind Reference Wind Sites and Wind Plant Performance

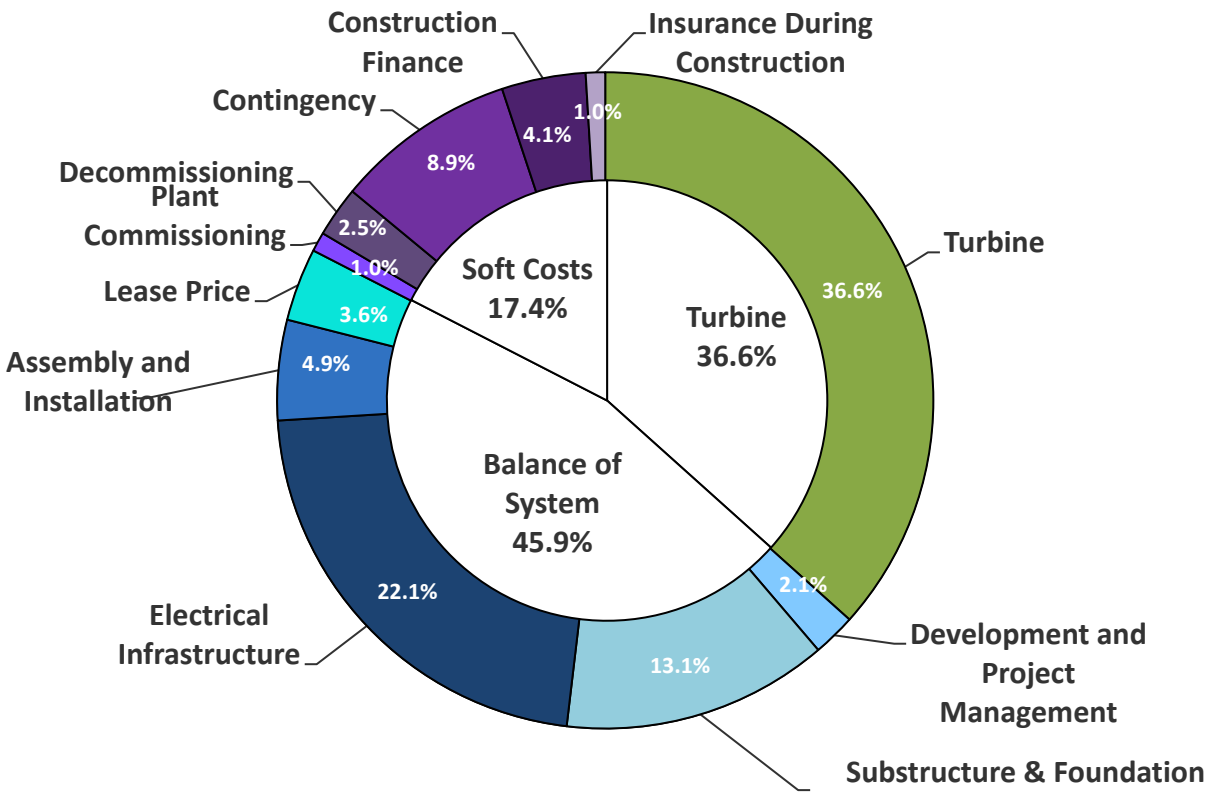
- The fixed-bottom offshore wind reference project represents near-term development in the U.S. Northeast.
- The floating offshore wind reference site represents the first leases in California.




Wind resource of the United States, annual average wind speed at 100 meters above surface level. Source: NREL (2017)

| 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 | % |

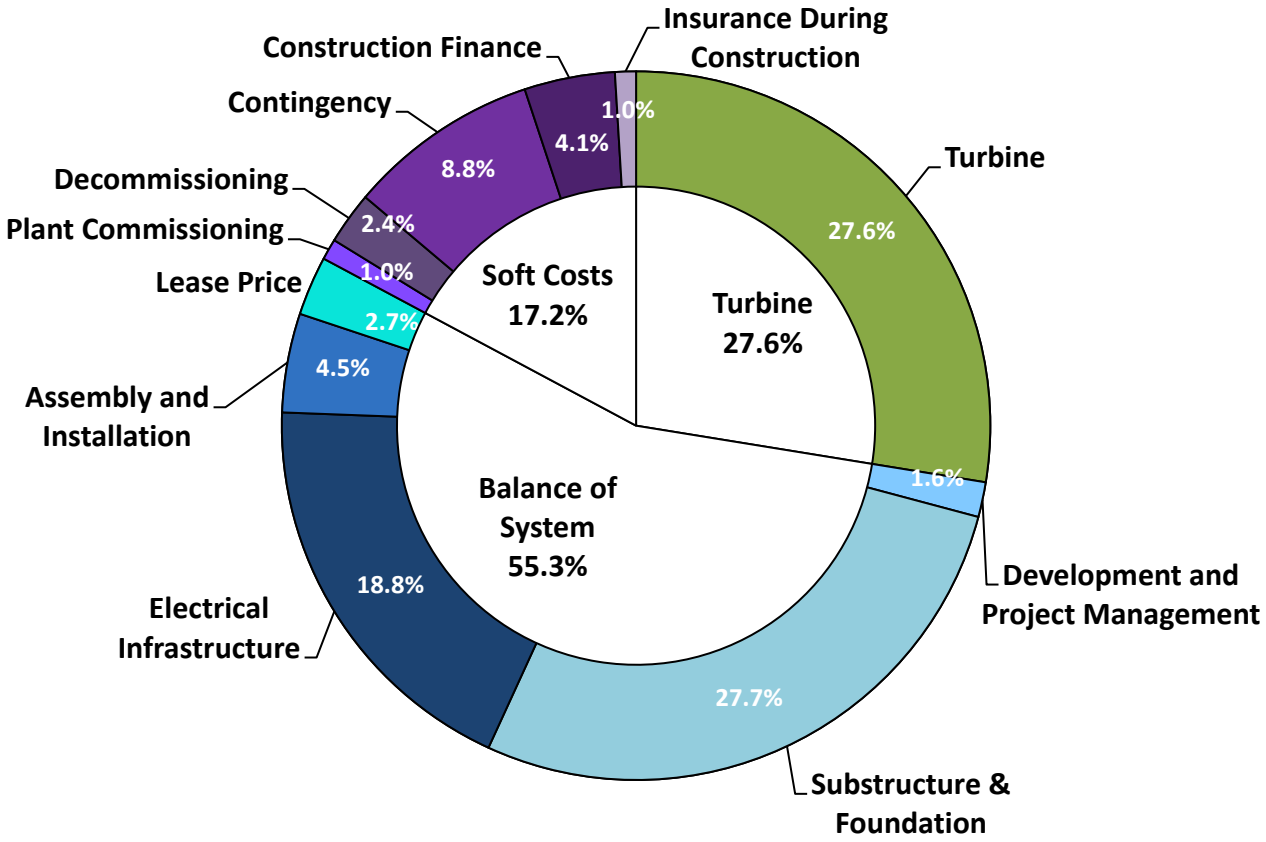
# Fixed-Bottom Offshore Wind System CapEx Component Cost Breakdown




| Parameter | Value ($/kW) |
|---|---|
| **Turbine** | **1,700** |
| **BOS** | **2,130** |
| Development and project management | 98 |
| Substructure and foundation | 609 |
| Electrical infrastructure | 1027 |
| Assembly and installation | 229 |
| Lease price | 167 |
| **Soft Costs** | **809** |
| Plant commissioning | 44 |
| Decommissioning | 116 |
| Contingency | 414 |
| Construction finance | 192 |
| Insurance during construction | 44 |
| **Total CapEx** | **4,640** |

Values rounded to the nearest dollar

# Floating Offshore Wind System CapEx Component Cost Breakdown




| Parameter | Value ($/kW) |
|---|---|
| **Turbine** | **1,700** |
| **BOS** | **3,409** |
| Development and project management | 98 |
| Substructure and foundation | 1,708 |
| Electrical infrastructure | 1,157 |
| Assembly and installation | 279 |
| Lease price | 167 |
| **Soft Costs** | **1,060** |
| Plant commissioning | 59 |
| Decommissioning | 147 |
| Contingency | 540 |
| Construction finance | 255 |
| Insurance during construction | 59 |
| **Total CapEx** | **6,169** |

# 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 a jack-up vessel for replacements.
  - Floating case executes replacements through a tow-to-port strategy.
  - Failure rates and costs associated with repairs and replacements informed by COREWIND (2021).

| Parameter | Fixed Value ($/kW-yr) | Floating Value ($/kW-yr) |
|---|---|---|
| **Maintenance** | **91** | **56** |
| Labor (technicians) | 4 | 4 |
| Materials | 2 | 3 |
| Equipment (vessels) | 85 | 49 |
| **Operations** | **17** | **30** |
| Management administration | 2 | 2 |
| Port fees | 1 | 14 |
| Insurance | 15 | 15 |
| **Total OpEx** | **108** | **87** |

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 | 6.23% | 3.64% |
| Capital recovery factor | 7.99% | 6.20% |
| Fixed charge rate | 8.42% | 6.48% |

- 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 6.23% and 3.64%, respectively, a project design lifetime of 25 years, and a net present value depreciation factor of 86.9% (assuming a 5-year MACRS depreciation schedule).
- Detailed financial assumptions are displayed in the Appendix.

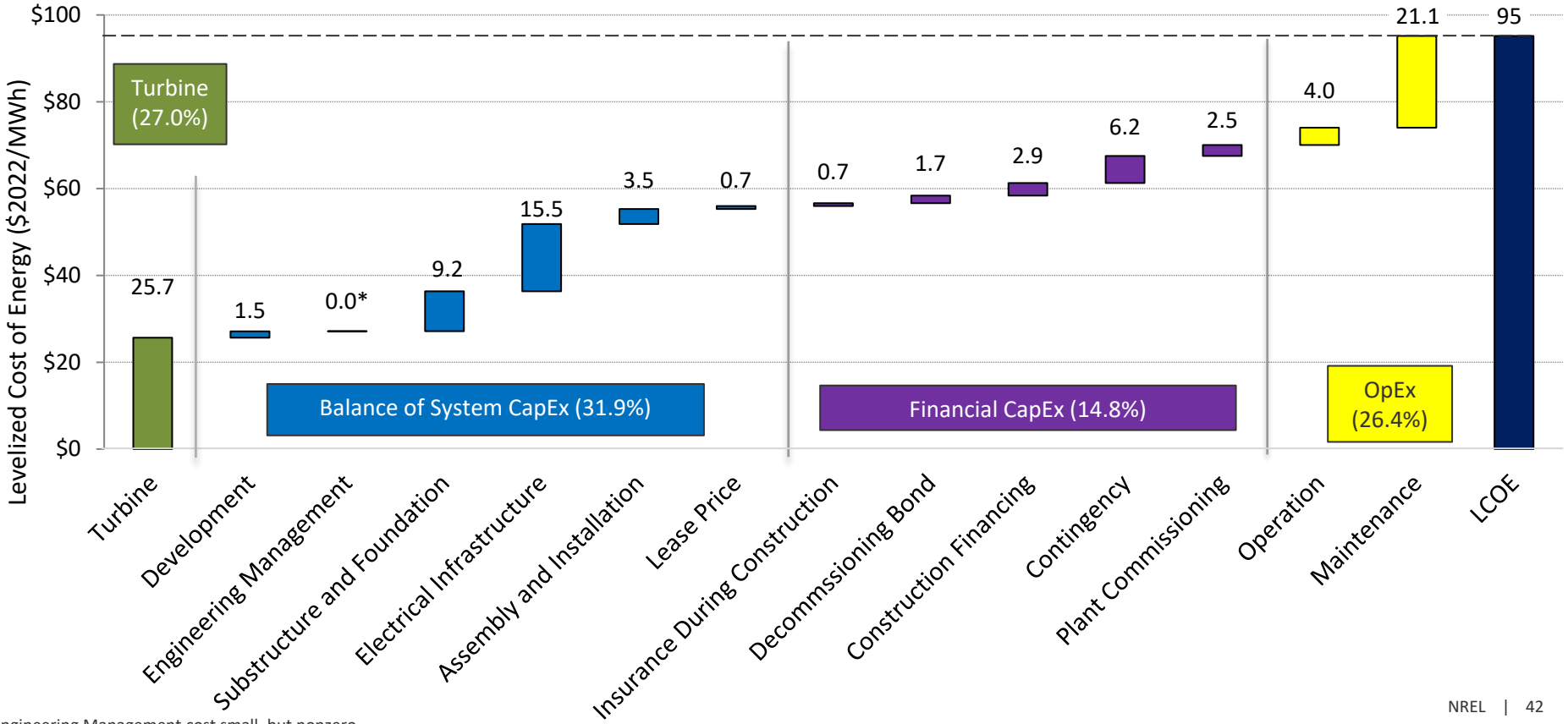
Note: The WACC for land-based wind is higher than for offshore wind because it considers the influences of the production tax credit and assumes a lower debt fraction.

# 2022 Offshore Wind Reference Plant LCOE Estimates

- **The LCOE values for the 2022 representative fixed-bottom and floating offshore wind plants are estimated at $95/MWh and $145/MWh, respectively.**
- Calculated with the formulation presented in NREL's Annual Technology Baseline and presented in Appendix.

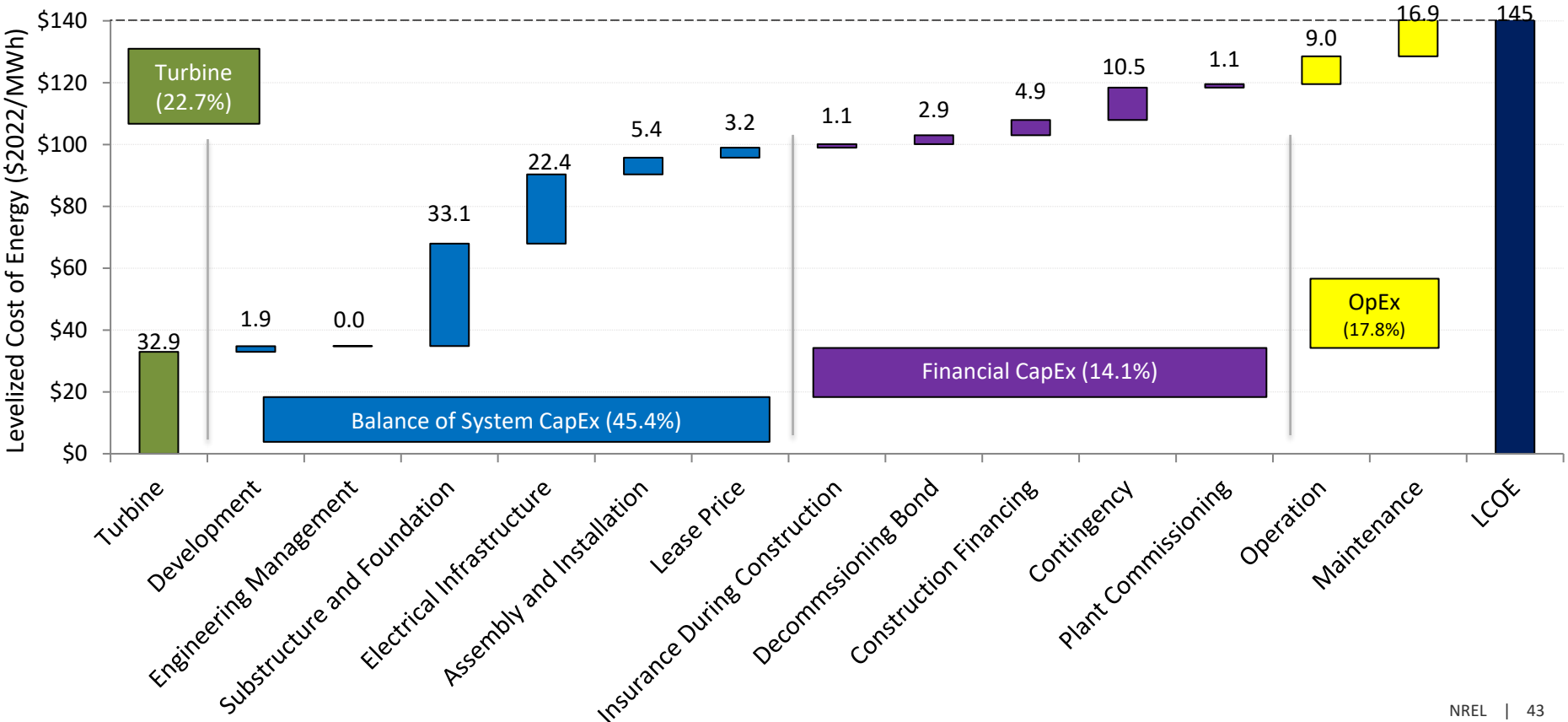
| Parameter | Fixed-Bottom 12.0-MW Offshore Wind Turbine | Floating 12.0-MW Offshore Wind Turbine | Units |
|---|---|---|---|
| Capital expenditures | 4,640 | 6,169 | $/kW |
| Fixed charge rate (real) | 6.48 | 6.48 | % |
| Operational expenditures | 108 | 87 | $/kW/yr |
| Net annual energy production | 4,295 | 3,346 | MWh/MW/yr |
| **Total LCOE** | **95** | **145** | **$/MWh** |

# Levelized Cost Breakdown for Reference Fixed-Bottom Offshore Wind Plant



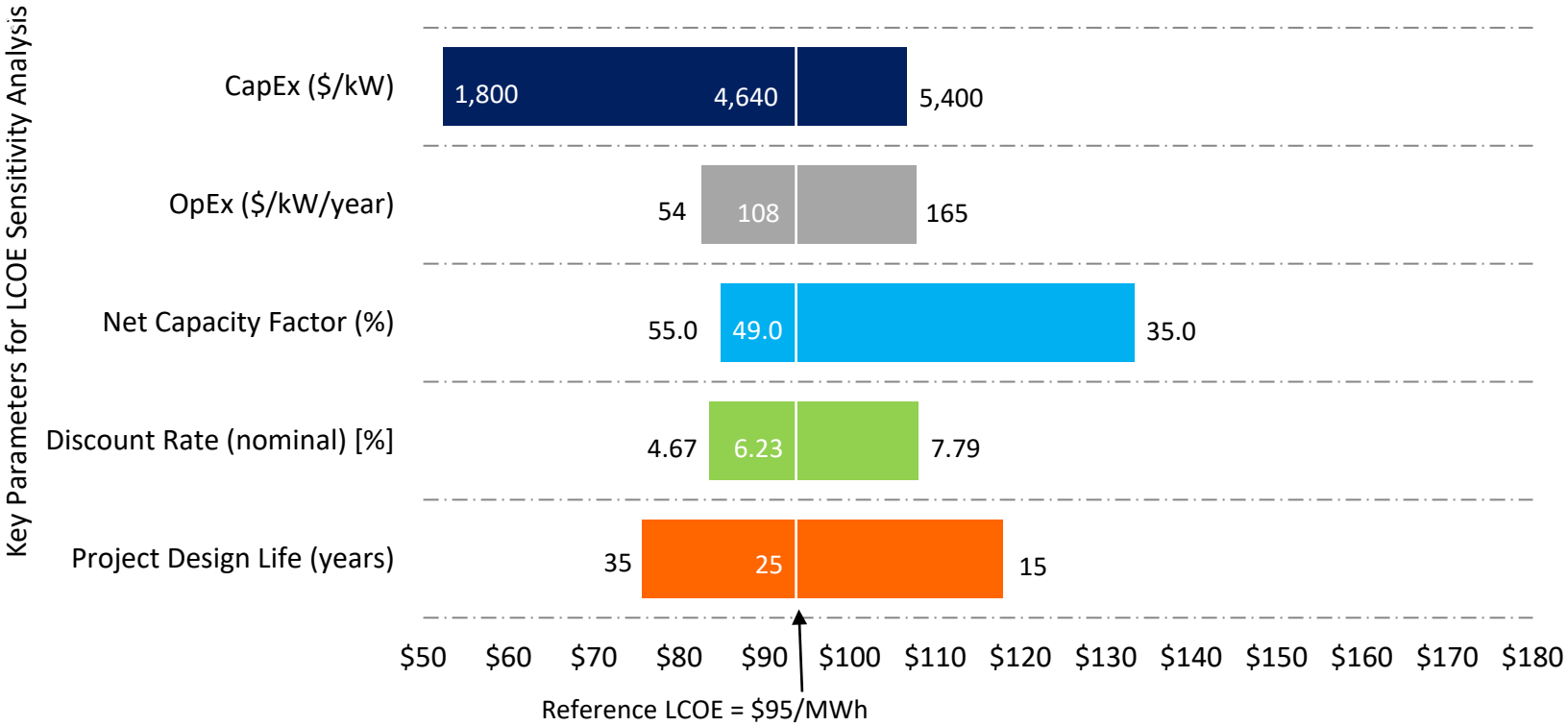

* Engineering Management cost small, but nonzero

# Levelized Cost Breakdown for Reference Floating Offshore Wind Plant



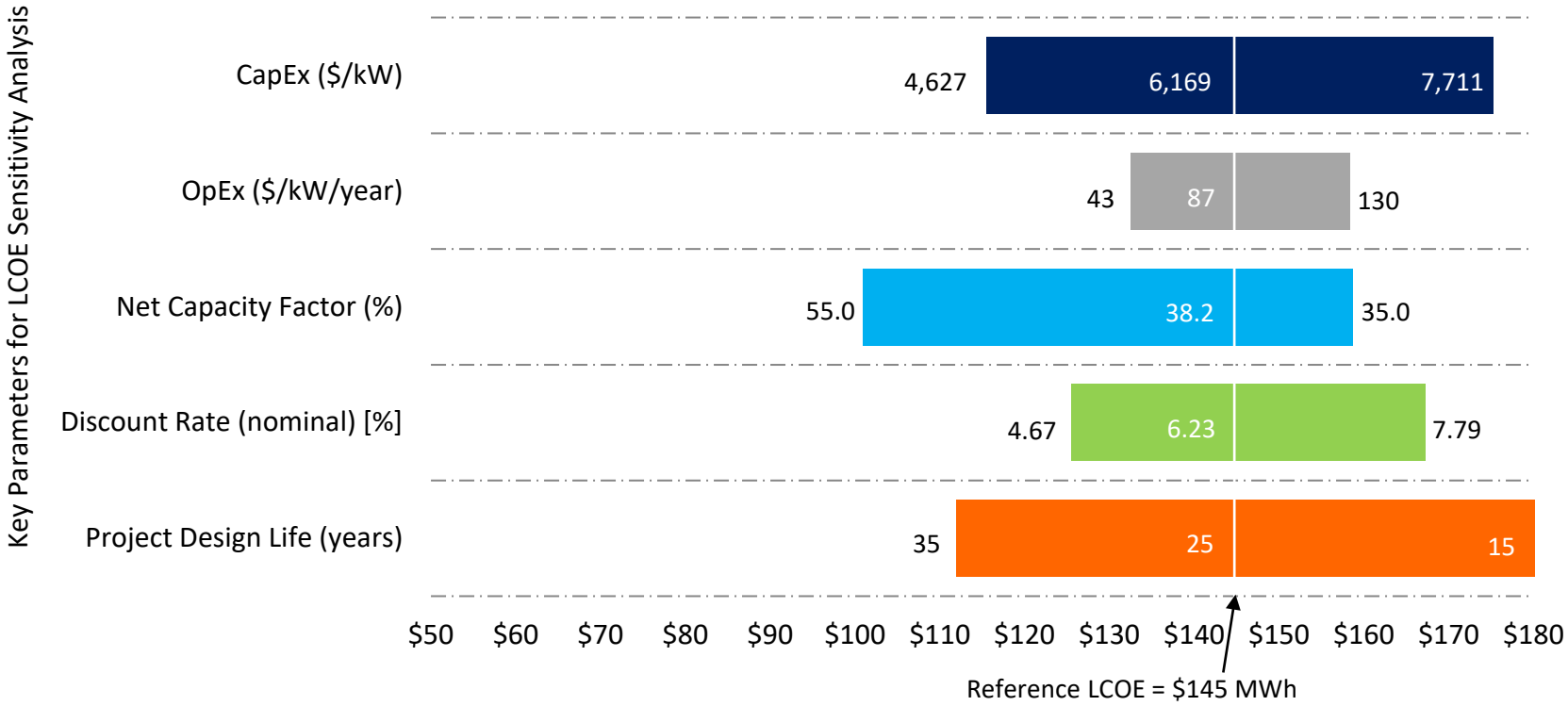

* Engineering Management cost small, but nonzero

# 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).

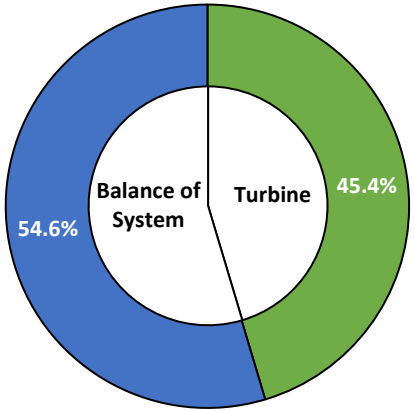
# Distributed Wind Site Characteristics and Performance

| 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 | 2.0 | 2.0 | 2.0 | 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 | 6.9 | 6.9 | 6.9 | % |
| 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 | % |

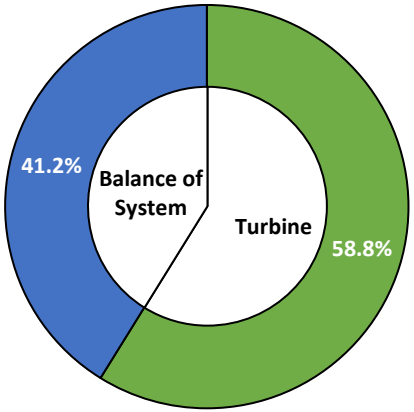
Residential and commercial wind turbines assume stall-regulated power curves; the large wind turbine assumes pitch-regulated power curve.
Power curve data available on https://github.com/NREL/turbine-models.

# Distributed Wind Project Component Cost Breakdown and Estimated Operational Expenditures

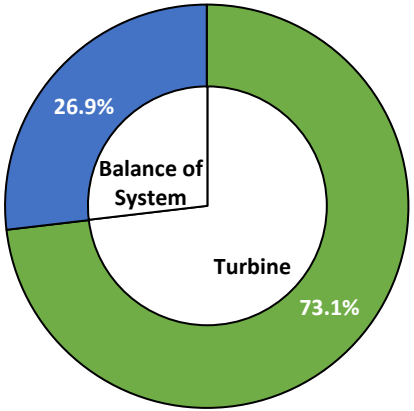
Residential (20 kW)




Commercial (100 kW)




Large (1,500 kW)




| Parameter | Wind Turbine Class | | | Units |
|---|---|---|---|---|
| | Residential | Commercial | Large | |
| Wind turbine CapEx | 3,823 | 3,723 | 2,392 | $/kW |
| BOS CapEx | 4,602 | 2,604 | 878 | $/kW |
| Total CapEx | 8,425 | 6,327 | 3,270 | $/kW |
| OpEx | 39 | 39 | 39 | $/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, $39/kW/yr is assumed for each wind class and is aligned with the 2023 ATB atb.nrel.gov.

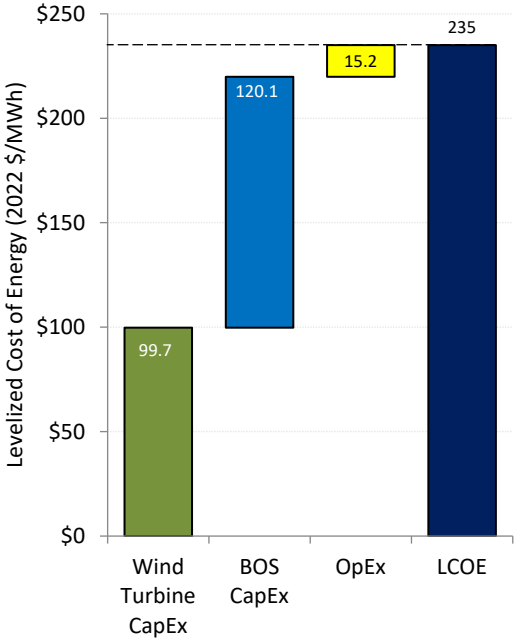
# Distributed Wind Project Financial Assumptions

| Parameter | Nominal | Real |
|---|---|---|
| Weighted average cost of capital (%) | 6.57 | 3.97 |
| Capital recovery factor (%) | 8.25 | 6.38 |
| Fixed charge rate (%) | 8.7 | 6.73 |

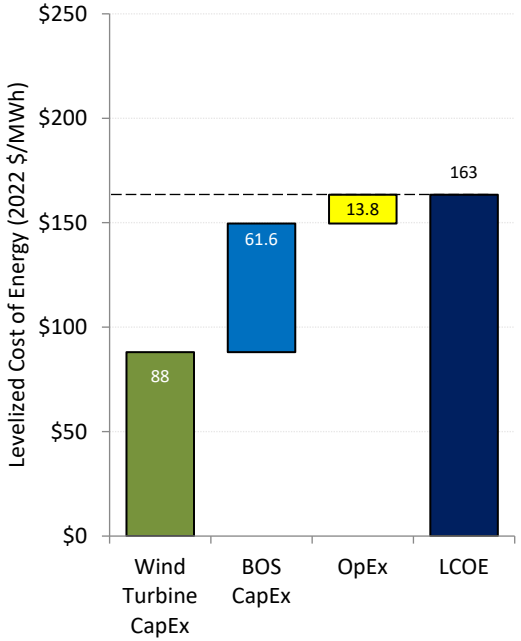
- The economic evaluation of wind energy investments in this analysis uses the fixed charge rate (FCR) method used in NREL's Annual Technology Baseline and Standard Scenarios web page: atb.nrel.gov.
- The FCR represents the amount of annual revenue required to pay the carrying charge as applied to the 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 2023 Annual Technology Baseline atb.nrel.gov.
- Additional financial assumption details are displayed in the Appendix.

# LCOE Breakdown for Reference Distributed Wind Projects

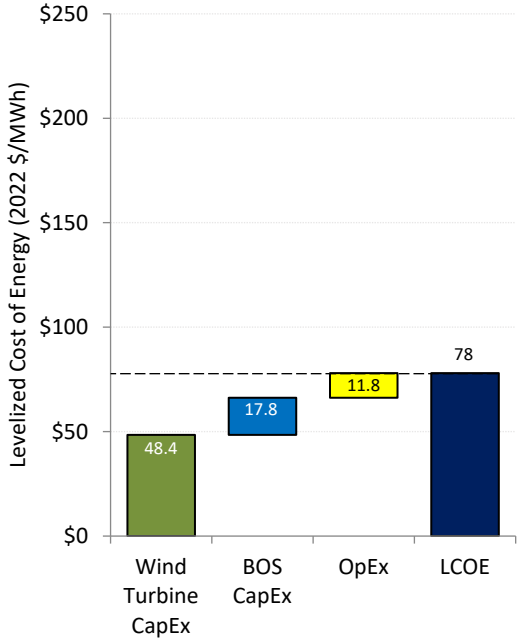
## Single-Turbine Residential (20 kW)




## Single-Turbine Commercial (100 kW)




## Single-Turbine Large (1,500 kW)



# 6. References

# References


Beiter, P., W. Musial, A. Smith, L. Kilcher, R. Damiani, M. Maness, et al. 2016. *A Spatial-Economic Cost Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015-2030*. Golden, CO: National Renewable Energy Laboratory. NREL/TP6A20-66579. https://www.nrel.gov/docs/fy16osti/66579.pdf.

Bureau of Labor and Statistics. Undated. "CPI Inflation Calculator." Accessed September 2022. https://www.bls.gov/data/#calculators.

COREWIND. 2021. *Floating Wind O&M Strategies Assessment*. COREWIND. August 2021. https://corewind.eu/wp-content/uploads/files/publications/COREWIND-D4.2-Floating-Wind-O-and-M-Strategies-Assessment.pdf.

Eberle, A., O. Roberts, A. Key, P. Bhaskar, and K. Dykes. 2019. *NREL's Balance-of-System Cost Model for Land-Based Wind*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72201. https://www.nrel.gov/docs/fy19osti/72201.pdf.

Hammond, R. and A. Cooperman. 2022. *Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT).* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-83712. https://www.nrel.gov/docs/fy23osti/83712.pdf.

McCabe, K., A. Prasanna, J. Lockshin, P. Bhaskar, T. Bowen, R. Baranowski, B. Sigrin, and E. Lantz. 2022. *Distributed Wind Energy Futures Study*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-82519. https://www.nrel.gov/docs/fy22osti/82519.pdf.

Musial, W., P. Spitsen, P. Duffy, P. Beiter, M. Shields, D. Mulas Hernando, R. Hammond, M. Marquis, J. King, and S. Sathish. 2023. *Offshore Wind Market Report: 2023 Edition*. Washington, D.C.: U.S. Department of Energy. DOE/GO-102023-6059. https://cms.doe.gov/sites/default/files/2023-08/offshore-wind-market-report-2023-edition_0.pdf.

National Renewable Energy Laboratory (NREL). 2017. "Wind Resource Maps and Data." https://www.nrel.gov/gis/wind-resource-maps.html.

National Renewable Energy Laboratory (NREL). Undated. "Annual Technology Baseline." Accessed September 2022. https://atb.nrel.gov/.

# References


Short, W., D. J. Packey, and T. Holt. 1995. *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-462-5176. http://www.nrel.gov/docs/legosti/old/5173.pdf.

Shields, M., P. Beiter, and J. Nunemaker. 2022. *A Systematic Framework for Projecting the Future Cost of Offshore Wind Energy.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-81819. https://www.nrel.gov/docs/fy23osti/81819.pdf.

Stehly, T. and P. Duffy. 2022. *2020 Cost of Wind Energy Review*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-81209. https://www.nrel.gov/docs/fy22osti/81209.pdf.

Stehly, T., P. Beiter, P. Duffy. 2020. *2019 Cost of Wind Energy Review*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-78471. https://www.nrel.gov/docs/fy21osti/78471.pdf.

UL Solutions. Undated. "Wind Farm Design Software Developed on More Than 30 Years of Expertise." https://aws-dewi.ul.com/software/openwind/.

U.S. Department of the Treasury. 2023a. "Domestic Content Bonus Credit Guidance under Sections 45, 45Y, 48, and 48E." Accessed December 2023. https://www.irs.gov/pub/irs-drop/n-23-38.pdf.

U.S. Department of the Treasury. 2023b. "Treasury Department Releases Guidance to Boost American Clean Energy Manufacturing." Accessed December 2023. https://home.treasury.gov/news/press-releases/jy1477.

Valpy, B. G. Hundleby, K. Freeman, A. Roberts, A. Logan. 2017. Future renewable energy costs: Offshore wind; 57 technology innovations that will have greater impact on reducing the cost of electricity from European offshore wind farms. InnoEnergy and BVG Associates. https://bvgassociates.com/wp-content/uploads/2017/11/InnoEnergy-Offshore-Wind-anticipated-innovations-impact-2017_A4.pdf.

Wiser, R. and M. Bolinger. 2023. *Land-Based Wind Market Report: 2023 Edition*. Washington, D.C.: U.S. Department of Energy DOE/GO-102023-6055. https://www.energy.gov/eere/wind/articles/land-based-wind-market-report-2023-edition.

# References

Wiser, R., J. Rand, J. Seel, P. Beiter, E. Baker, E. Lantz, and P. Gilman. 2021. “Expert Elicitation Survey Predicts 37% to 49% Declines in Wind Energy Costs by 2050.” *Nature Energy* 6: 555–565. https://doi.org/10.1038/s41560-021-00810-z.

# 7. Appendix

# FY 2023 GPRA Values Reported in Original Baseline Plant Terms

- WETO is required to report annual GPRA results in the same terms as they were established.
- The table reports the FY 2023 GPRA values in the same terms as when the GPRA targets were established (i.e., land-based wind 2015 USD and offshore wind 2018 USD).
- All WETO FY 2023 GPRA targets were met.
- In FY 2024 WETO will report against the new GPRA targets as established in this report.

| | | Land-Based Wind | | Fixed-Bottom Offshore Wind | |
|---|---|---|---|---|---|
| **Parameter** | **Unit** | **FY22 Value** | **FY23 Value** | **FY22 Value** | **FY23 Value** |
| Annual average wind speed (50 m above the ground) | m/s | 7.25 | 7.25 | 8.43 | 8.43 |
| Wind turbine rating | MW | 3 | 3.3 | 8 | 12 |
| Rotor diameter | m | 127 | 148 | 159 | 216 |
| Hub height | m | 95 | 100 | 102 | 137 |
| CapEx | $/kW | 1,501 | 1,750 | 3,871 | 3,965 |
| OpEx | $/kW-yr | 40 | 41 | 111 | 90 |
| Net capacity factor | (%) | 43.1 | 46.8 | 49 | 49 |
| Real fixed charge rate | (%) | 5.88 | 5.88 | 5.82 | 5.82 |
| LCOE | 2015$/MWh | 29 | 28 | 70 | 63 |
| | 2018$/MWh | N/A | N/A | 70 | 63 |
| | 2022$/MWh | 36 | 35 | 83 | 75 |
| FY23 GPRA LCOE target (inflation adjusted) | cents/kWh | 2.9 | 2.8 | 7 | 6.9 |
| FY23 GPRA status | N/A | Met | Met | Met | Met |

# Methodology for Estimating Manufactured Product Component Breakdown for Land-Based Wind Facilities

- The categorization of applicable project components for a land-based wind facility are specified in the Internal Revenue Service Notice 2023-38, section 3.04 and are subject to steel/iron or manufactured product requirement.
  - Manufactured product costs and cost contributions were calculated for a range of wind turbine sizes.
  - Wind turbine component masses from planned or offered wind turbines in the United States in the range of 2–6 MW were used to develop scaling relationships.
  - The Cost and Scaling Model (https://github.com/WISDEM/WISDEM) was then used to estimate component masses and costs.
  - Average component price values and relative manufactured product contributions were reviewed by industry members, including representatives from turbine original equipment manufacturers and blade manufacturers.

**Table 2 - Categorization of Applicable Project Components**

| Applicable Project | Applicable Project Component | Categorization |
|---|---|---|
| Land-based wind facility | Tower | Steel/Iron |
| | Steel or iron rebar in foundation | Steel/Iron |
| | Nacelle | Manufactured Product |
| | Blades | Manufactured Product |
| | Rotor hub | Manufactured Product |
| | Power Converter | Manufactured Product |
| | Wind tower flanges | Manufactured Product |

Table source: U.S. Department of the Treasury (2023a)

# 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/m2 | 192 | Calculation |
| Annual average wind speed at 50 meters | m/s | 7.25 | Reference site wind speed |
| Annual average wind speed at hub height | m/s | 8.01 | Between International Electrotechnical Class (IEC) class III (7.5 m/s) and IEC class II (8.5 m/s) |
| Weibull k factor | | 2.0 | |
| Shear exponent | | 0.143 | Shear for neutral stability conditions |
| Total system losses | % | 18.9% | atb.nrel.gov |
| Net energy capture | MWh/MW/yr | 4,100 | System Advisor Model (SAM) calculation |
| Net capacity factor | % | 46.8% | |

# Land-Based Wind System CapEx Breakdown

| Parameter | Value ($/kW) | Notes |
|---|---|---|
| **CapEx** | | |
| Total CapEx | 1,750 | Calculation |
| Turbine | 969 | Cost and Scaling Model (https://github.com/WISDEM/WISDEM) |
| Rotor module | 300 | |
| Blades | 251 | |
| Pitch assembly | 12 | |
| Hub assembly | 38 | |
| Nacelle module | 424 | |
| Nacelle structural assembly | 67 | |
| Drivetrain assembly | 210 | |
| Nacelle electrical assembly | 122 | |
| Yaw assembly | 25 | |
| Tower module | 245 | |

(Continued on next slide)

# Land-Based Wind System CapEx Breakdown (continued)

| Parameter | Value | Notes |
|---|---|---|
| **CapEx** | | |
| Balance of system | 517 | Land-based Balance of System Systems Engineering [LandBOSSE] (Eberle et al. 2019) |
| Development | 32 | |
| Engineering and project management | 12 | |
| Foundation | 106 | |
| Site access and staging | 42 | |
| Assembly and installation | 89 | |
| Electrical infrastructure | 64 | |
| Wind turbine transport | 172 | |
| Soft costs | 264 | |
| Construction finance | 102 | atb.nrel.gov |
| Contingency | 48 | Includes insurance, permitting, bonding, and markup estimates |
| Wind turbine warranty | 115 | Assumes 2-year warranty |

# Land-Based Wind OpEx and Financing Terms

| Parameter | Units | Value | Notes |
|---|---|---|---|
| **OpEx** | | | |
| Total OpEx | $/kW/year | 41 | 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) | % | 6.5% | |
| Construction finance factor | % | 106.2% | Calculation |
| Debt fraction | % | 71.5% | atb.nrel.gov |
| Debt interest rate (nominal) | % | 7% | |
| Return on equity (nominal) | % | 10% | |
| WACC (nominal; after-tax) | % | 6.57% | Calculation |
| WACC (real; after-tax) | % | 3.97% | |
| Capital recovery factor (nominal; after-tax) | % | 8.25% | |
| Capital recovery factor (real; after-tax) | % | 6.38% | |
| 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]) | % | 84.1% | Calculation |
| Project finance factor | % | 106% | |
| FCR (nominal) | % | 8.70% | |
| FCR (real) | % | 6.73% | |
| Levelized cost of energy | $/MWh | 39 | 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 | Number | 50 | Calculation |
| Turbine rating | MW | 12 | Informed by Offshore Wind Market Report: 2023 Edition (Musial et al. 2023) and early U.S. fixed-bottom offshore wind projects |
| Rotor diameter | m | 216 | |
| Hub height | m | 137.0 | |
| Specific power | W/m2 | 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 | Units | Value | Notes |
|---|---|---|---|
| **CapEx** | | | |
| Total CapEx | $/kW | 4,640 | |
| Turbine | $/kW | 1,700 | Informed by Offshore Wind Market Report: 2023 Edition (Musial et al. 2023) and conversatons with industry partners |
| Rotor nacelle assembly | $/kW | 1,462 | |
| Tower | $/kW | 238 | |
| Balance of System | $/kW | 2,130 | BOS Costs computed with ORBIT (Nunemaker et al. 2020) |
| Development | $/kW | 96 | |
| Project management | $/kW | 2 | |
| Substructure and foundation | $/kW | 609 | |
| Substructure | $/kW | 226 | |
| Foundation | $/kW | 383 | |
| Port and staging, logistics, transportation | $/kW | 0 | |
| Electrical infrastructure | $/kW | 1,027 | |
| Array cable system | $/kW | 392 | |
| Export cable system | $/kW | 436 | |
| Grid connection | $/kW | 200 | |
| Assembly and installation | $/kW | 229 | |
| Turbine installation | $/kW | 90 | |
| Substructure and foundation installation | $/kW | 139 | |
| Soft Costs | $/kW | 810 | Soft Costs computed using same methodology as ORCA (Beiter et al. 2016) |
| Insurance during construction | $/kW | 44 | |
| Decommissioning bond | $/kW | 116 | |
| Construction finance | $/kW | 192 | |
| Sponsor contingency | $/kW | 414 | |
| Procurement contingency | $/kW | 182 | |
| Installation contingency | $/kW | 231 | |
| Project completions / commissioning | $/kW | 44 | |

# Fixed-Bottom Offshore Wind OpEx and Financing Terms

| Assumption | Units | Value | Notes |
|---|---|---|---|
| **OpEx** | | | |
| Total OpEx | $/kW/year | 108 | Calculated with WOMBAT |
| Operations (pretax) | $/kW/year | 17 | |
| Maintenance | $/kW/year | 91 | |
| **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 | % | 60% | |
| Debt interest rate (nominal) | % | 5.9% | |
| Return on equity (nominal) | % | 9.0% | |
| WACC (nominal; after-tax) | % | 6.2% | Calculation |
| WACC (real; after-tax) | % | 3.6% | |
| Capital recovery factor (nominal; after-tax) | % | 8.0% | |
| Capital recovery factor (real; after-tax) | % | 6.2% | |
| Depreciable basis | % | 100% | Simplified depreciation schedule |
| Depreciation schedule | | 5 year MACRS | Standard for U.S. wind projects |
| Depreciation adjustment (NPV) | % | 84.8% | Calculation |
| Project finance factor | % | 105% | |
| FCR (nominal) | % | 8.4% | |
| FCR (real) | % | 6.5% | |
| Levelized cost of energy | $/MWh | 95 | 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 | Number | 50 | Calculation |
| Turbine rating | MW | 12 | Informed by Offshore Wind Market Report: 2023 Edition (Musial et al. 2023) and early U.S. fixed-bottom offshore wind projects |
| Rotor diameter | m | 216 | |
| Hub height | m | 137.0 | |
| Specific power | W/m2 | 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 | Units | Value | Notes |
|---|---|---|---|
| **CapEx** | | | |
| Total CapEx | $/kW | 6,169 | |
| Turbine | $/kW | 1,700 | Informed by Offshore Wind Market Report: 2023 Edition (Musial et al. 2023) and conversatons with industry partners |
| Rotor nacelle assembly | $/kW | 1,462 | |
| Tower | $/kW | 238 | |
| Balance of System | $/kW | 3,409 | BOS Costs computed with ORBIT (Nunemaker et al. 2020) |
| Development | $/kW | 96 | |
| Project management | $/kW | 2 | |
| Substructure and foundation | $/kW | 1,708 | |
| Substructure | $/kW | 1,189 | |
| Foundation | $/kW | 519 | |
| Port and staging, logistics, transportation | $/kW | 0 | |
| Electrical infrastructure | $/kW | 1,157 | |
| Array cable system | $/kW | 536 | |
| Export cable system | $/kW | 408 | |
| Grid connection | $/kW | 213 | |
| Assembly and installation | $/kW | 279 | |
| Turbine installation | $/kW | 0 | |
| Substructure and foundation installation | $/kW | 279 | |
| Lease price | $/kW | 167 | |
| Soft Costs | $/kW | 1,060 | Soft Costs computed using same methodology as ORCA (Beiter et al. 2016) |
| Insurance during construction | $/kW | 59 | |
| Decommissioning bond | $/kW | 147 | |
| Construction finance | $/kW | 255 | |
| Sponsor contingency | $/kW | 540 | |
| Procurement contingency | $/kW | 245 | |
| Installation contingency | $/kW | 295 | |
| Project completions / commissioning | $/kW | 59 | |

# Floating Offshore Wind OpEx and Financing Terms

| Assumption | Units | Value | Notes |
|---|---|---|---|
| **OpEx** | | | |
| Total OpEx | $/kW/year | 87 | Calculated with WOMBAT |
| Operations (pretax) | $/kW/year | 30 | |
| Maintenance | $/kW/year | 56 | |
| **Financials** | | | |
| Project design life | Years | 25 | Offshore wind roject 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 | % | 60% | |
| Debt interest rate (nominal) | % | 5.9% | |
| Return on equity (nominal) | % | 9.0% | |
| WACC (nominal; after-tax) | % | 6.2% | Calculation |
| WACC (real; after-tax) | % | 3.6% | |
| Capital recovery factor (nominal; after-tax) | % | 8.0% | |
| Capital recovery factor (real; after-tax) | % | 6.2% | |
| Depreciable basis | % | 100% | Simplified depreciation schedule |
| Depreciation schedule | | 5 year MACRS | Standard for U.S. wind projects |
| Depreciation adjustment (NPV) | % | 84.8% | Calculation |
| Project finance factor | % | 105% | |
| FCR (nominal) | % | 8.4% | |
| FCR (real) | % | 6.5% | |
| Levelized cost of energy | $/MWh | 145 | 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 | 1500 | Representative of residential distributed wind project |
| Number of turbines | | 1 | 1 | 1 | |
| Turbine rating | kW | 20 | 100 | 1500 | "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/m2 | 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 | International Electrotechnical Commission (IEC) class IV |
| Weibull k factor | N/a | 2.0 | 2.0 | 2.0 | |
| Shear exponent | N/a | 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 (undated): 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 | 8,425 | 6,327 | 3,270 | |
| Turbine | $/kW | 3,823 | 3,723 | 2,392 | atb.nrel.gov |
| Balance of system | $/kW | 4,602 | 2,604 | 879 | "NREL's Balance-of-System Cost Model for Land-Based Wind" (Eberle et. al., 2019) |
| **OpEx** | | | | | |
| Total OpEx | $/kW/year | 39 | 39 | 39 | "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% | 2021 Annual Technology Baseline (NREL's Annual Technology Baseline and Standard Scenarios web page: atb.nrel.gov) |
| Inflation rate | % | 2.5% | 2.5% | 2.5% | |
| Debt fraction | % | 72% | 72% | 72% | "Assessing the Future of Distributed Wind: Opportunities for Behind-the Meter Projects" (Lantz et. al., 2016) |
| Debt interest rate (nominal) | % | 7.00% | 7.00% | 7.00% | Lawrence Berkeley National Laboratory 2021 financial analysis |
| Return on equity (nominal) | % | 10.00% | 10.00% | 10.00% | |
| WACC (nominal; after-tax) | % | 6.57% | 6.57% | 6.57% | Calculation |
| WACC (real; after-tax) | % | 3.97% | 3.97% | 3.97% | |
| Capital recovery factor (nominal; after-tax) | % | 8.25% | 8.25% | 8.25% | |
| Capital recovery factor (real; after-tax) | % | 6.38% | 6.38% | 6.38% | |
| Depreciable basis | % | 100% | 100% | 100% | Simplified depreciation schedule |
| Depreciation schedule | N/a | 5-year MACRS | 5-year MACRS | 5-year MACRS | |
| Depreciation adjustment (NPV) | % | 84.1% | 84.1% | 84.1% | Calculation |
| Project finance factor | % | 106% | 106% | 106% | |
| FCR (nominal) | % | 8.70% | 8.70% | 8.70% | |
| FCR (real) | % | 6.73% | 6.73% | 6.73% | |
| Levelized cost of energy | $/MWh | 235 | 163 | 78 | Calculation |

# Thank You

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NREL/PR-5000-88335

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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