2021 Cost of Wind Energy Review

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List of Acronyms

AEP	annual energy production
ATB	Annual Technology Baseline
BOS	balance of system
CapEx	capital expenditures
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
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
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
OpEx	operational expenditures
ORCA	Offshore Wind Regional Cost Analyzer
PTC	production tax credit
USD	U.S. dollars
WACC	weighted-average cost of capital
WETO	Wind Energy Technologies Office
yr	year

Executive Summary

Executive Summary

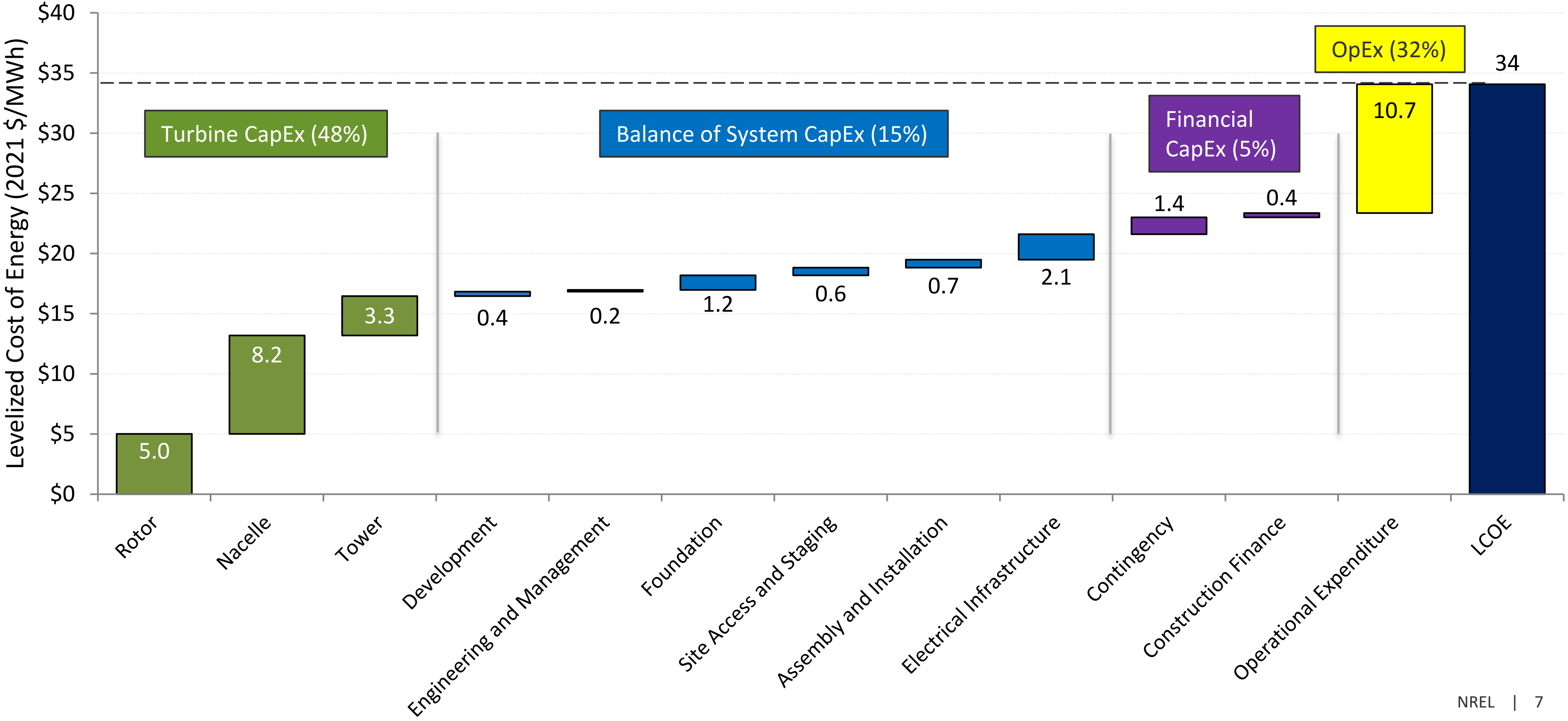
- The 11th annual *Cost of Wind Energy Review*, now presented in slide deck format, uses representative utility-scale and distributed wind energy projects to estimate the levelized cost of energy (LCOE) for land-based and offshore wind power plants in the United States.
  - Data and results are derived from 2021 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 2021 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 2022 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

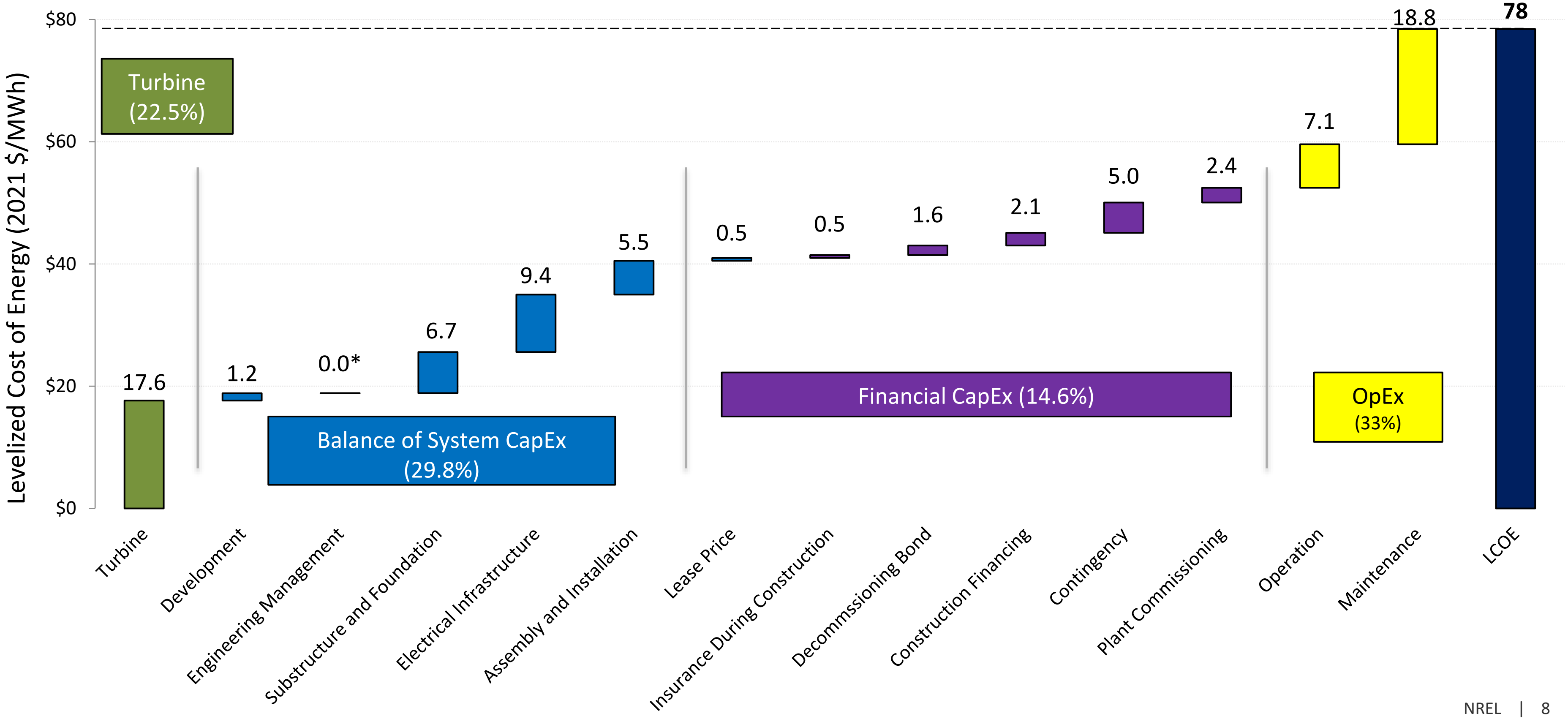
		Land-Based	Offshore		Distributed		
Parameter	Unit	Utility-Scale Land-Based	Utility-Scale (Fixed-Bottom)	Utility-Scale (Floating)	Single-Turbine (Residential)	Single-Turbine (Commercial)	Single-Turbine (Large)
Wind turbine rating	MW	3	8	8	20 (kW)	100 (kW)	1.5
Capital expenditures (CapEx)	$/kW	1,501	3,871	5,577	5,675	4,300	3,540
Fixed charge rate (FCR) [real]	%	5.88	5.82	5.82	5.88	5.42	5.42
Operational expenditures (OpEx)	$/kW/yr	40	111	118	35	35	35
Net annual energy production	MWh/MW/yr	3,775	4,295	3,336	2,580	2,846	3,326
Levelized Cost of Energy (LCOE)	$/MWh	34	78	133	143	94	68

Note: Unless specifically stated, all cost data are reported in 2021 U.S. dollars (USD).

Levelized Cost Breakdown for Reference Land-Based Wind Plant

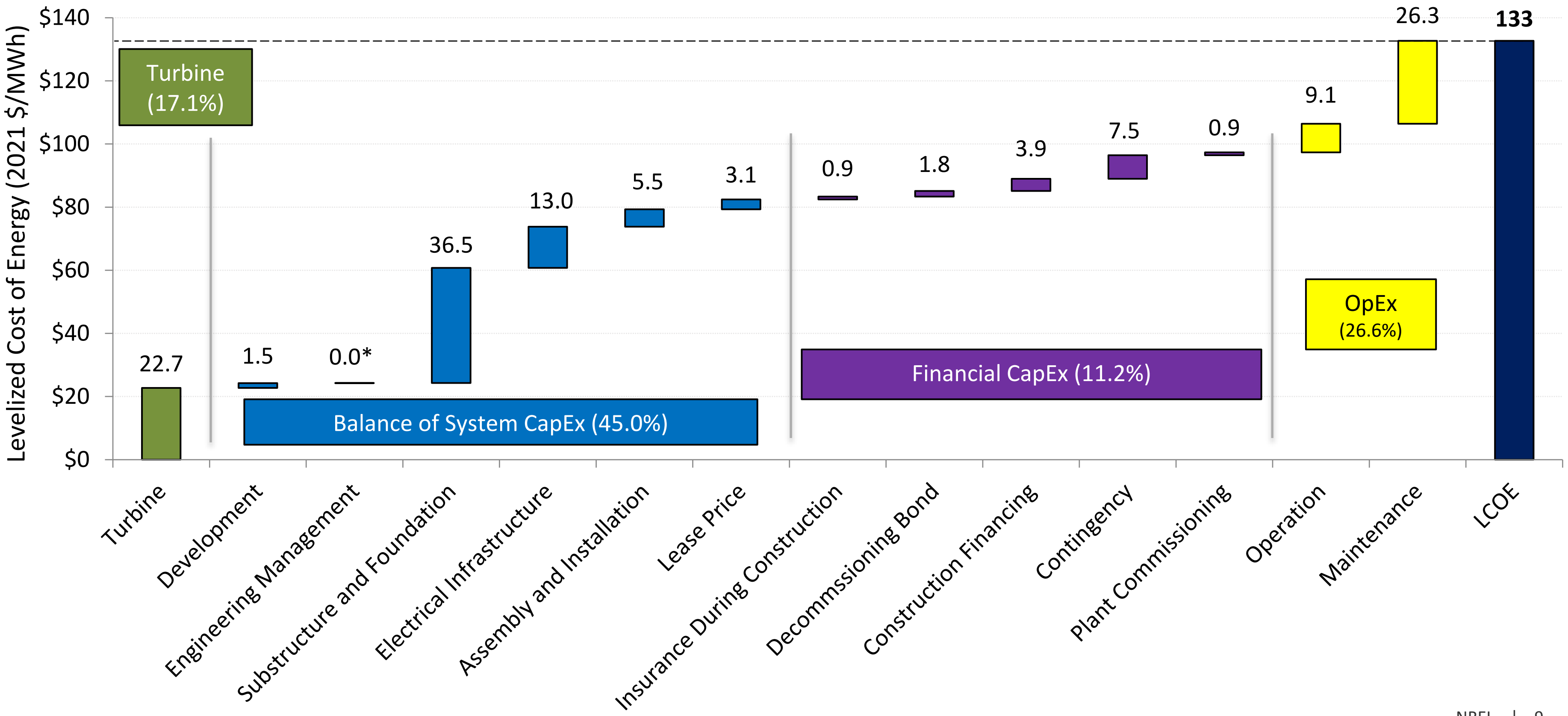


Levelized Cost Breakdown for Reference Fixed-Bottom Offshore Wind Plant



* Engineering Management cost small, but nonzero

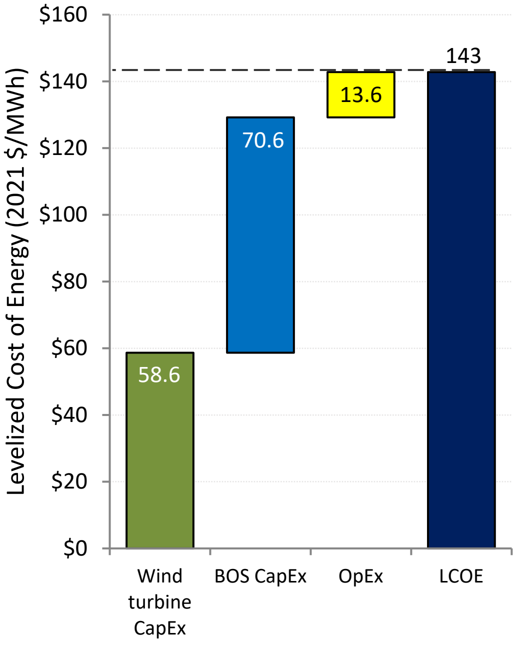
Levelized Cost Breakdown for Reference Floating Offshore Wind Plant



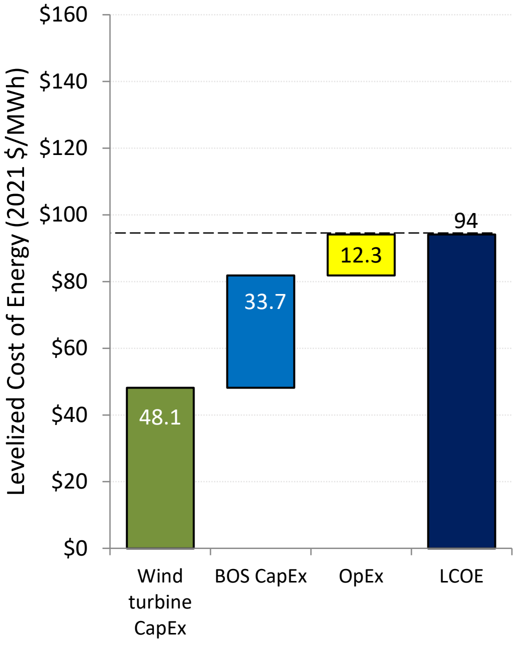
* Engineering Management cost small, but nonzero

Levelized Cost Breakdown for Reference Distributed Wind Projects

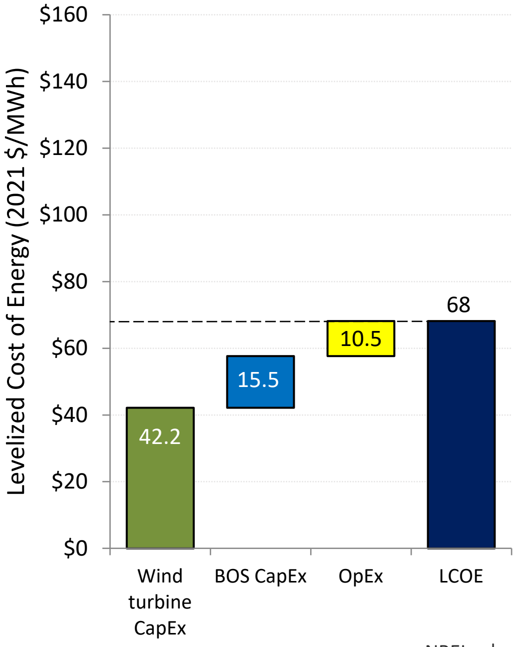
Single-Turbine Residential (20 kW)



Single-Turbine Commercial (100 kW)



Single-Turbine Large (1,500 kW)



Key Conclusions

- The reference project LCOE for **land-based installations is $34/MWh**, with a range of land-based estimates from the single-variable sensitivity analysis covering $28–$70/MWh.

- The **fixed-bottom offshore wind estimate is $78/MWh**, and the **floating substructure reference project estimate is $133/MWh**. These two reference projects give a single-variable sensitivity range of $53–$179/MWh. This range is primarily caused by the large variation in CapEx ($1,990–$6,971/kW) and project design life.

- The **residential and commercial reference distributed wind** system LCOE are estimated at **$143/MWh and $94/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 **$68/MWh**.

Contents

1. Background

Background

- The *2021 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])
- AEPnet = net average annual energy production (megawatt-hours per megawatt per year [MWh/MW/yr])
- OpEx = operational expenditures ($/kW/yr).

Background

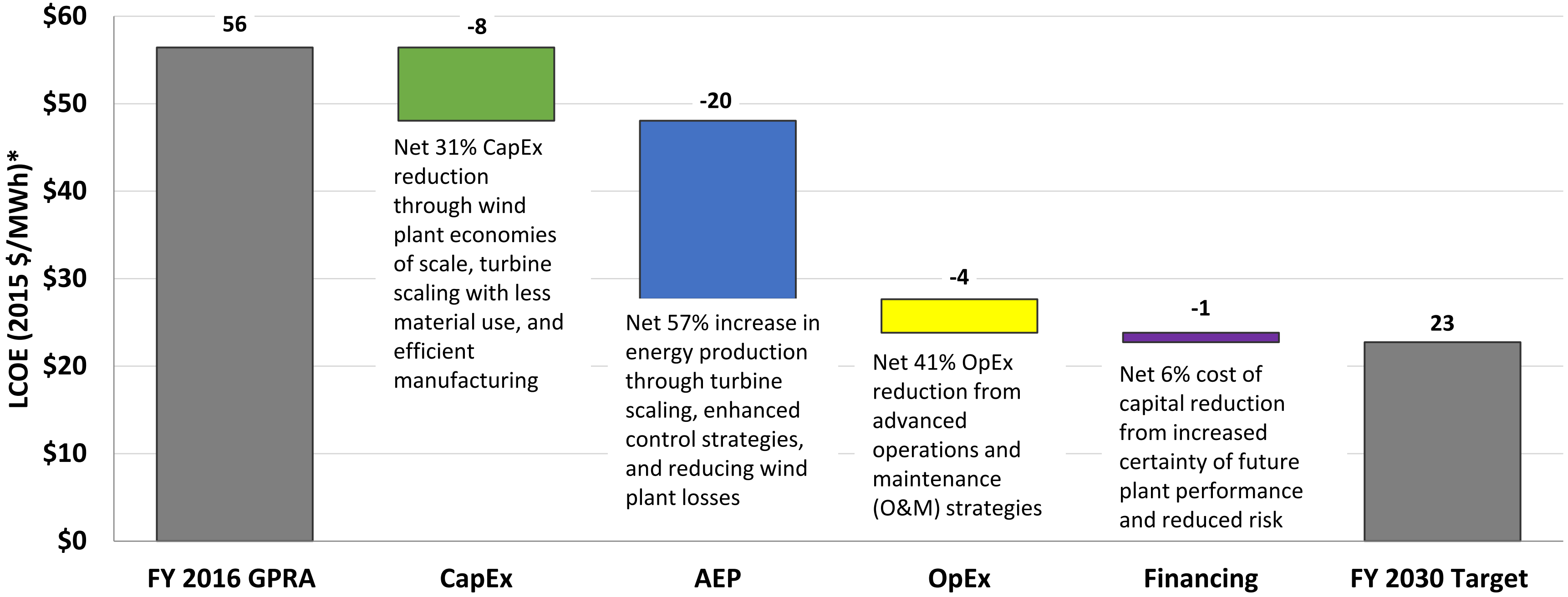
- This review also provides an update to the *2020 Cost of Wind Energy Review* (Stehly and Duffy 2021) and examines wind turbine costs, financing, and market conditions. The analysis includes:
  - Estimated LCOE for a representative **land-based wind energy project** installed in a moderate wind resource (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 2021 through 2030 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.
- The official GPRA LCOE end-point targets presented in this report were set in Fiscal Year (FY) 2016 for land-based wind energy and updated in FY 2019 for fixed-bottom offshore wind energy.
- Updates to the LCOE targets are periodically implemented to keep performance measures current with developments in the market and reduce the impact of inflation on LCOE for land-based and offshore wind energy projects.
- The GPRA targets are based on trajectories for land-based and fixed-bottom offshore wind projects that span from the current year to FY 2030.
- It is required that each year the actual costs for land-based and fixed-bottom wind LCOE be reported against the GPRA targets.
- This work provides the cost data to DOE to meet the annual GPRA reporting requirement.

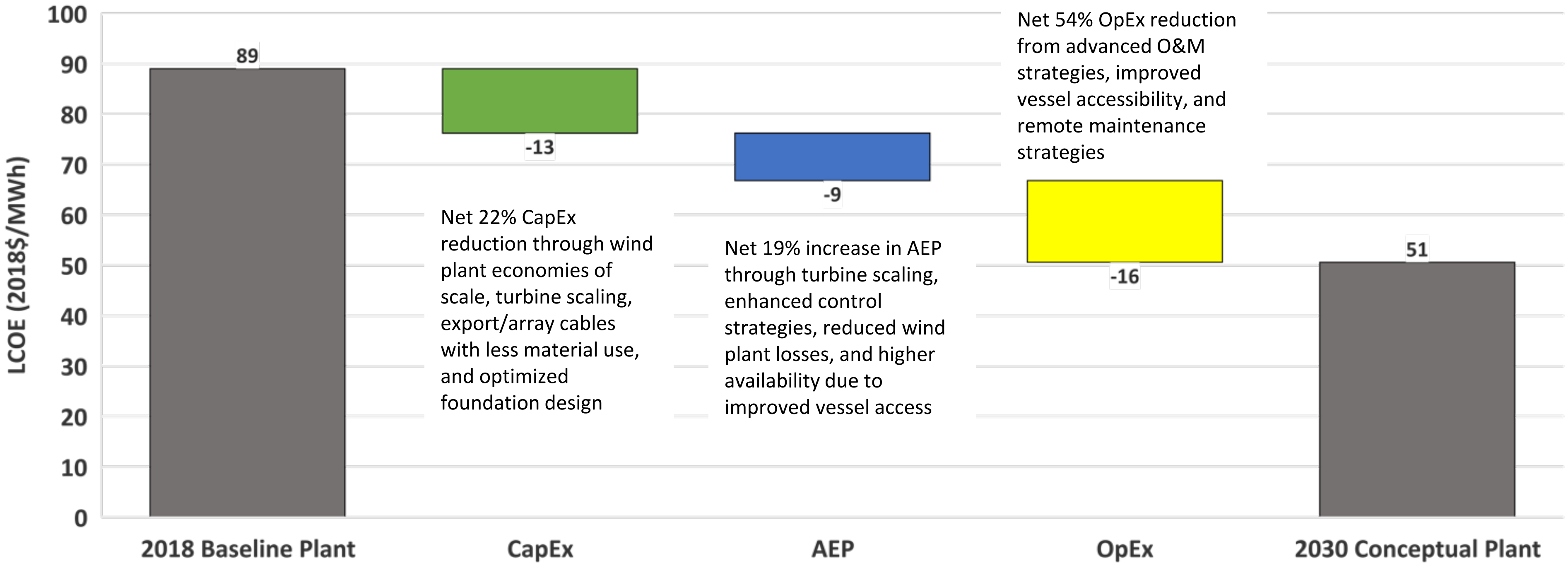
Government Performance and Results Act Cost Reduction Pathway From 2016 to 2030 for Land-Based Wind



- The land-based wind **GPRA baseline value starts at $56/MWh** (in 2015 USD) set in FY 2016, using the 2015 reference project data presented in Moné et al. (2017).
- The land-based wind **GPRA target is $23/MWh** by 2030 (in 2015 USD) and is derived from the analysis conducted in *Enabling the SMART Wind Power Plant of the Future Through Science-Based Innovation* (Dykes et al. 2017).

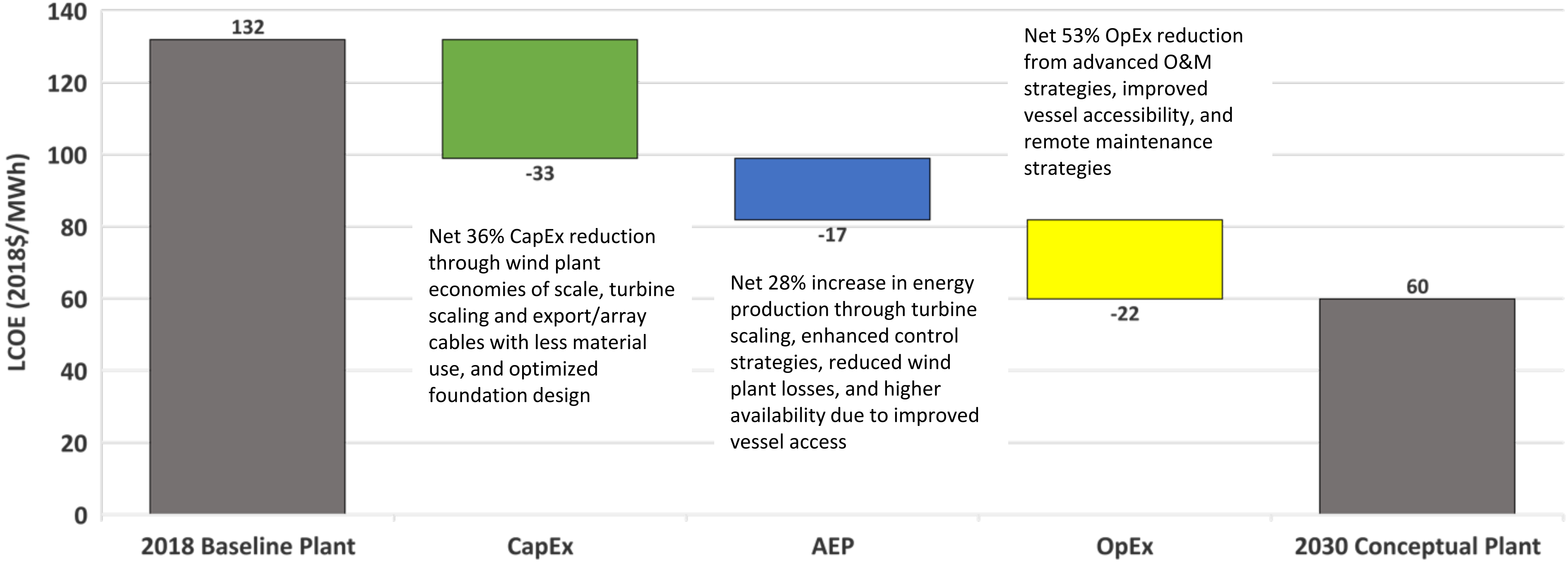
*The GPRA baseline and target LCOE are reported in 2015 USD for land-based wind energy because WETO will report land-based wind values in 2015 USD.

Government Performance and Results Act Cost Reduction Pathway From 2018 to 2030 for Fixed-Bottom Offshore Wind



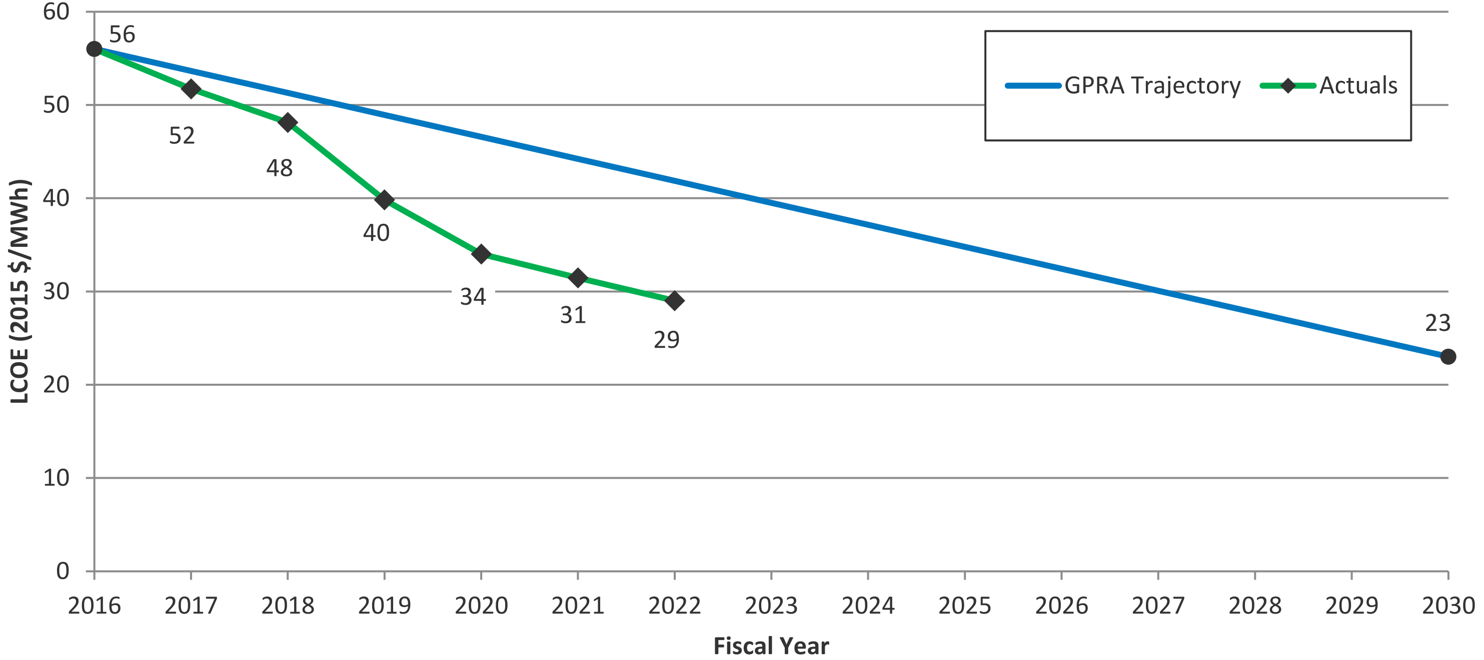
- The **GPRA baseline value starts at $89/MWh** (in 2018 USD) set in FY 2019 using 2018 reference project data reported in Stehly and Beiter (2019).
- The **GPRA target is $51/MWh by 2030** (in 2018 USD) and is derived for a fixed-bottom wind plant with 15 MW at the reference site based on cost reductions informed by technology innovations considered in the spatial economic analysis by Beiter et al. (2016).

Modeled Cost Reduction Pathway From 2018 to 2030 for Floating Offshore Wind Energy



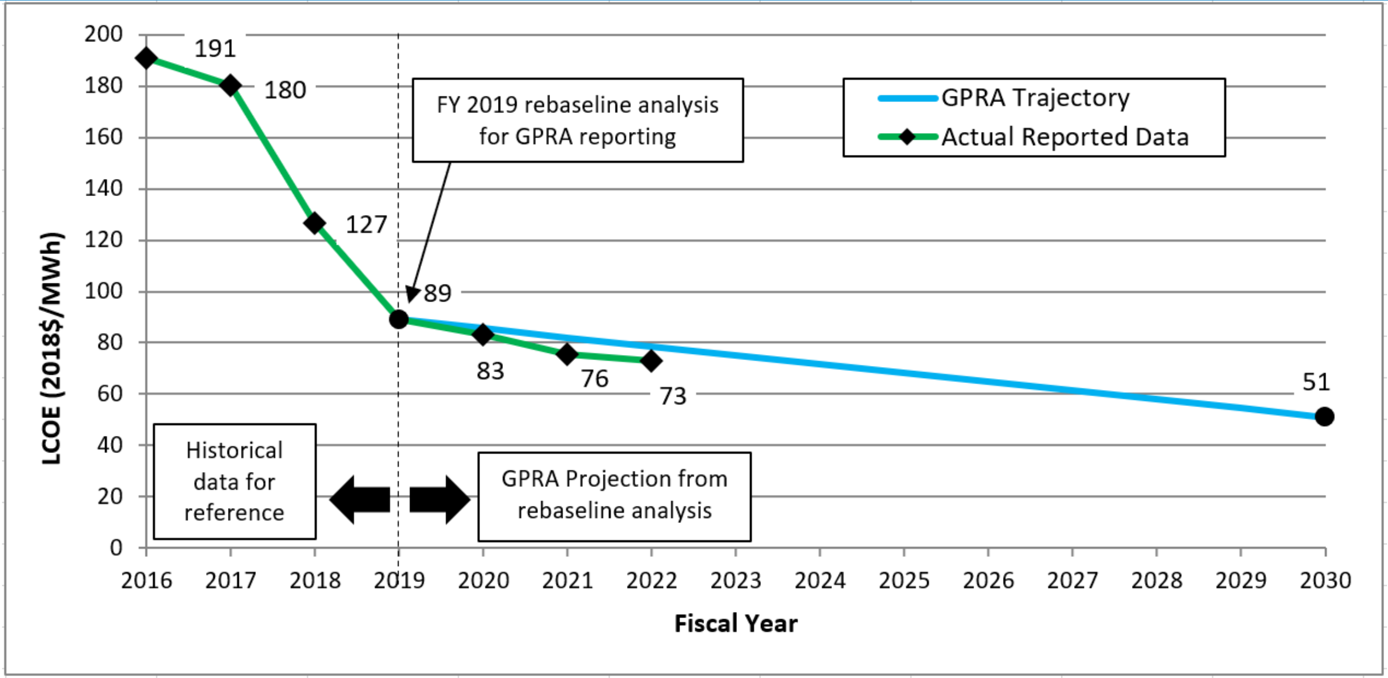
- **DOE had no official GPRA reporting requirement for floating offshore wind energy costs.**
- Projected floating offshore wind cost reductions are mapped to **$60/MWh in 2030** using similar methodology as fixed-bottom offshore wind.
- DOE has established a Floating Offshore Wind Shot target of $45/MWh by 2035 for a different reference site using a different set of assumptions.

GPRA Cost Reduction Pathway and Historical Cost Data From 2016 to 2030 for Land-Based Wind Energy



- The current and historical LCOE values (labeled as "Actuals") are tracked against the GPRA trajectory.
- The GPRA trajectory and LCOE values are reported in 2015 USD since WETO will report land-based wind energy values in 2015 USD.
- The FY 2022 LCOE is reported as $29/MWh instead of $34/MWh, as it was converted from 2021 USD to 2015 USD assuming a −12.5% cumulative rate of inflation from the Bureau of Labor and Statistics (undated), to compare against the GPRA trajectory.

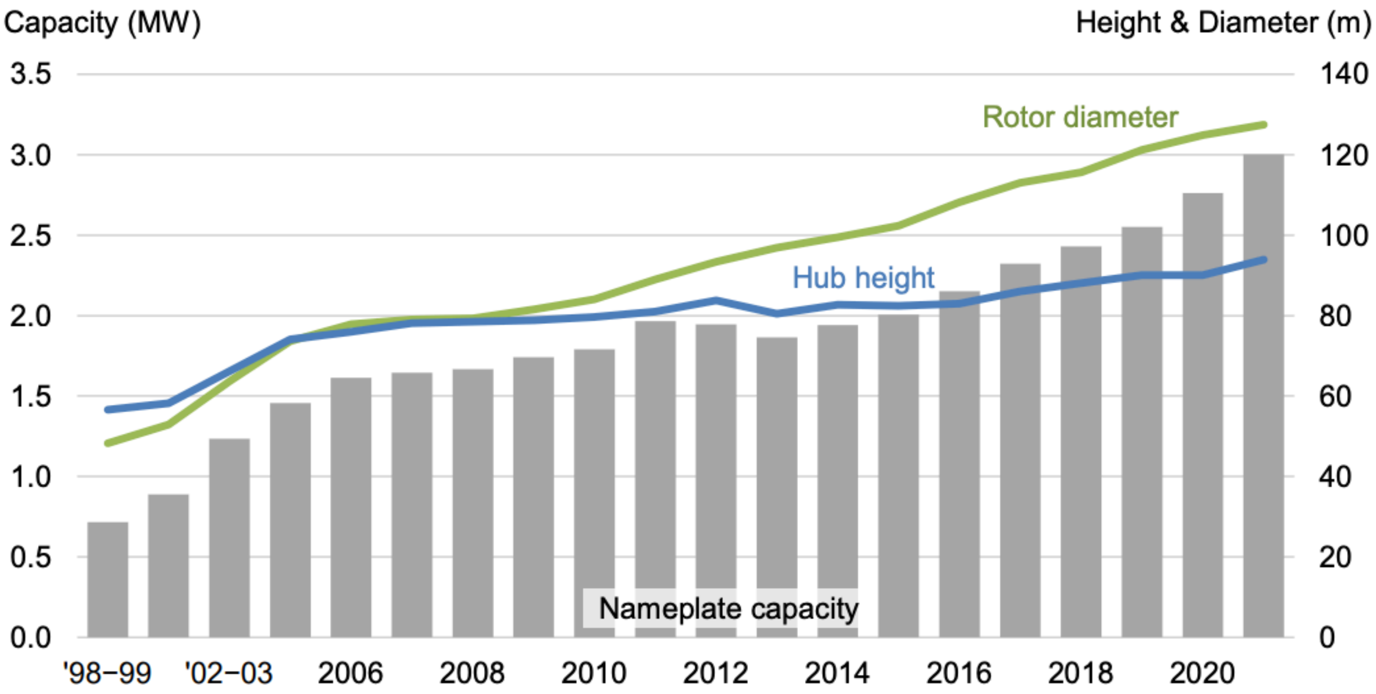
GPRA Cost Reduction Pathway and Historical Cost Data From 2016 to 2030 for Fixed-Bottom Offshore Wind Energy



- The current and historical LCOE values (labeled as "Actuals") are tracked against the GPRA trajectory.
- The GPRA trajectory and LCOE values are reported in 2018 USD per WETO's congressional reporting requirements.
- The **FY 2022 LCOE is $73/MWh (2018 USD)** after being converted from 2021 USD to compare against the GPRA trajectory.

3. Land-Based Wind Energy

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



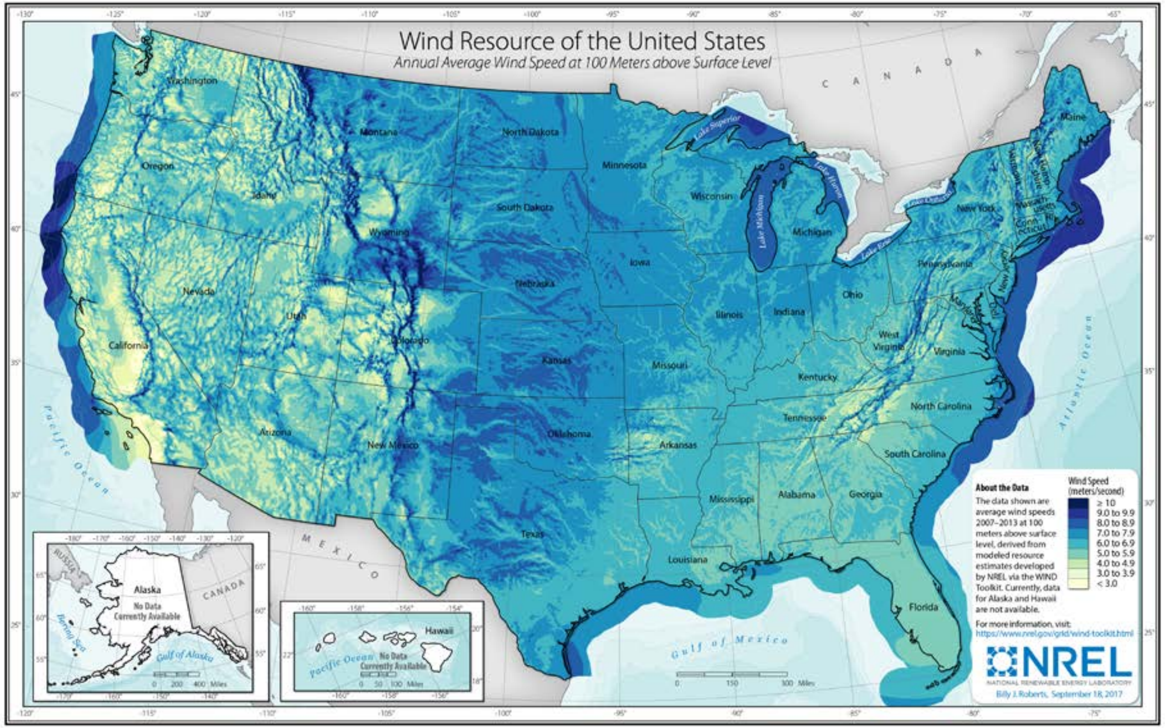
Source: Wiser and Bolinger (2022)

2021 average wind turbine characteristics

Parameter	Value
Wind turbine rating	3.0 MW
Rotor diameter	127 m
Hub height	95 m
Specific power	237 W/m^2
Wind plant capacity	200 MW
Number of turbines	67

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

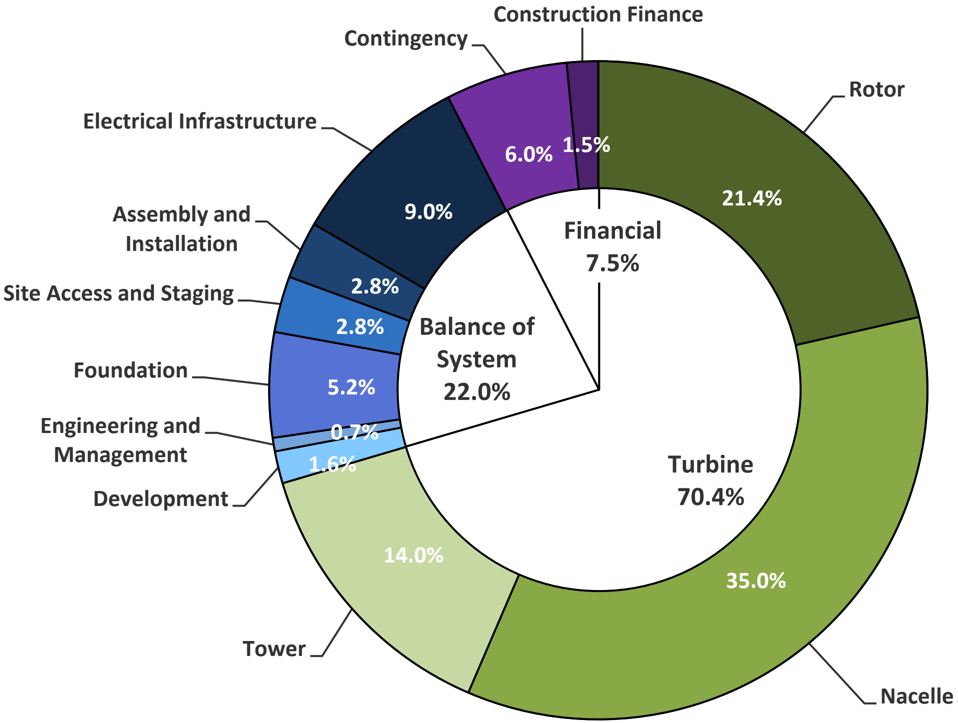
Reference Land-Based Wind Site Characteristics and Performance



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	7.95 m/s
Weibull k	2.0 (factor)
Shear exponent	0.14
Gross energy capture	4,395 MWh/MW/yr
Gross capacity factor	50.2%
Losses	15%
Availability	98%
Total losses	16.7%
Net energy capture	3,661 MWh/MW/yr
Net capacity factor	41.8%

Land-Based Wind Project Component Cost Breakdown

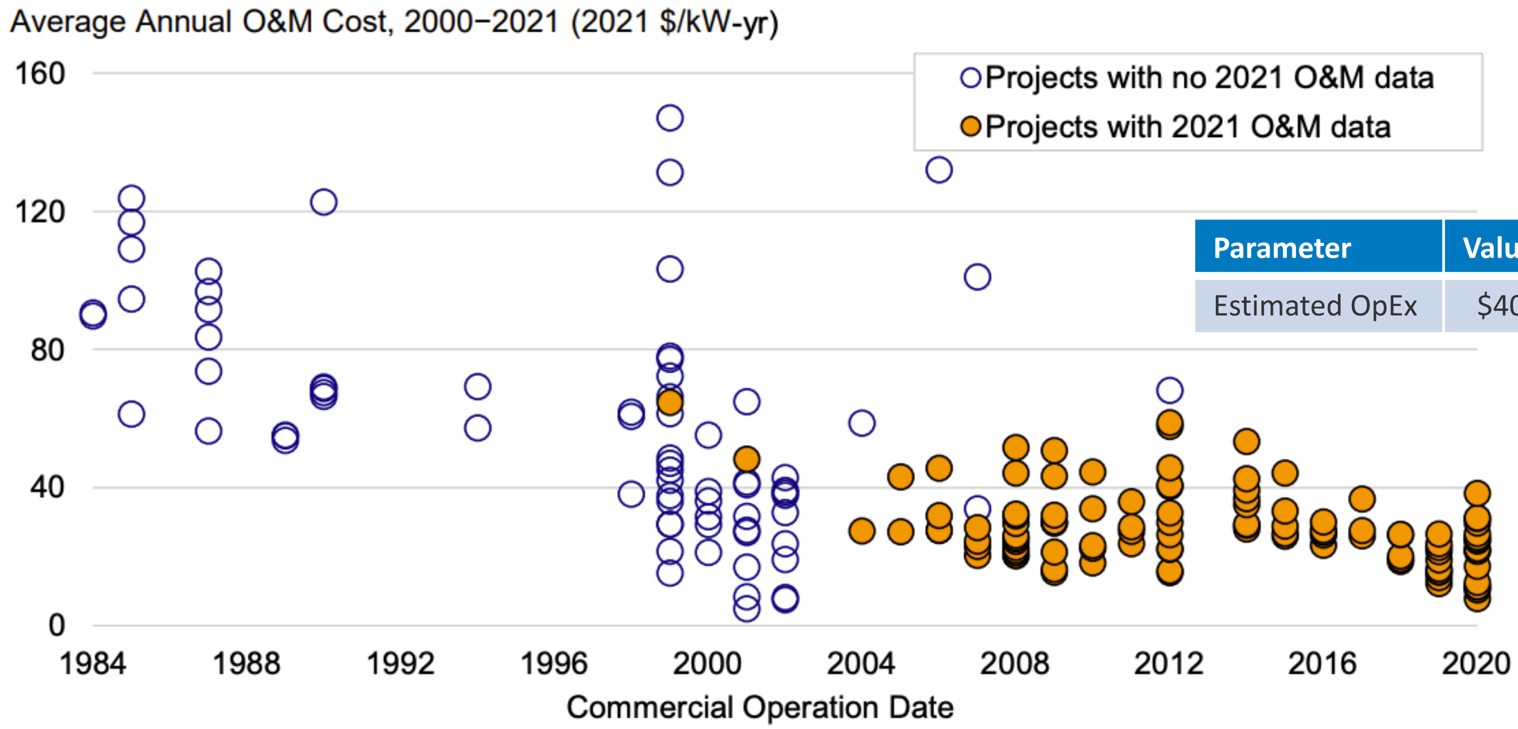


Parameter	Value ($/kW)
Wind Turbine CapEx	**1,030**
Rotor	$313
Nacelle	512
Tower	204
BOS CapEx	**322**
Engineering	23
Project management	10
Foundation	75
Site access, staging, and facilities	40
Assembly and installation	41
Electrical infrastructure	132
Financial CapEx	**113**
Construction finance	23
Contingency	90
Total CapEx	**1,501**

All costs reported in 2021 USD

- Turbine component cost estimates are derived from the 2015 Cost and Scaling Model, used as an internal reference and not publicly available.
- BOS component cost estimates are obtained from the Land-based Balance of System Systems Engineering (LandBOSSE) model (Eberle et al. 2019).
- Construction financing was estimated assuming a 3-year construction duration and distributing the capital and interest over the 3 years.
- Project contingency assumes 6% of total CapEx.
- Total installed project CapEx for U.S. projects in 2021 averaged $1,501/kW (Wiser and Bolinger 2022).

Land-Based Wind Plant Operational Expenditures Estimate and Historical Data



Parameter	Value
Estimated OpEx	$40/kW-yr

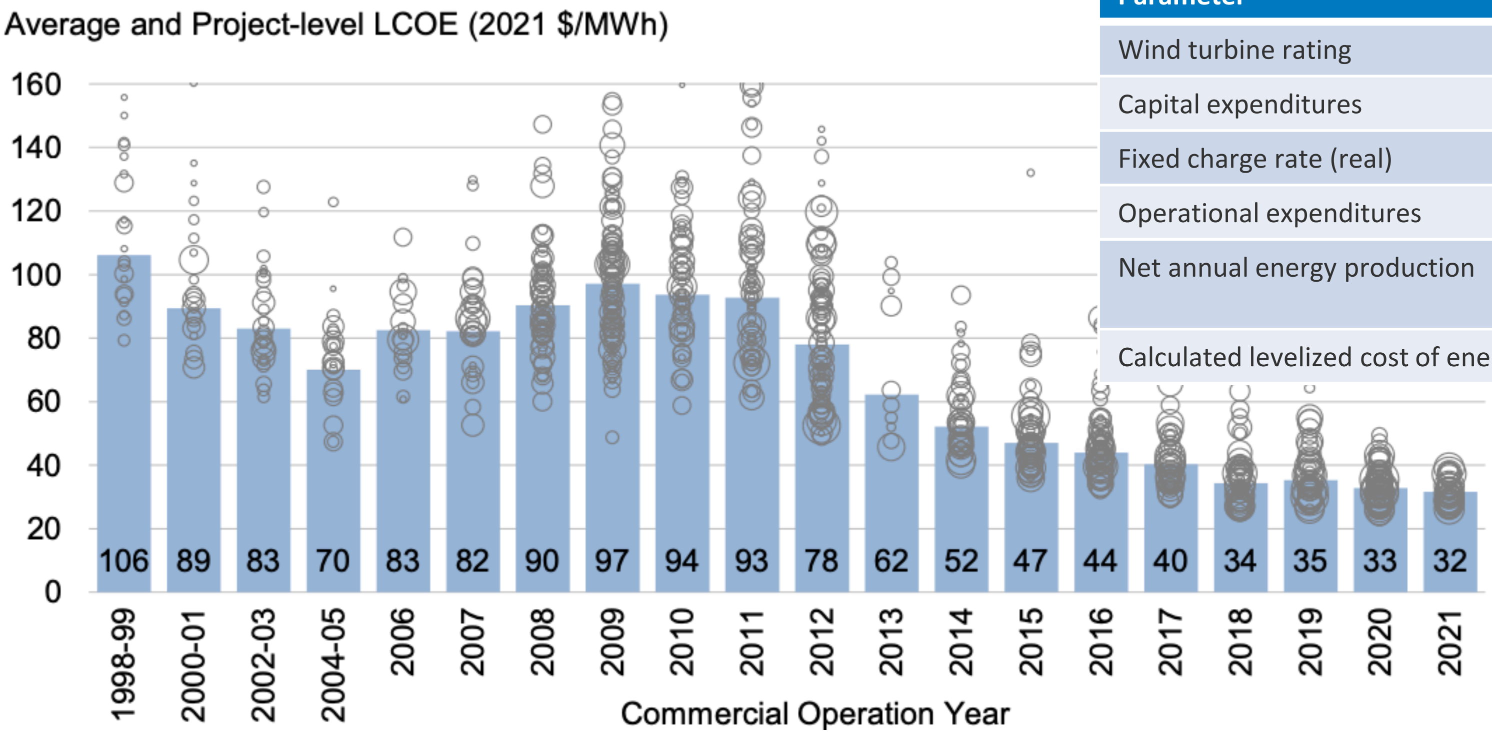
- Source: Wiser and Bolinger (2022)
- Sample is limited; few projects in sample have complete records of OpEx from 2000 to 2020; OpEx reported here do not include all operating costs.
- Data from "Assessing Wind Power Operating Costs in the United States: Results From a Survey of Wind Industry Experts" (Wiser, Bolinger, and Lantz 2019) are used to estimate all-in project OpEx for a representative project commissioned in 2021.

Land-Based Wind Project Financial Assumptions

Parameter	Nominal Value	Real Value
Weighted-average cost of capital	5.37%	2.8%
Capital recovery factor	7.36%	5.62%
Fixed charge rate	7.7%	5.88%

- 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 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

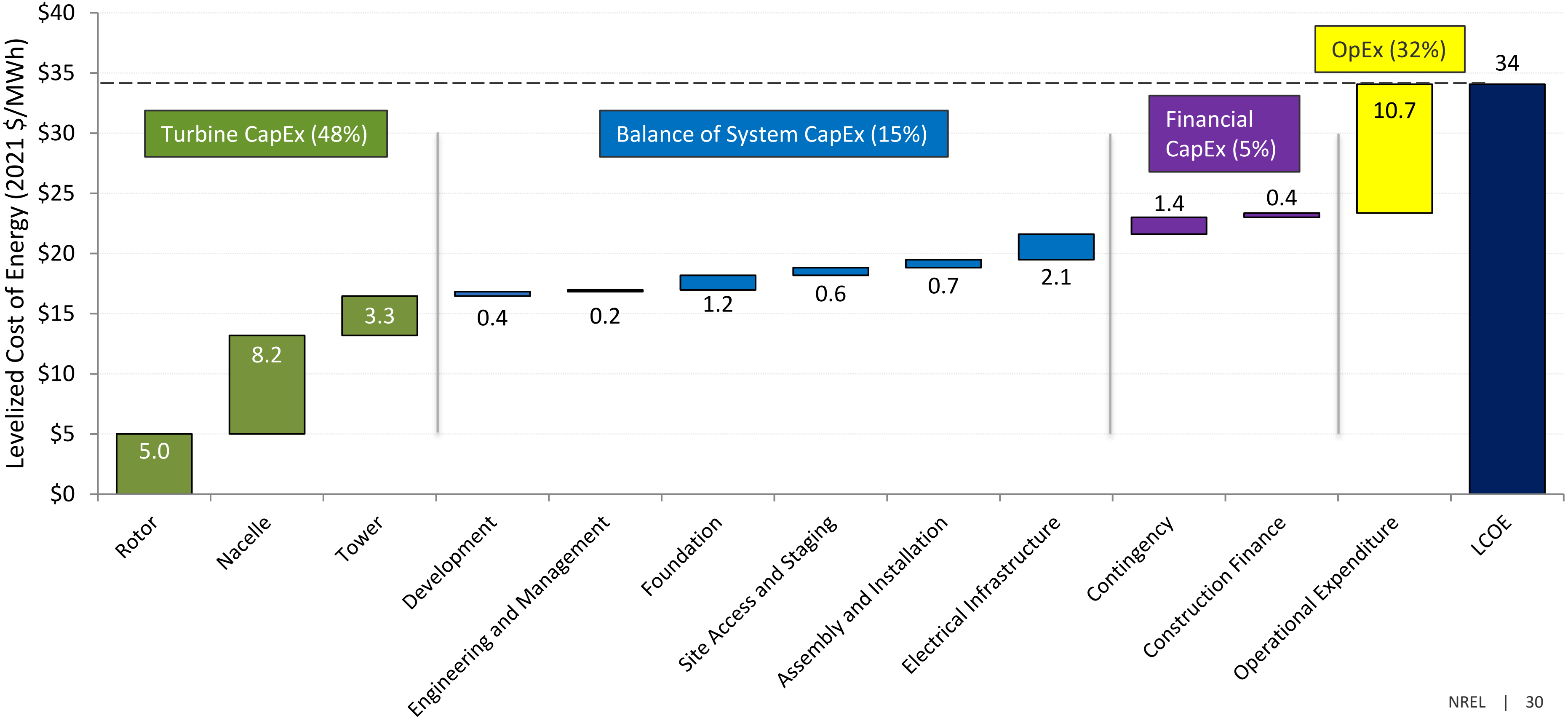


Parameter	Value
Wind turbine rating	3 MW
Capital expenditures	$1,501/kW
Fixed charge rate (real)	5.88%
Operational expenditures	$40/kW/yr
Net annual energy production	3,775 MWh/MW/yr
Calculated levelized cost of energy	$34/MWh

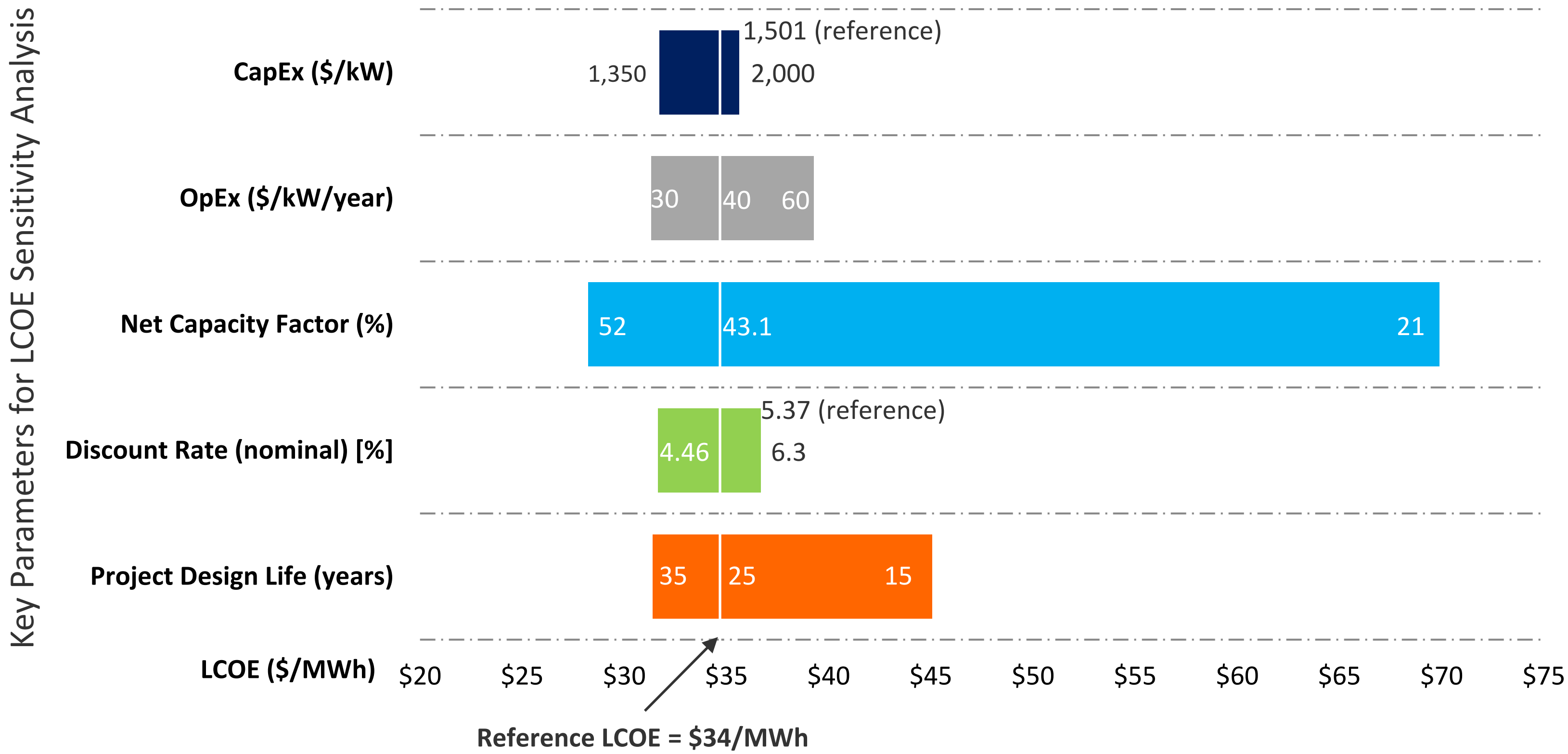
Source: Wiser and Bolinger (2022)

Note: Yearly estimates reflect variations in installed cost, capacity factors, operational costs, cost of financing, and project life; includes accelerated depreciation but excludes production tax credit.

LCOE Breakdown for Reference Land-Based Wind Plant



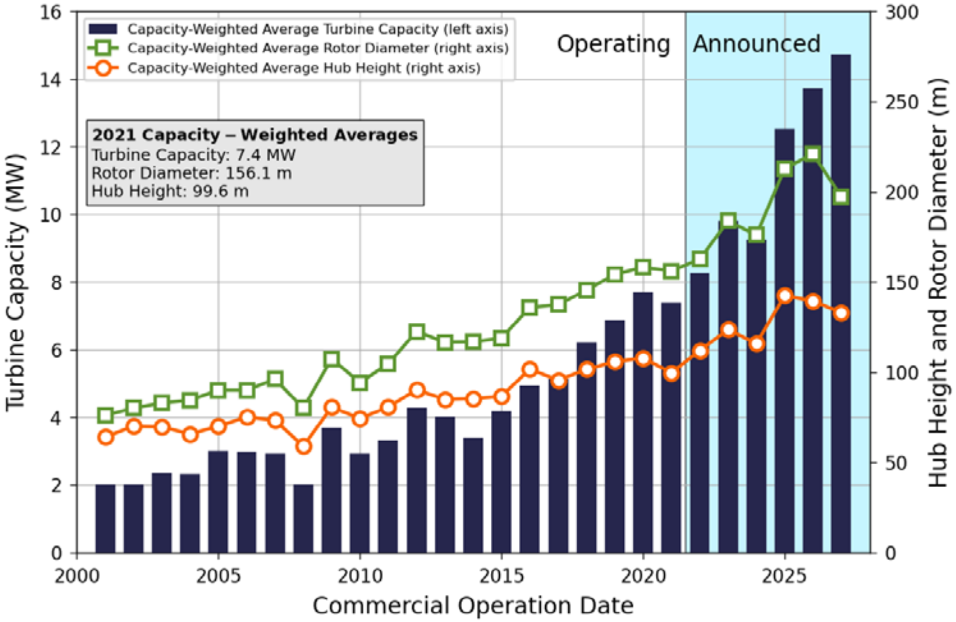
Range of LCOE Parameters for Land-Based Wind



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

2021 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 2021. Source: *Offshore Wind Market Report: 2022 Edition* (Musial et al. 2022)

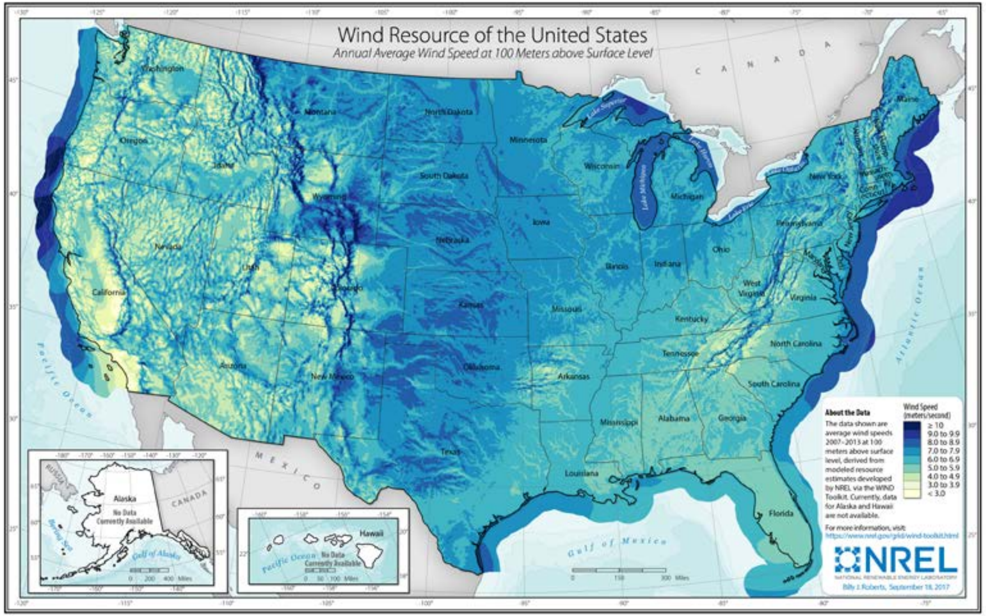
Parameter	Value
Wind turbine rating	8.0 MW
Rotor diameter	159 m
Hub height	102 m
Specific power	403 W/m^2
Wind plant capacity	600 MW
Number of turbines	75

Representative turbine parameters and power curves available on GitHub

- Global capacity-weighted-average turbine rating in 2021 was 7.4 MW, down slightly from 7.6 MW in 2020 (Musial et al. 2022).
- Representative wind plant parameters are held constant with respect to *2020 Cost of Wind Energy Review* (Stehly and Duffy 2022).

Offshore Wind Reference Wind Sites and Wind Plant Performance

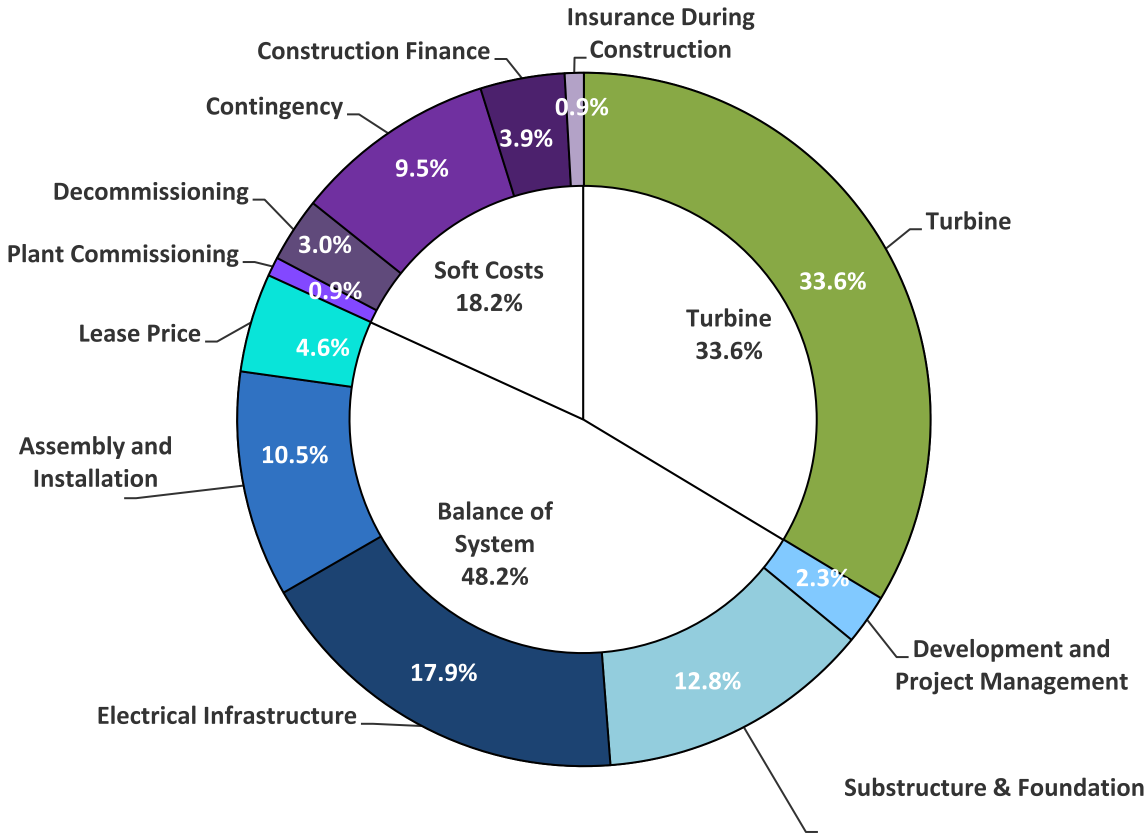
- The fixed-bottom offshore wind reference project represents near-term development in the U.S. Northeast.
- The floating offshore wind reference site represents the first leases in California.



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

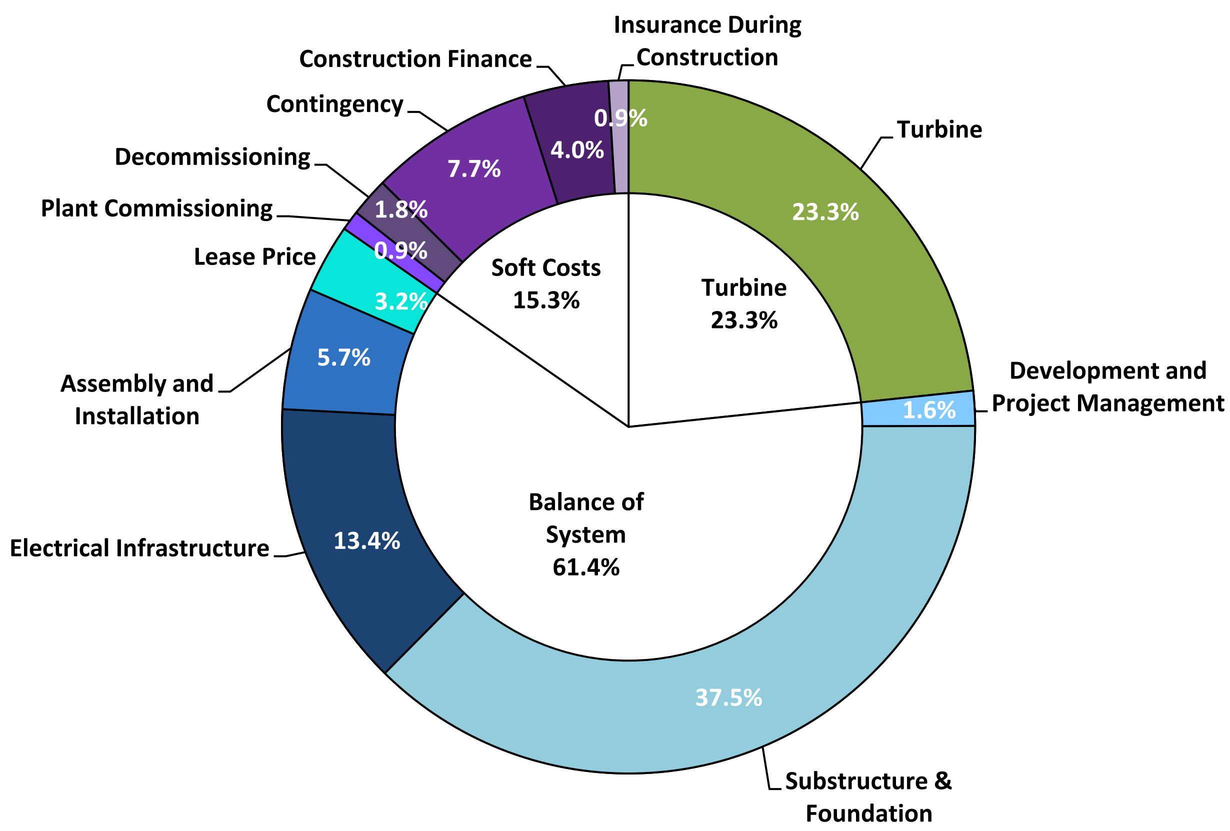
Parameter	Fixed-bottom	Floating	Units
Water depth	34	739	m
Export cable length	50	36	km
Annual average wind speed at 50 meters	8.43	7.67	m/s
Annual average wind speed at hub height	9.05	8.24	m/s
Weibull k	2.1	2.1	factor
Shear exponent	0.1	0.1	#
Gross energy capture	5,081	4,205	MWh/MW/yr
Gross capacity factor	58.0	48.0	%
Total losses	15.5	20.7	%
Net energy capture	4,295	3,336	MWh/MW/yr
Net capacity factor	49.0	38.1	%

Fixed-bottom Offshore Wind System CapEx Component Cost Breakdown



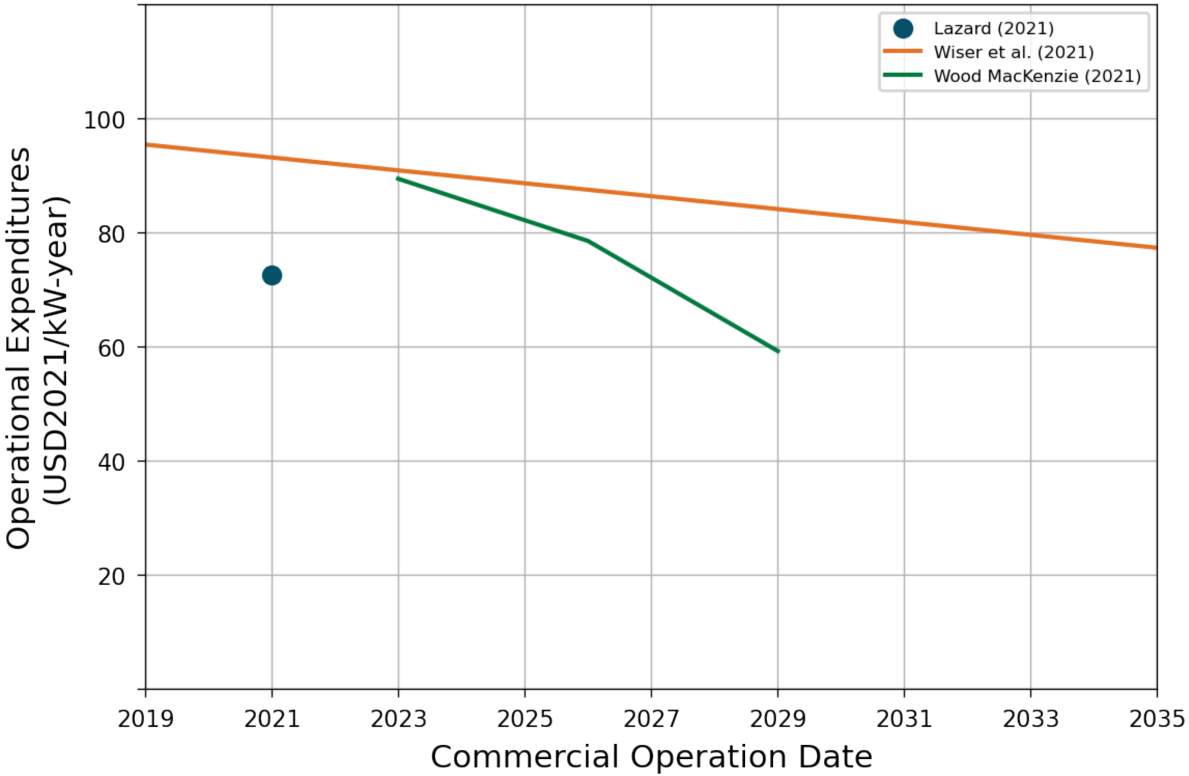
Parameter	Value ($/kW)
Turbine	**1,301**
BOS	**1,866**
Development and project management	91
Substructure and foundation	496
Electrical infrastructure	693
Assembly and installation	408
Lease price	178
Soft Costs	**704**
Plant commissioning	34
Decommissioning	117
Contingency	366
Construction finance	152
Insurance during construction	34
Total CapEx	**3,871**

Floating Offshore Wind System CapEx Component Cost Breakdown



Parameter	Value ($/kW)
Turbine	**1,301**
BOS	**3,422**
Development and project management	91
Substructure and foundation	2,089
Electrical infrastructure	747
Assembly and installation	316
Lease price	178
Soft Costs	**854**
Plant commissioning	52
Decommissioning	101
Contingency	428
Construction finance	221
Insurance during construction	52
Total CapEx	**5,577**

Fixed-Bottom and Floating Offshore Wind OpEx Estimates



Projected U.S. offshore wind plant OpEx costs between 2021 and 2035. Source: Musial et al. (2022)

Parameter	Fixed Value	Floating Value
OpEx ($/kW-yr)	111	118

- Public OpEx data are scarce, and estimates vary among existing projects in Europe and Asia.
- Estimated fixed-bottom and floating OpEx values are calculated with NREL's Offshore Regional Cost Analyzer (ORCA) model (Beiter et al. 2016) which varies in the definition of OpEx scope when compared with more recent trends and analyses.
- Continued work to develop and validate the open-source offshore OpEx model *Windfarm Operations & Maintenance cost-Benefit Analysis Tool* (WOMBAT) is expected to improve current OpEx estimating capabilities.

(follow model development on GitHub)

Fixed-Bottom and Floating Offshore Wind Project Financial Assumptions

Parameter	Nominal Value	Real Value
Weighted-average cost of capital	5.29%	2.72%
Capital recovery factor	7.30%	5.60%
Fixed charge rate	7.64%	5.82%

- 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 2021.
- The WACC, CRF, and FCR are given in nominal and real terms using the after-tax WACC discount rate of 5.29% and 2.72%, 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.

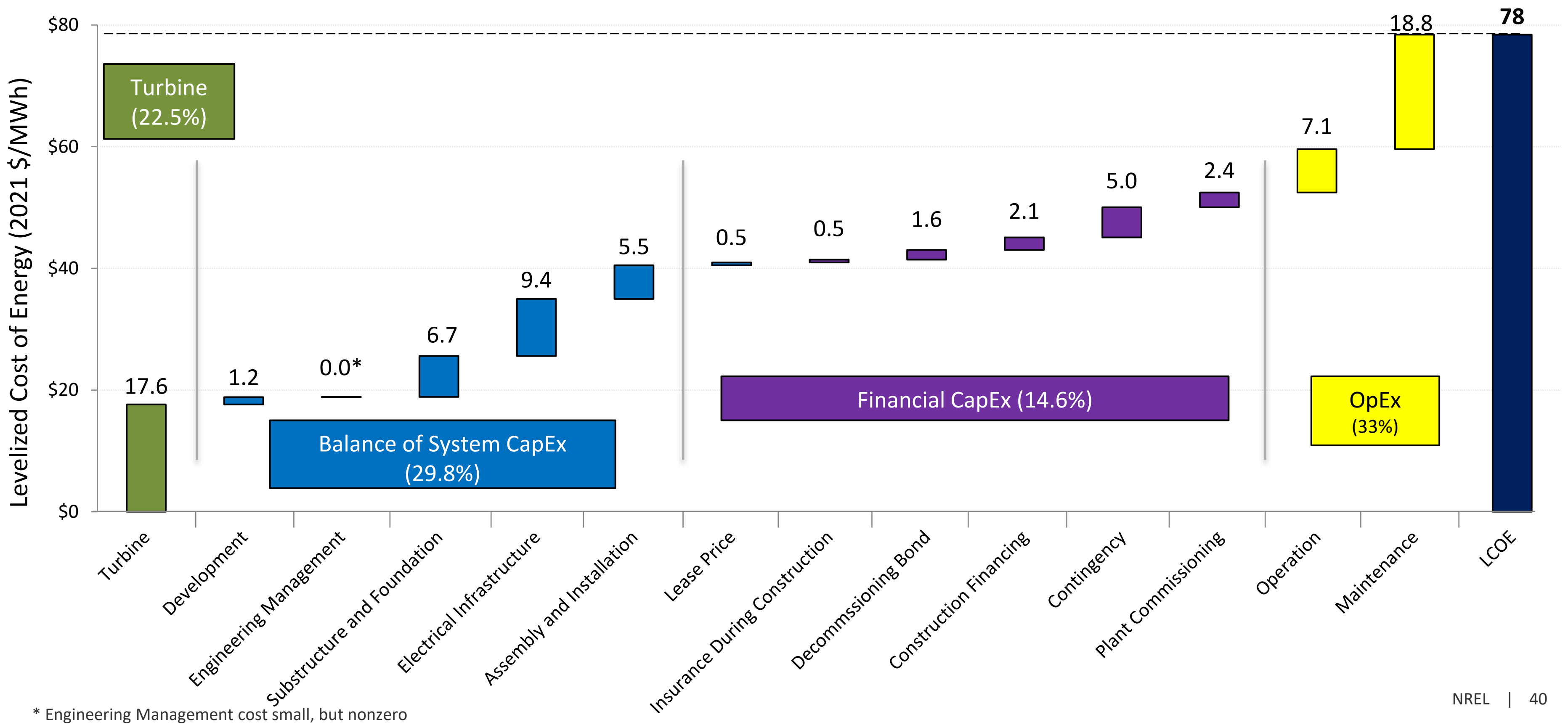
Note: The calculated weighted-average cost of capital for land-based wind is higher than offshore wind because it considers the influences of the production tax credit and assumes a lower debt fraction.

2021 Offshore Wind Reference Plant LCOE Estimates

- **The LCOE values for the 2021 representative fixed-bottom and floating offshore wind plants are estimated at $78/MWh and $133/MWh, respectively.**
- Calculated with the formulation presented in NREL's Annual Technology Baseline and presented in Appendix.

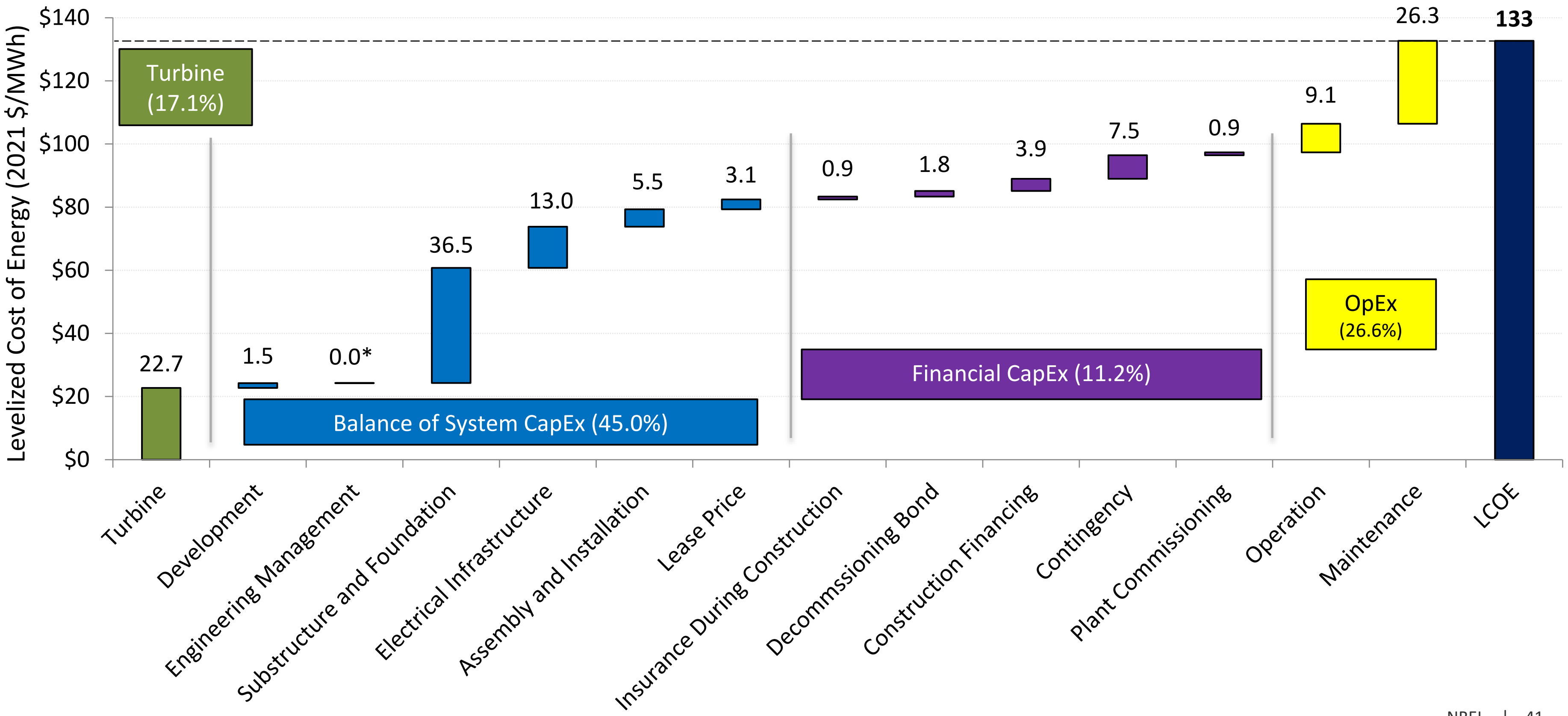
Parameter	Fixed-bottom 8.0-MW Offshore Wind Turbine	Floating 8.0-MW Offshore Wind Turbine	Units
Capital expenditures	3,871	5,577	$/kW
Fixed charge rate (real)	5.82	5.82	%
Operational expenditures	111	118	$/kW/yr
Net annual energy production	4,295	3,336	MWh/MW/yr
Total LCOE	**78**	**133**	**$/MWh**

Fixed-Bottom Offshore Wind Reference Plant LCOE Component Cost Breakdown



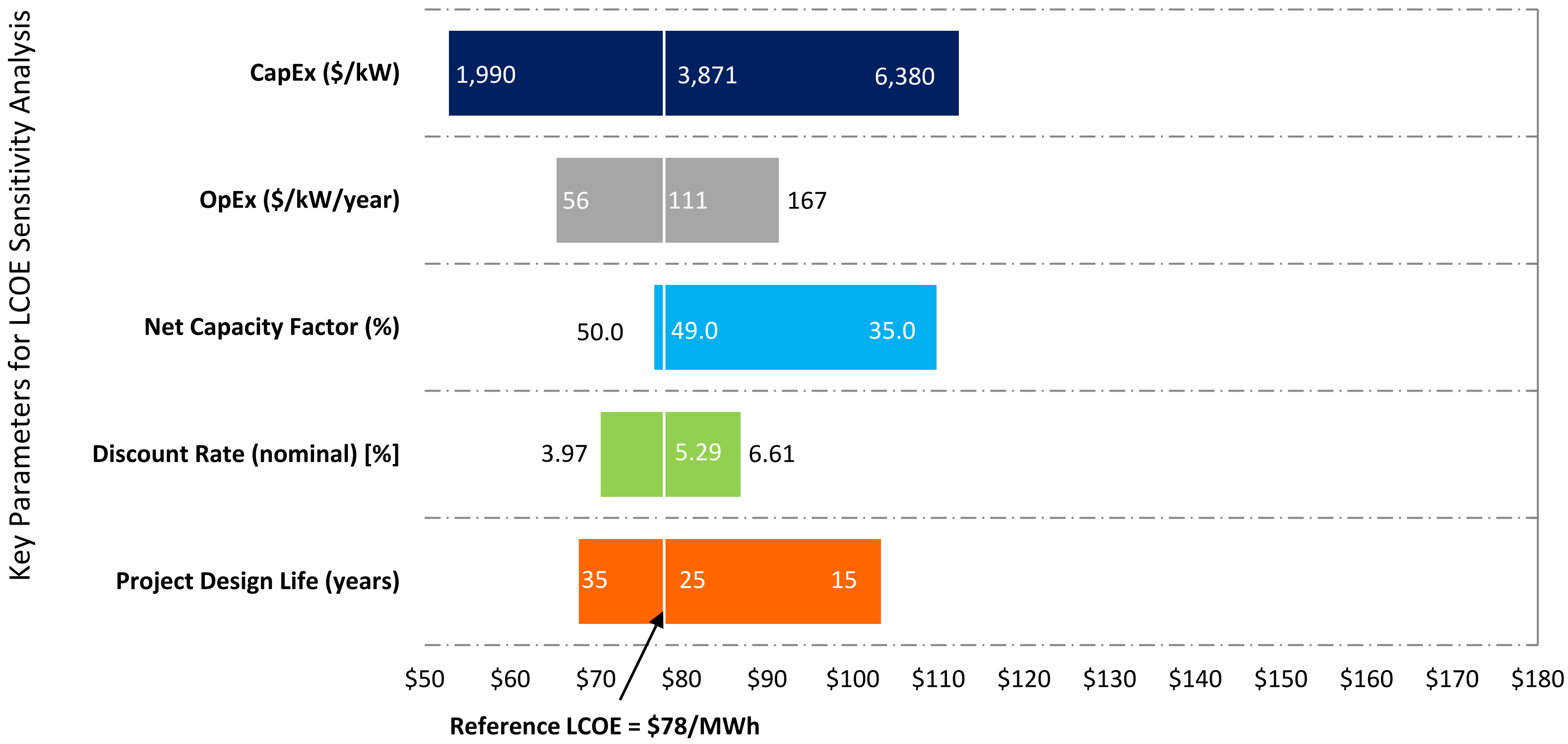
* Engineering Management cost small, but nonzero

Floating Offshore Wind Reference Plant LCOE Component Cost Breakdown



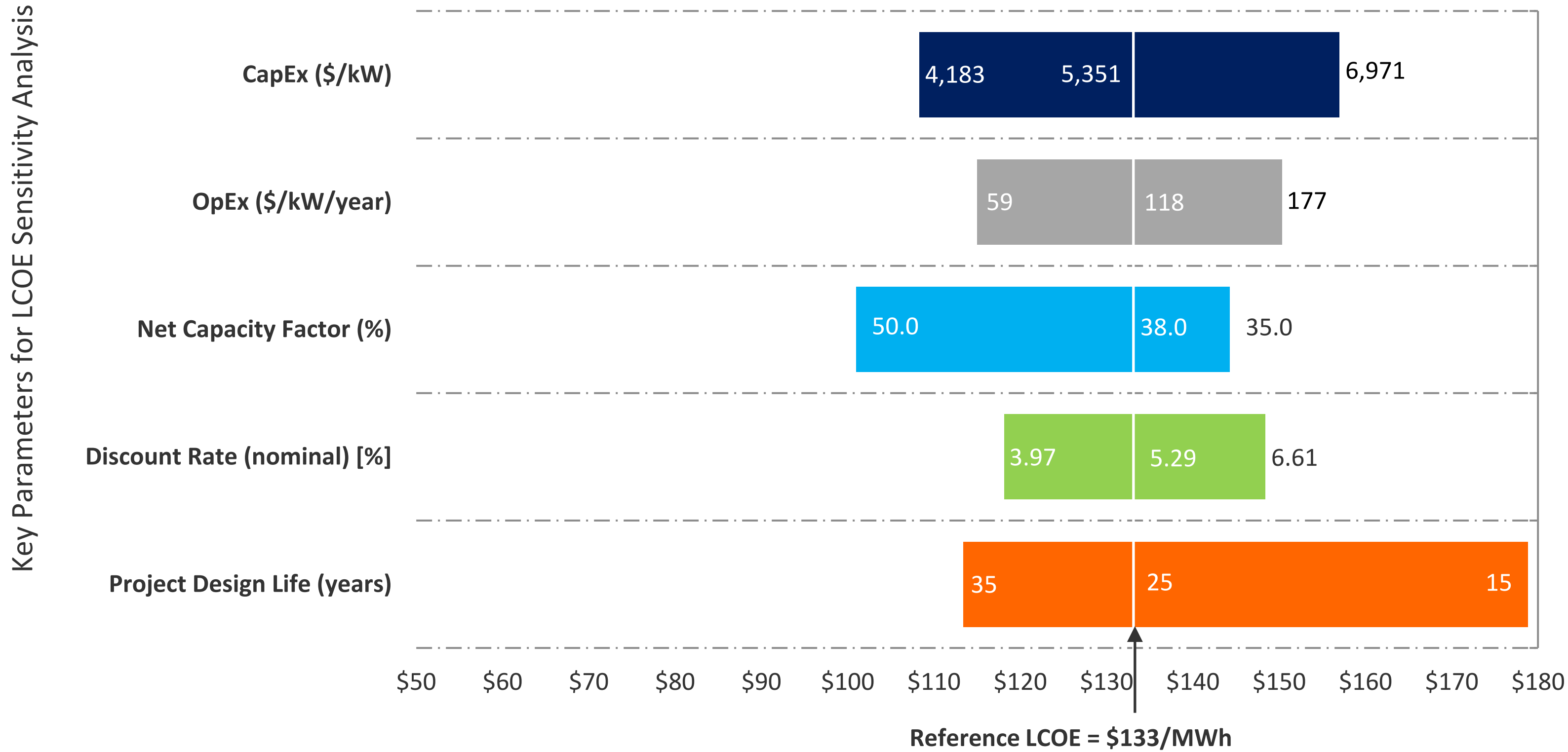
* Engineering Management cost small, but nonzero

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	#

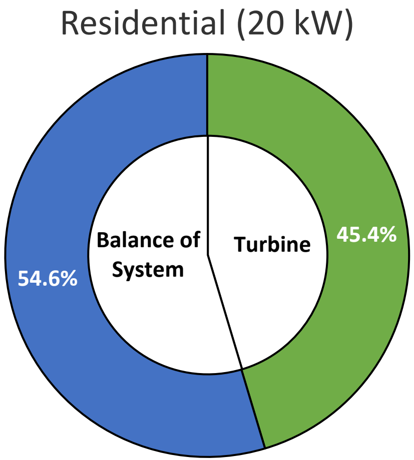
Wind turbine classes are aligned with the *Distributed Wind Energy Futures Study* (McCabe et al. 2022).

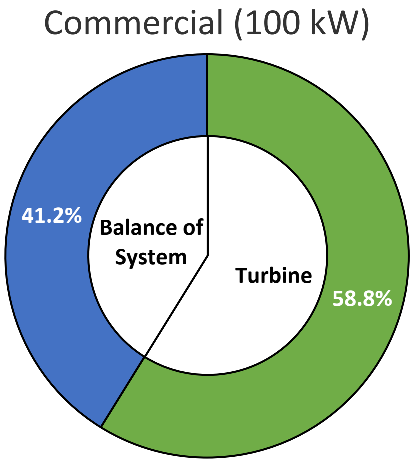
Distributed Wind Site Characteristics and Performance

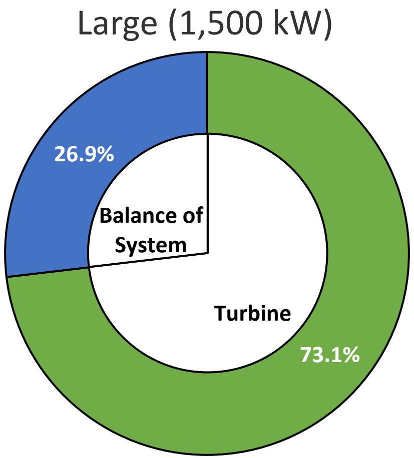
Parameter	Wind Turbine Class			Units
	Residential	Commercial	Large	
Annual average wind speed at 50 m above surface level	6	6	6	m/s
Annual average wind speed at hub height	5.58	5.81	6.42	m/s
Weibull k	2.0	2.0	2.0	factor
Shear exponent	0.14	0.14	0.14	#
Gross energy capture	2,916	3,217	3,759	MWh/MW/yr
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







Parameter	Wind Turbine Class			Units
	Residential	Commercial	Large	
Wind turbine CapEx	2,575	2,530	2,589	$/kW
BOS CapEx	3,100	1,770	951	$/kW
Total CapEx	5,675	4,300	3,540	$/kW
OpEx	35	35	35	$/kW/yr

- Turbine component cost estimates are derived from the *Distributed Wind Market Report: 2022 Edition* (Orrell et al. 2022).
- BOS component cost estimates are obtained from the Land-based Balance of System Systems Engineering (LandBOSSE) model (Eberle et al. 2019) and presented in Bhaskar and Stehly (2021).
- 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, $35/kW/yr are assumed for each wind class.

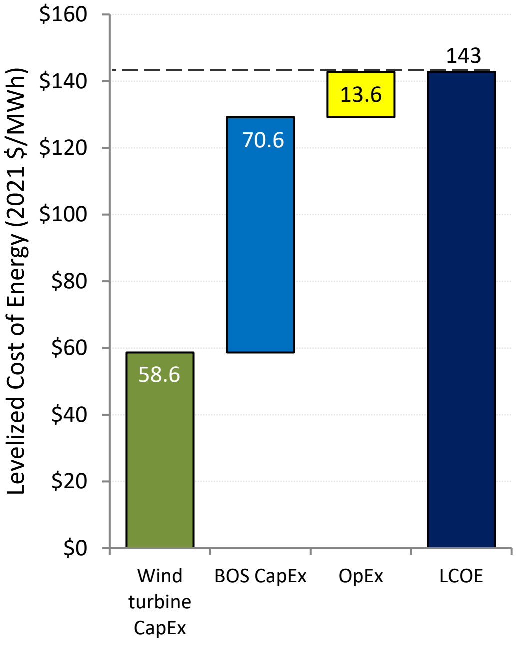
Distributed Wind Project Financial Assumptions

Parameter	Wind Turbine Class					
	Residential		Commercial		Large	
	Nominal	Real	Nominal	Real	Nominal	Real
Weighted-average cost of capital (%)	4.69	2.13	4.69	2.13	4.69	2.13
Capital recovery factor (%)	6.87	5.2	6.87	5.2	6.87	5.2
Fixed charge rate (%)	7.76	5.88	7.16	5.42	7.16	5.42

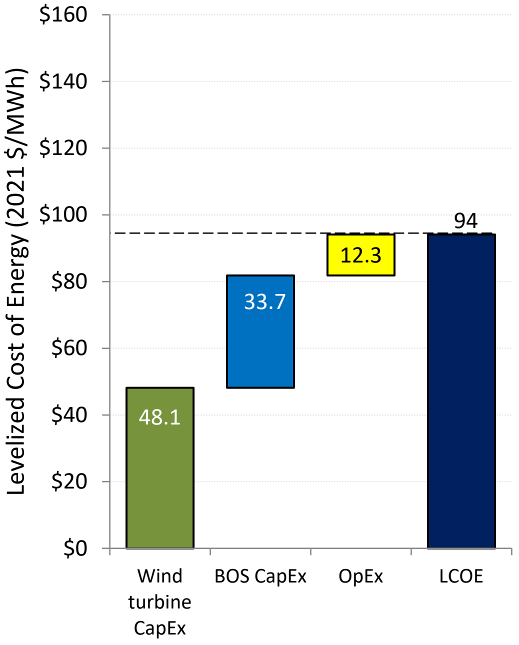
- The economic evaluation of wind energy investments in this analysis uses the fixed charge rate (FCR) method used in NREL's Annual Technology Baseline and Standard Scenarios web page: atb.nrel.gov.
- The FCR represents the amount of annual revenue required to pay the carrying charge as applied to the CapEx on that investment during the expected project economic life and is based on the capital recovery factor (CRF) but also reflects corporate income taxes and depreciation.
- The analysis assumes the reference projects operate for 25 years; residential host-owned assumes a 20-year straight-line depreciation schedule, and the commercial/industrial host-owned project assumes a 5-year MACRS depreciation schedule.
- Additional financial assumption details are displayed in the Appendix.

LCOE Breakdown for Reference Distributed Wind Projects

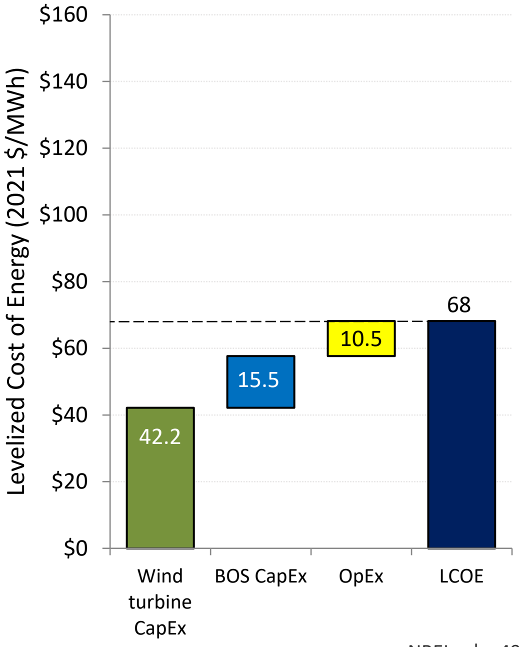
Single-Turbine Residential (20 kW)



Single-Turbine Commercial (100 kW)



Single-Turbine Large (1,500 kW)



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7. Appendix

Land-Based Wind Reference Project Details

Parameter	Units	Value	Notes
Wind plant and reference site characteristics			
Wind plant capacity	MW	200	Representative of commercial-scale projects
Number of turbines		67	
Turbine rating	MW	3	"Land-Based Wind Market Report: 2022 Edition" (Wiser and Bolinger 2022)
Rotor diameter	m	127	
Hub height	m	95	
Specific power	W/m2	237	Calculation
Cut-in wind speed	m/s	3	Typical turbine characteristics
Cut-out wind speed	m/s	25	
Annual average wind speed at 50 meters	m/s	7.25	Reference site wind speed
Annual average wind speed at hub height	m/s	7.95	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
Altitude above mean sea level	m	450	Altitude at turbine foundation
Losses	%	15%	"Wind Vision" (U.S. Department of Energy 2015)
Availability	%	98%	
Net energy capture	MWh/MW/yr	3,775	System Advisor Model (SAM) calculation
Net capacity factor	%	43.1%	

Land-Based Wind System CapEx Breakdown

Parameter	Units	Value	Notes
CapEx			
Total CapEx	$/kW	1,501	"Land-Based Wind Market Report: 2022 Edition" (Wiser and Bolinger 2022)
Turbine	$/kW	1,057	2015 Cost and Scaling Model
Rotor module	$/kW	322	
Blades	$/kW	208	
Pitch assembly	$/kW	65	
Hub assembly	$/kW	49	
Nacelle module	$/kW	526	
Nacelle structural assembly	$/kW	106	
Drivetrain assembly	$/kW	210	
Nacelle electrical assembly	$/kW	170	
Yaw assembly	$/kW	39	
Tower module	$/kW	210	
Balance of system	$/kW	331	Land-based Balance of System Systems Engineering [LandBOSSE] (Eberle et. al. 2019)
Development	$/kW	24	
Engineering and project management	$/kW	10	
Foundation	$/kW	77	
Site access and staging	$/kW	41	
Assembly and installation	$/kW	42	
Electrical infrastructure	$/kW	136	
Soft costs	$/kW	113	
Construction finance	$/kW	23	Project construction over 3 years
Contingency	$/kW	90	6% of total CapEx

Land-Based Wind OpEx and Financing Terms

Parameter	Units	Value	Notes
OpEx			
Total OpEx	$/kW/year	40	Assessing Wind Power Operating Costs in the United States (Wiser et al. 2019)
Financials			
Project design life	Years	25	Project life for Government Performance and Reporting Act (GPRA) reporting
Tax Rate (combined state and federal)	%	25.7%	2022 Annual Technology Baseline (NREL's Annual Technology Baseline and Standard Scenarios web page: atb.nrel.gov)
Inflation rate	%	2.5%	
Interest during construction (nominal)	%	3.11%	Land-Based Wind Market Report: 2022 Edition (Wiser and Bolinger 2022)
Construction finance factor	%	102%	Calculation
Debt fraction	%	48.5%	Lawrence Berkeley National Laboratory 2021 financial analysis
Debt interest rate (nominal)	%	3.11%	
Return on equity (nominal)	%	8.25%	
Weighted-average cost of capital [WACC] (nominal; after-tax)	%	5.37%	Calculation
WACC (real; after-tax)	%	2.80%	
Capital recovery factor (nominal; after-tax)	%	7.36%	
Capital recovery factor (real; after-tax)	%	5.62%	
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 (NPV)	%	86.6%	Calculation
Project finance factor	%	105%	
FCR (nominal)	%	7.70%	
FCR (real)	%	5.88%	
Levelized cost of energy	$/MWh	34	Calculation

Fixed-Bottom Offshore Wind Reference Project Details

Parameter	Units	Value	Notes
Wind plant and reference site characteristics			
Wind plant capacity	MW	600	Representative of commercial-scale projects
Number of turbines	Number	75	Calculation
Turbine rating	MW	8	Informed by Offshore Wind Market Report: 2022 Edition (Musial et al. 2022)
Rotor diameter	m	159	
Hub height	m	102.1	
Specific power	W/m2	403	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%	Offshore Regional Cost Analyzer (ORCA) (based on Beiter et al. 2016)
Net capacity factor	%	49.0%	

Fixed-Bottom Offshore Wind System CapEx Breakdown

Parameter	Units	Value	Notes
CapEx			
Total CapEx	$/kW	3,871	
Turbine	$/kW	1,301	Informed by Offshore Wind Market Report: 2022 Edition (Musial et al. 2022)
Rotor nacelle assembly	$/kW	1,119	
Tower	$/kW	182	
Balance of System	$/kW	1,866	BOS Costs computed with ORBIT (Nunemaker et al. 2020)
Development	$/kW	89	
Project management	$/kW	2	
Substructure and foundation	$/kW	496	
Substructure	$/kW	194	
Foundation	$/kW	302	
Port and staging, logistics, transportation	$/kW	0	
Electrical infrastructure	$/kW	693	
Array cable system	$/kW	117	
Export cable system	$/kW	387	
Grid connection	$/kW	188	
Assembly and installation	$/kW	408	
Turbine installation	$/kW	222	
Substructure and foundation installation	$/kW	186	
Soft Costs	$/kW	704	Soft Costs computed using same methodology as ORCA (Beiter et al. 2016)
Insurance during construction	$/kW	34	
Decommissioning bond	$/kW	117	
Construction finance	$/kW	152	
Sponsor contingency	$/kW	366	
Procurement contingency	$/kW	133	
Installation contingency	$/kW	233	
Project completions / commissioning	$/kW	34	

Fixed-Bottom Offshore Wind OpEx and Financing Terms

Parameter	Units	Value	Notes
OpEx			
Total OpEx	$/kW/year	111	Offshore Regional Cost Analyzer (ORCA) (based on Beiter et al. 2016)
Operations (pretax)	$/kW/year	30	
Maintenance	$/kW/year	81	
Financials			
Project design life	Years	25	Offshore wind project life for GPRA reporting
Tax Rate (combined state and federal)	%	26%	Feldman et al. 2020 and NREL's Annual Technology Baseline, updated with data from industry partners
Inflation rate	%	2.5%	
Debt fraction	%	67%	
Debt interest rate (nominal)	%	4.0%	
Return on equity (nominal)	%	10.0%	
WACC (nominal; after-tax)	%	5.3%	Calculation
WACC (real; after-tax)	%	2.7%	
Capital recovery factor (nominal; after-tax)	%	7.3%	
Capital recovery factor (real; after-tax)	%	5.6%	
Depreciable basis	%	100%	Simplified depreciation schedule
Depreciation schedule		5-year MACRS	Standard for U.S. wind projects
Depreciation adjustment (NPV)	%	86.8%	Calculation
Project finance factor	%	105%	
FCR (nominal)	%	7.6%	
FCR (real)	%	5.8%	

Floating Offshore Wind Reference Project Details

Parameter	Units	Value	Notes
Wind plant and reference site characteristics			
Wind plant capacity	MW	600	Representative of commercial-scale projects
Number of turbines	Number	75	Calculation
Turbine rating	MW	8	Informed by Offshore Wind Market Report: 2022 Edition (Musial et al. 2022)
Rotor diameter	m	159	
Hub height	m	102.1	
Specific power	W/m2	403	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	8.2	
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	3,336	
Gross capacity factor	%	48.0%	Offshore Regional Cost Analyzer (ORCA) (based on Beiter et al. 2016)
Net capacity factor	%	38.1%	

Floating Offshore Wind System CapEx Breakdown

Parameter	Units	Value	Notes
CapEx			
Total CapEx	$/kW	5,577	
Turbine	$/kW	1,301	Informed by Offshore Wind Market Report: 2022 Edition (Musial et al. 2022)
Rotor nacelle assembly	$/kW	1,119	
Tower	$/kW	182	
Balance of System	$/kW	3,422	BOS Costs computed with ORBIT (Nunemaker et al. 2020)
Development	$/kW	89	
Project management	$/kW	2	
Substructure and foundation	$/kW	2,089	
Substructure	$/kW	1,353	
Foundation	$/kW	736	
Port and staging, logistics, transportation	$/kW	0	
Electrical infrastructure	$/kW	747	
Array cable system	$/kW	218	
Export cable system	$/kW	339	
Grid connection	$/kW	191	
Assembly and installation	$/kW	316	
Turbine installation	$/kW	0	
Substructure and foundation installation	$/kW	0	
Lease price	$/kW	178	
Soft Costs	$/kW	854	Soft Costs computed using same methodology as ORCA (Beiter et al. 2016)
Insurance during construction	$/kW	52	
Decommissioning bond	$/kW	101	
Construction finance	$/kW	221	
Sponsor contingency	$/kW	428	
Procurement contingency	$/kW	225	
Installation contingency	$/kW	203	
Project completions / commissioning	$/kW	52	

Floating Offshore Wind OpEx and Financing Terms

Parameter	Units	Value	Notes
OpEx			
Total OpEx	$/kW/year	118	Offshore Regional Cost Analyzer (ORCA) (based on Beiter et al. 2016)
Operations (pretax)	$/kW/year	30	
Maintenance	$/kW/year	87	
Financials			
Project design life	Years	25	Offshore wind roject life for GPRA reporting
Tax Rate (combined state and federal)	%	26%	Feldman et al. 2020 and NREL's Annual Technology Baseline, updated with data from industry partners
Federal	%	21%	
State	%	4.7%	
Inflation rate	%	2.5%	
Debt fraction	%	67%	
Debt interest rate (nominal)	%	4.0%	
Return on equity (nominal)	%	10.0%	
WACC (nominal; after-tax)	%	5.3%	Calculation
WACC (real; after-tax)	%	2.7%	
Capital recovery factor (nominal; after-tax)	%	7.3%	
Capital recovery factor (real; after-tax)	%	5.6%	
Depreciable basis	%	100%	Simplified depreciation schedule
Depreciation schedule		5 year MACRS	Standard for U.S. wind projects
Depreciation adjustment (NPV)	%	86.8%	Calculation
Project finance factor	%	105%	
FCR (nominal)	%	7.6%	
FCR (real)	%	5.8%	

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 meters	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	5,675	4,300	3,540	
Turbine	$/kW	2,575	2,530	2,589	"2019 Distributed Wind Data Summary" (Orrell et. al., 2020)
Balance of system	$/kW	3,100	1,770	951	"NREL's Balance-of-System Cost Model for Land-Based Wind" (Eberle et. al., 2019)
OpEx					
Total OpEx	$/kW/year	35	35	35	"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	%	60%	60%	60%	"Assessing the Future of Distributed Wind: Opportunities for Behind-the Meter Projects" (Lantz et. al., 2016)
Debt interest rate (nominal)	%	3.11%	3.11%	3.11%	Lawrence Berkeley National Laboratory 2021 financial analysis
Return on equity (nominal)	%	8.25%	8.25%	8.25%	
WACC (nominal; after-tax)	%	4.69%	4.69%	4.69%	Calculation
WACC (real; after-tax)	%	2.13%	2.13%	2.13%	
Capital recovery factor (nominal; after-tax)	%	6.87%	6.87%	6.87%	
Capital recovery factor (real; after-tax)	%	5.20%	5.20%	5.20%	
Depreciable basis	%	100%	100%	100%	Simplified depreciation schedule
Depreciation schedule	N/a	20-year straight line	5-year MACRS	5-year MACRS	
Depreciation adjustment (NPV)	%	62.6%	88.2%	88.2%	Calculation
Project finance factor	%	113%	104%	104%	
FCR (nominal)	%	7.76%	7.16%	7.16%	
FCR (real)	%	5.88%	5.42%	5.42%	
Levelized cost of energy	$/MWh	143	94	68	Calculation

Thank You

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