2020 Cost of Wind Energy Review

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National Renewable Energy Laboratory

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Errata

This report, originally published in December 2021, has been revised in January 2022 to correct the reference residential and commercial distributed wind levelized cost of energy values presented in the last bullet point of the Executive Summary on page xiv.

Acknowledgments

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
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
NREL	National Renewable Energy Laboratory
O&M	operation 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

This report 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 detailed here are derived from 2020 commissioned plants and representative industry data as well as state-of-the-art modeling capabilities. Modeling is conducted to provide more granular detail on specific cost categories. This report represents the tenth annual installment and is intended to provide insight into current component-level costs as well as a basis for understanding variability in wind energy LCOE across the country.

The primary elements of this 2020 report include:

- Estimated LCOE for a representative, land-based wind energy project installed in a moderate wind resource in the United States

- Estimated LCOE for a representative offshore, fixed-bottom, wind energy project installed in the North Atlantic region of the United States and a representative offshore, floating, wind energy project installed off the Pacific Coast region of the United States

- Updated LCOE estimates for representative residential- and commercial-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

- Updated national supply curves for land-based and offshore wind energy based on geographically specific wind resource conditions paired with approximate wind turbine cost characteristics

- Updated Fiscal Year 2021 values for land-based and offshore wind energy used for Government Performance and Results Act (GPRA) reporting as well as illustrated progress toward established GPRA targets.

Key Inputs and Results

Throughout this report, the representative land-based, offshore, and distributed wind energy project types are referred to as "reference projects." Table ES1, Table ES2, Table ES3, Table ES4, and Table ES5 summarize the basic LCOE inputs and outputs for the reference land-based, fixed-bottom, and floating offshore wind and residential and commercial distributed wind energy projects. The LCOE inputs include project capital expenditures (CapEx), operational expenditures (OpEx), project financing (characterized by a fixed charge rate [FCR]) and the respective turbine capacity factor associated with the net annual energy production estimates. Unless specifically stated, all data and analysis in the report are in 2020 U.S. dollars.

Table ES1. Summary of the Land-Based Reference Project Using 2.8-megawatt (MW) Wind Turbines

	2.8-MW Land-Based Wind Turbine ($/kilowatt [kW])	2.8-MW Land-Based Wind Turbine ($/megawatt-hour [MWh])
Turbine capital cost	1,021	15.9
Balance of system	319	5.0
Financial costs	122	1.9
Capital expenditures (CapEx)	**1,462**	**22.8**
Operational expenditures (OpEx; $/kW/year [yr])	**43**	**11.5**
Fixed charge rate (FCR; %) [real]	5.78%	
Net annual energy production (MWh/MW/yr)	3,703	
Net capacity factor (%)	42.3%	
TOTAL LCOE ($/MWh)	**34**	

Table ES2. Summary of the Fixed-Bottom Reference Project Using 8.0-MW Wind Turbines

	8.0-MW Offshore Wind Turbine ($/kW)	8.0-MW Offshore Wind Turbine ($/MWh)
Turbine capital cost	1,301	17.7
Balance of system	1,782	24.2
Financial costs	672	9.1
CapEx	**3,756**	**51.0**
OpEx ($/kW/yr)	**110**	**25.8**
FCR (real) [%]	5.8%	
Net annual energy production (MWh/MW/yr)	4,283	
Net capacity factor (%)	48.9%	
Total LCOE ($/MWh)	**77**	

Table ES3. Summary of the Floating Offshore Wind Reference Project Using 8.0-MW Turbines

	8.0-MW Floating Offshore Wind Turbine ($/kW)	8.0-MW Floating Offshore Wind Turbine ($/MWh)
Turbine capital cost	1,301	22.7
Balance of system	3,234	56.5
Financial costs	816	14.3
CapEx	**5,351**	**93.5**
OpEx ($/kW/yr)	**118**	**35.4**
FCR (real) [%]	5.8%	
Net annual energy production (MWh/MW/yr)	3,332	
Net capacity factor (%)	38.0%	
Total LCOE ($/MWh)	**129**	

Note: GPRA values are not reported for floating offshore wind technology.

Table ES4. Summary of the Residential Distributed Wind Reference Project Using a 20-kW Wind Turbine

	20-kW Residential Wind Turbine ($/kW)	20-kW Residential Wind Turbine ($/MWh)
Turbine CapEx	2,575	62.4
Balance-of-system CapEx	3,100	75.1
Total CapEx	**5,675**	**137.5**
OpEx ($/kW/yr)	**35**	**13.6**
FCR (real) [%]	6.2%	
Net annual energy production (kWh/kW/yr)	2,580	
Net capacity factor (%)	29.5%	
TOTAL LCOE ($/MWh)	**151**	

Table ES5. Summary of the Commercial Distributed Wind Reference Project Using a 100-kW Wind Turbine

	100-kW Commercial Wind Turbine ($/kW)	100-kW Commercial Wind Turbine ($/MWh)
Turbine CapEx	2,530	51.0
Balance-of-system CapEx	1,770	35.7
Total CapEx	**4,300**	**86.6**
OpEx ($/kW/yr)	**35**	**12.3**
FCR (real) [%]	5.7%	
Net annual energy production (kWh/kW/yr)	2,846	
Net capacity factor (%)	32.5%	
TOTAL LCOE ($/MWh)	**99**	

In this report, 2020 installed land-based wind energy project data and costs are primarily informed from Wiser and Bolinger (2021). These data are supplemented with outputs from the National Renewable Energy Laboratory's (NREL's) cost models to obtain wind turbine and balance-of-system component cost details. The offshore reference project data are estimated from installed 2020 global offshore wind projects as well as data collected from U.S.-proposed projects. The assumed wind resource regime and geospatial power plant characteristics (e.g., water depth and distance from shore) for the offshore reference plants are comparable to sites on the U.S. North Atlantic and Pacific Coast and are detailed in Appendix A. The residential and commercial distributed wind reference projects are informed by 2019 market data from Orrell et al. (2020) because the market data for distributed wind energy projects in 2020 only comprised retrofits or upgrades (Orrell et al. 2021). The distributed wind balance-of-system values are estimated from NREL's Balance-of-System Cost Model for Land-Based Wind (Eberle et al. 2019). The details for land-based, offshore, and distributed wind representative sites are reported in Appendix B.

The four major component LCOE categories—wind turbine CapEx, balance-of-system CapEx, finance CapEx, and OpEx—and many subcategories are represented in Figure ES1, Figure ES2, Figure ES3, and Figure ES4. These figures include wind turbine (e.g., wind turbine components), balance of system (e.g., development, electrical infrastructure, assembly, and installation), and financial costs (e.g., insurance and construction financing). Most of the land-based reference project LCOE (46.4%) is in the wind turbine itself, whereas the balance of system is the major contributor for the fixed-bottom and floating offshore reference projects, making up 31.5% and 43.8%, respectively. The LCOE categories for the representative distributed wind energy projects only consider the turbine, balance of system, and operation and maintenance (O&M) costs because there is limited empirical data on more detailed system cost breakdown for distributed wind projects. For the representative residential distributed wind energy project, the balance-of-system cost comprises a majority of the LCOE at 49.8%, whereas the commercial

distributed wind project cost is accounted for by the wind turbine itself, contributing 51.6% of the LCOE.
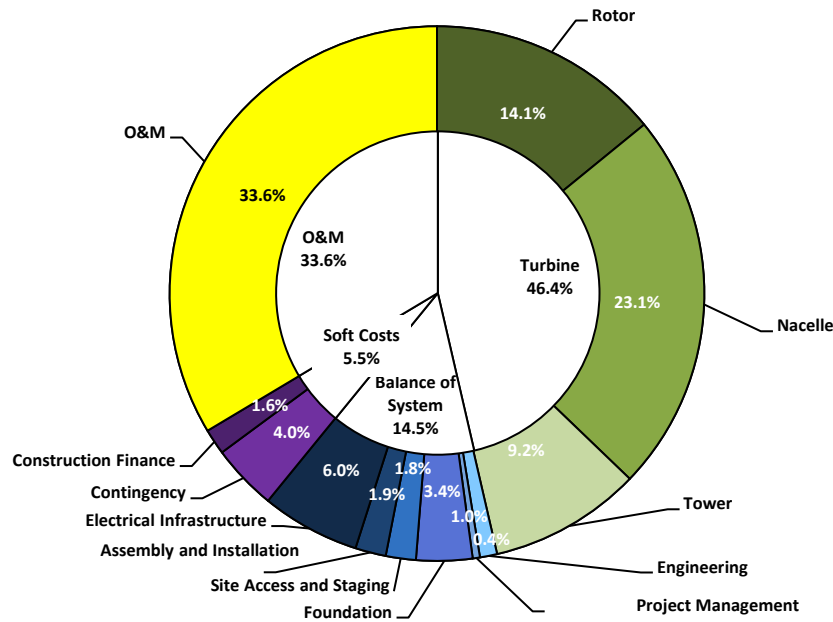
Figure ES1. Component-level LCOE contribution for the 2020 land-based wind reference project operating for 25 years
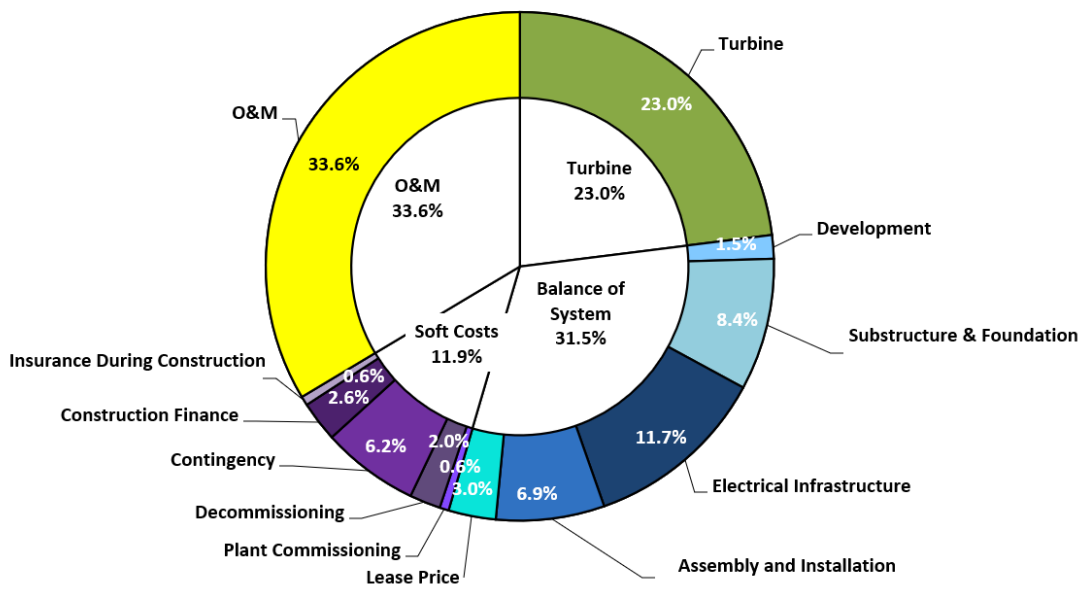
Figure ES2. Component-level LCOE contribution for the 2020 fixed-bottom offshore wind reference project operating for 25 years
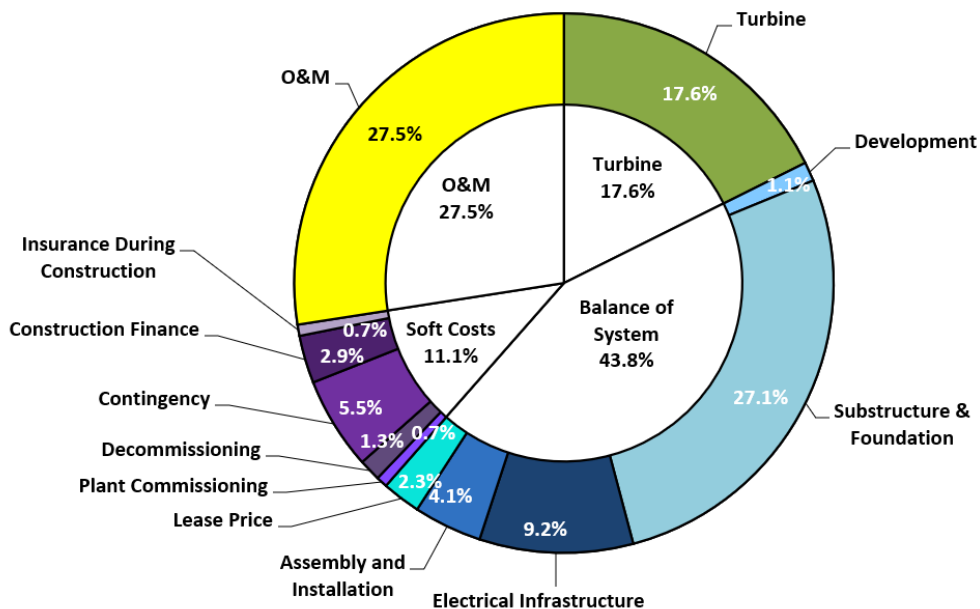
Figure ES3. Component-level LCOE contribution for the 2020 floating offshore wind reference project operating for 25 years
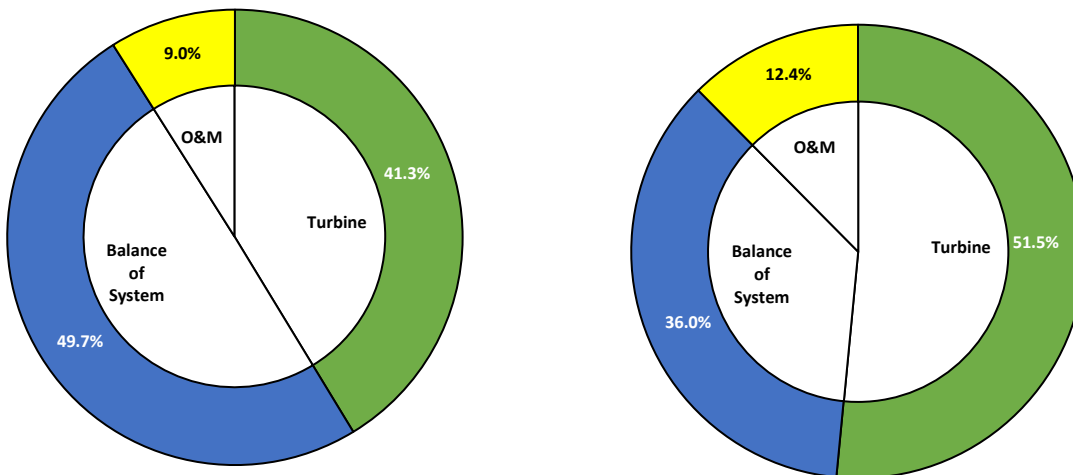
Figure ES4. Component-level LCOE contribution for the 2020 residential (left) and commercial (right) distributed wind reference projects operating for 25 years.

Note: Empirical data and cost model representation for residential and commercial distributed wind energy projects are limited; hence, detailed component-level LCOE contributions are not presented in this report.

Figure ES5, Figure ES6, and Figure ES7 illustrate the LCOE associated with the land-based and offshore reference power plants and provide a range of independent, single-variable sensitivities

showing how these variables affect cost and performance.[1] More specifically, these figures show the effect that CapEx, OpEx, net capacity factor, nominal discount rate, and project design life[2] have on the LCOE for land-based, offshore, and distributed wind energy projects. Reference project values of $34/MWh for land-based wind, $77/MWh for fixed-bottom offshore wind, and $129/MWh for floating offshore wind rely on inputs summarized in Table ES1 through Table ES3 and are identified by the vertical white line in these figures. The figures also show sensitivity ranges pulled from representative industry data contained in the "Land-Based Wind Market Report: 2021 Edition" (Wiser and Bolinger 2021) for the LCOE inputs and the resulting calculated impacts on LCOE for land-based wind energy. The sensitivity ranges for fixed-bottom and floating offshore wind energy are informed by the "Offshore Wind Market Report: 2021 Edition" (Musial et al. 2021) and NREL's offshore wind database. The sensitivity ranges for residential and commercial distributed wind are presented in the "2019 Cost of Wind Energy Review" (Stehly et al. 2020) produced from representative industry data and analysis contained in the "2019 Distributed Wind Data Summary" (Orrell et al. 2020). The ranges for land-based and offshore wind LCOE inputs vary significantly (note the different axes in these figures). More detailed descriptions of the ranges and assumptions are included in Section 4.7 (land-based wind), and Section 5.7 (offshore wind).
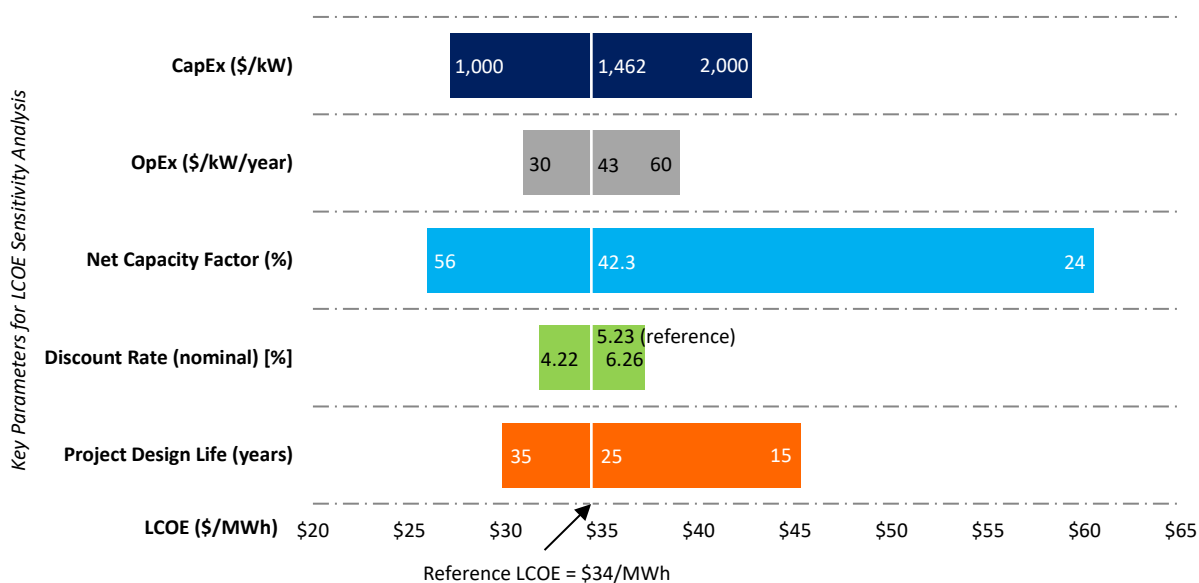
Figure ES5. Land-based wind power plant assumptions and ranges for key LCOE input parameters.

Note: The reference LCOE represents the estimated LCOE for the NREL reference project. 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, assuming that all others are constant. For example, as capacity factor decreases toward 24%, the LCOE shown on the x-

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[1] Single-variable sensitivity results for residential and commercial distributed wind energy projects are omitted in this year's report because cost and performance estimates for the representative projects remain the same as reported in last year's report (Stehly et al. 2020).

[2] Project design life refers to the time in which the wind power plant is expected to operate (not referring to the wind turbine's design life for engineering or certification purposes).

axis will increase accordingly to approximately $60/MWh. Or, as the operational life for the reference project moves toward 35 years, the period in which a project achieves the requisite cash flow it needs to recover its initial CapEx and meet investors' internal rate of return threshold is assumed to be 35 years; therefore, the resulting LCOE decreases to nearly $30/MWh.
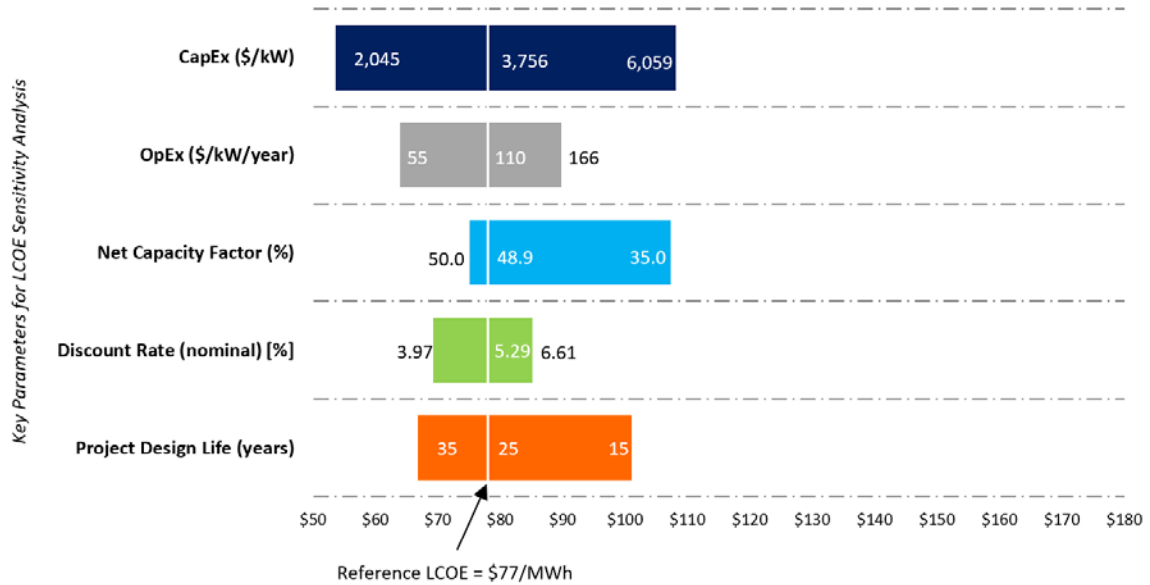
Figure ES6. Fixed-bottom offshore wind power plant assumption and ranges for key LCOE input parameters
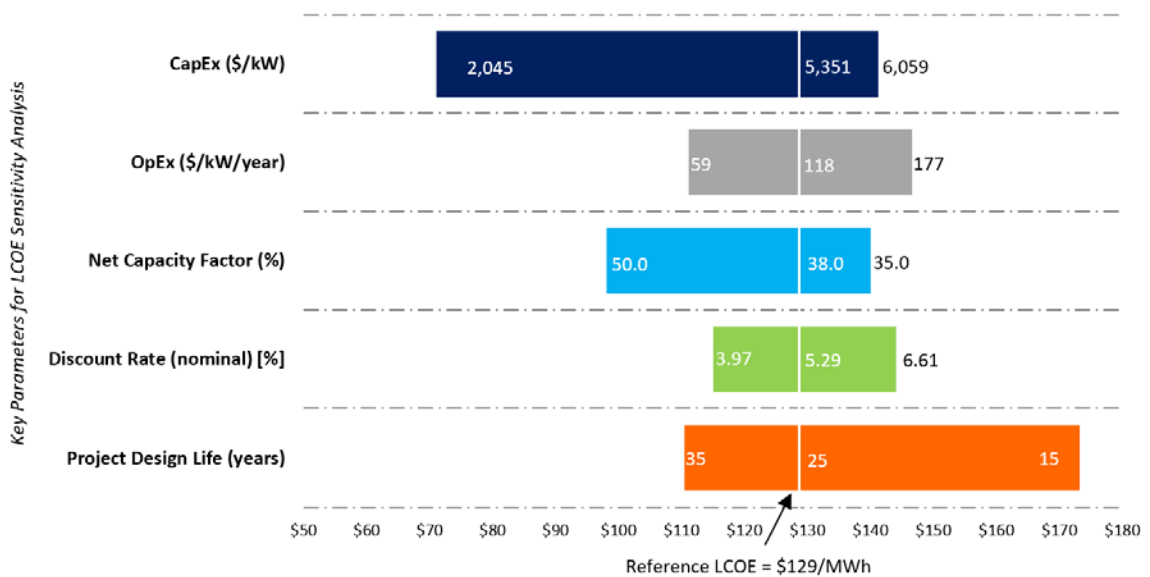
Figure ES7. Floating offshore wind power plant assumptions and ranges for key LCOE input parameters

From the analysis detailed in this report, we derived the following key conclusions:

- Land-based wind power plant LCOE estimates continue to show a downward trend from the "2010 Cost of Wind Energy Review" (Tegen et al. 2012) to the 2020 review. The reference project LCOE for land-based installations was observed to be $34/MWh,[3] with a range of land-based estimates from the single-variable sensitivity analysis covering $26–$60/MWh.[4]

- Offshore wind power plant LCOE estimates continue to decrease. The fixed-bottom reference project offshore estimate is $77/MWh, and the floating substructure reference project estimate is $129/MWh. These two reference projects give a single-variable sensitivity range of $54–$173/MWh. This range is primarily caused by the large variation in CapEx ($2,045–$6,059/kW), which is partially a function of water depth and distance from shore reported by project developers. More recent European and U.S. auction bids as of 2018 suggest that costs for offshore wind energy could fall further in the coming years.[5]

- The LCOE estimates for reference residential and commercial distributed wind energy projects are informed by 2019 market data from Orrell et al. (2020) because new project data were not available in 2020; however, assumptions to the financial inputs were updated for 2020. The residential and commercial reference distributed wind system LCOE are estimated at $151/MWh and $99/MWh, respectively. Single-variable sensitivity analysis for the representative systems is presented in the "2019 Cost of Wind Energy Review" (Stehly et al. 2020).

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[3] As the production tax credit ramps down and expires in 2021, it is likely that wind energy project weighted-average cost of capital or discount rate will be reduced, as leverage increases and tax equity is replaced with cheaper debt.

[4] LCOE estimates reflect a cost to a wind power plant developer and are not directly comparable with power purchase agreements that reflect the sale of electricity.

[5] Additional information on the recent European and U.S. auction bids can be found in the "2018 Offshore Wind Technologies Market Report" (Musial et al. 2019).

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1 Background

This report estimates the levelized cost of energy (LCOE) for land-based and offshore 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 et al. 1995).

In addition, this report provides an update to the "2019 Cost of Wind Energy Review" (Stehly et al. 2020) and a look at the 2020 wind energy industry LCOE, wind turbine costs, financing, and market conditions. More specifically, this 2020 report 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 and commercial 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 2020 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).

This report addresses many assumptions and cost variables but does not include the full spectrum of drivers that affect wind energy prices. For example, it does not consider policy incentives (such as the production tax credit [PTC]), factors from underlying economic conditions (such as an economic recession), the cost of building long-haul interstate transmission, or potential grid integration costs (though offshore wind LCOE values include export cables and onshore spur lines). These important variables can have an impact by increasing or decreasing project costs or delaying projects. Nevertheless, their exclusion is consistent with past economic analyses conducted by NREL, as LCOE is not traditionally defined as a measure of all societal costs and benefits associated with power generation resources.

The standard Annual Technology Baseline (ATB) LCOE equation (NREL's Annual Technology Baseline and Standard Scenarios web page: atb.nrel.gov) can be simplified for each technology.

For wind energy, the following equation is used to calculate LCOE:

$$LCOE = \frac{(CapEx \times FCR) + OpEx}{(AEP_{net}/1{,}000)} \tag{1}$$

where

LCOE = levelized cost of energy ($/megawatt-hour [MWh])

FCR = fixed charge rate (%)

CapEx = capital expenditures ($/kilowatt [kW])

AEP_{net} = net average annual energy production (MWh/megawatt [MW]/year [yr])

 OpEx = operational expenditures ($/kW/yr).

The first three basic inputs into the LCOE equation—CapEx, OpEx, and AEP_{net}—enable this equation to capture system-level impacts from design changes (e.g., larger rotors or taller wind turbine towers). The fourth basic input—FCR—represents the amount of revenue required to pay the annual carrying charges as applied to the CapEx on that investment during the expected project economic life. All analysis and LCOE results are in 2020 U.S. dollars (USD) throughout this report unless otherwise noted. The upcoming sections define the approach to calculating the LCOE following the respective NREL system cost breakdown structures to organize data. This report also describes each component of the LCOE equation (such as CapEx, OpEx, AEP, and FCR), the market context, and a range of data for typical U.S. wind energy projects in 2020.

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

Every year, the DOE Wind Energy Technologies Office (WETO) reports the LCOE for land-based and fixed-bottom offshore wind energy to satisfy GPRA reporting requirements. The annually reported LCOE values are measured against current year and future LCOE targets set by WETO. The official GPRA levelized cost of energy 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[6] wind projects that span from the current year to FY 2030. A summary of the GPRA targets for land-based wind is shown in Table 1 and for offshore fixed-bottom wind in Table 2. It is required that each year the actual costs for land-based and fixed-bottom wind LCOE be reported against the GPRA targets. This report provides the cost data to DOE to meet the annual reporting requirement required by the GPRA. The assumptions and calculations for land-based and fixed-bottom offshore wind energy projects used in GPRA reporting are presented in more detail in Section 4.9 and Section 5.9, respectively.

Table 1. Land-Based Wind GPRA Baseline and Target LCOE

	FY 2016 (Baseline)	FY 2030 (Target)
Land-based LCOE (2015$/MWh)	56	23

Note: The GPRA baseline and target levelized cost of energy in Table 1 are reported in 2015 USD for land-based wind energy because WETO will report land-based wind values in 2015 USD.

Table 2. Offshore Fixed-Bottom Wind GPRA Baseline and Target LCOE

	FY 2019 (Baseline)	FY 2030 (Target)
Offshore fixed-bottom LCOE (2018$/MWh)	89	51

Note: The GPRA baseline and target levelized cost of energy in Table 2 are reported in 2018 USD because WETO will report offshore fixed-bottom wind values in 2018 USD.

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[6] As of Fiscal Year 2021, WETO does not report GPRA costs or targets for floating offshore wind or distributed wind energy technologies.

3 Approach

This "2020 Cost of Wind Energy Review" applies a similar approach as the past cost of wind energy review reports (Tegen et al. 2012, 2013; Moné et al. 2015a, 2015b, 2017; Stehly et al. 2017, 2018, 2019, 2020). The analysis uses several data sources and models to estimate the cost of wind energy. These models and data have been tested, documented, and verified within NREL, other national laboratories, universities, and industry to ensure that the methodology and tools are as accurate as possible. The land-based wind data use the annually released "Land-Based Wind Market Report" authored by Lawrence Berkeley National Laboratory. Specific to the "2020 Cost of Wind Energy Review," the data come from Wiser and Bolinger (2021). The market data supporting the offshore wind energy analysis are limited to international projects and proposed U.S. projects reported in the "Offshore Wind Market Report: 2021 Edition" (Musial et al. 2021) and stored in NREL's offshore wind database[7] of global offshore projects. Given the market and model data available, the general approach to estimating the levelized cost of wind energy includes:

- Evaluating market conditions and data for projects that have been installed in the United States each year to understand total land-based CapEx, annual energy production (AEP), annual OpEx for recently installed projects, and representative wind turbine technology. Representative turbine characteristics (i.e., rating, rotor diameter, and hub height) are taken as market averages of the turbines installed in 2020. Accordingly, LCOE estimates reflect average empirical conditions to the extent possible.

- Evaluating market conditions and data for projects that have been installed in Europe and Asia when considering offshore wind technology each year to understand total CapEx, OpEx, and representative turbine technology. AEP and balance-of-system (BOS) costs are modeled using the specified U.S. North Atlantic site conditions. The primary sources for these data are NREL's offshore wind database and the "Offshore Wind Market Report: 2021 Edition" (Musial et al. 2021).

- Supplementing available market data with modeled data based on a representative or reference project that reflects technology and project parameters for a given year. Analysts used the following suite of NREL models to complete the LCOE analysis:

  o **The 2015 Cost and Scaling Model[8] (CSM)**. We used the CSM to estimate utility-scale land-based wind turbine costs by applying scaling relationships at the component level (e.g., blade, hub, generator, and tower) that reflect the component-specific and often nonlinear relationships between size and cost.

  o **The Land-based Balance of System Systems Engineering (LandBOSSE) model**. We used the LandBOSSE model to estimate all BOS components of the utility-scale[9] and distributed wind (residential and commercial) reference projects. This model is based on a bottom-up assessment of inputs and outputs associated with each BOS operation and is supplemented by top-down estimate of costs from industry. Additional details on the model can be found in Eberle et al. (2019). Prior versions of

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[7] NREL's offshore wind database is used as an internal reference and is not publicly available.
[8] NREL's 2015 Cost and Scaling Model is used as an internal reference and is not publicly available.
[9] This is the first year LandBOSSE was used to estimate BOS costs for utility-scale land-based wind energy; hence, BOS cost differences may be observed from prior versions of this report.

this report used a former BOS cost model to estimate land-based utility scale BOS costs that utilizes scaling relationships based on historical empirical wind industry data. Compared to the legacy model, LandBOSSE is a more sophisticated process-based model comprising more recent cost and wind turbine characteristic data that are expected to provide more representative BOS component cost estimates.

- o **The NREL Offshore Wind Cost Model** (Beiter et al. 2016). Also referred to as the Offshore Wind Regional Cost Analyzer (ORCA), we used ORCA to estimate the soft costs in CapEx as well as OpEx. This report represents the first time that the Offshore Renewables Balance-of-System and Installation Tool (ORBIT) has been used for calculating BOS costs in lieu of ORCA.

- o **ORBIT**. We used ORBIT to estimate the BOS components of the utility-scale[10] fixed-bottom and floating offshore wind reference projects. ORBIT is NREL's Python-based, open-source, bottom-up offshore wind BOS cost model and is capable of analyzing the installation phases of offshore wind projects to estimate installation times and costs. ORBIT offers greater transparency than ORCA when modeling the physical and spatial relationships of BOS costs for offshore wind energy. Core cost relationships represented in ORBIT have been vetted with industry partners, offering a higher degree of confidence than ORCA for capturing recent offshore BOS cost trends on a site-specific level.

- o **The System Advisor Model** (https://sam.nrel.gov/). We used the System Advisor Model to develop an idealized power curve[11] and estimate net energy production for land-based wind energy on turbine rated capacity, rotor diameter, hub height, and a representative wind resource.

- Combining the market and modeled data described earlier to estimate the primary elements necessary to calculate LCOE (i.e., CapEx, OpEx, AEP, and FCR) and provide details about wind technology costs and performance that are aligned with market data but reported at a more detailed resolution. Unless specifically stated, all data and analysis used in this report are in 2020 USD, considering changes resulting from inflation from previous reports.

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[10] This is the first year ORBIT was used to estimate BOS costs for utility-scale offshore wind in the "2020 Cost of Wind Energy Review"; hence, BOS cost differences may be observed from prior versions of this report. Code and documentation are available on GitHub at https://github.com/WISDEM/ORBIT, and the model methodology is described in Nunemaker et al. (2020).
[11] The resulting power curve is available on GitHub through an NREL-hosted repository of tabular data and documentation of wind turbine power curves at https://github.com/NREL/turbine-models.

4   Land-Based Wind Energy

The wind turbine characteristics used in the land-based wind reference project were derived from the "Land-Based Wind Market Report: 2021 Edition" (Wiser and Bolinger 2021). Reference project wind turbine and component costs are based on a hypothetical wind turbine that comprises the average parameters—nameplate capacity, rotor diameter, and hub height—of turbines that were installed in the United States in 2020. This type of turbine rests on a standard spread-foot foundation design and incorporates a three-stage planetary/helical gearbox feeding a high-speed asynchronous generator. The 2020 reference project wind regime is intended to reflect an International Electrotechnical Commission (IEC) class IIb (IEC 2020). This wind resource site is consistent with prior versions of this report and a typical power plant size of 200 MW.

4.1   Land-Based Reference Project

The land-based reference project is intended to represent a wind site found in the interior region of the United States. The wind power plant specific to this analysis comprises 73 wind turbines that are each rated at 2.8 MW (based on the average wind turbine size installed in the United States in 2020), equating to a capacity of 200 MW. These reference project parameters are summarized in Table 3, with further detail on the turbine parameters provided in Table 5. The wind power plant layout is roughly placed in a grid layout at an elevation around 450 meters (m) above sea level—the reference elevation is used for calculating the wind plant's AEP. The wind power plant is assumed to be operating for 25 years with no catastrophic operation and maintenance (O&M) events.

Table 3. Land-Based Reference Project Parameters

Project Parameters	
Turbine rated power (MW)	2.8
Number of wind turbines	73
Wind power plant capacity (MW)	200
Elevation above sea level (m)	450
Project design life (years)	25

Note: Project design life refers to the time in which the wind power plant is expected to operate (not referring to the turbine's design life for engineering or certification purposes).

4.2   Land-Based Capital Expenditures

The weighted-average CapEx data are published annually by DOE (Wiser and Bolinger 2021). We used the NREL 2015 CSM to determine the component cost breakdown given the total CapEx cost estimates reported by Wiser and Bolinger (2021). The NREL 2015 CSM uses curve fits from commercial wind turbine component design and cost data while providing the ability to adjust inputs, such as overhead, profit, and transportation. Figure 1 illustrates the breakdown of CapEx for the NREL land-based reference wind project. In the figure, the CapEx component percentages highlighted in shades of green capture the turbine capital cost, the percentages highlighted in blue capture the BOS share of capital costs, and the components highlighted in purple capture the financial CapEx. For information on the assumptions and inclusions of the individual components, see the "2013 Cost of Wind Energy Review" (Moné et al. 2015a). Some

costs, such as transportation, are rolled up into higher categories (such as nacelle and blades), as the specific data are difficult to obtain based on a theoretical reference site.
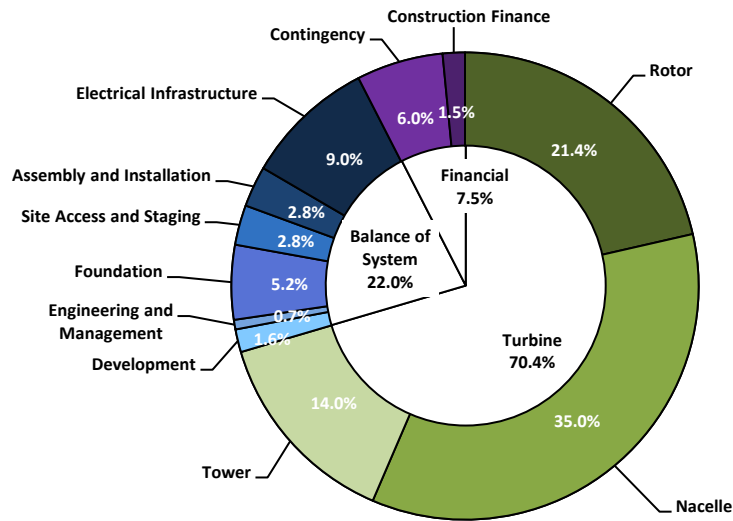
Figure 1. CapEx for the land-based reference wind power plant project

Table 4 summarizes the costs for the reference project's individual components (including their contribution to LCOE). More details on the representative wind power plant's energy production and financial assumptions used to calculate LCOE are provided in Section 4.3 and Section 4.5, respectively.

Table 4. Land-Based CapEx and LCOE Breakdown

	2.8-MW Land-Based Wind Turbine ($/kilowatt [kW])	2.8-MW Land-Based Wind Turbine ($/MWh)
Rotor module	**311**	**4.8**
Blades	201	3.1
Pitch assembly	62	1.0
Hub assembly	47	0.7
Nacelle module	**508**	**7.9**
Nacelle structural assembly	102	1.6
Drivetrain assembly	203	3.2
Nacelle electrical assembly	164	2.6
Yaw assembly	38	0.6
Tower module	**203**	**3.2**
Turbine capital cost	**1,021**	**15.9**
Development	23	0.4
Engineering and project management	10	0.2
Foundation	75	1.2
Site access and staging	40	0.6
Assembly and installation	41	0.6
Electrical infrastructure	131	2.0
Balance of system	**319**	**5.0**
Construction financing cost	34	0.5
Contingency fund	88	1.4
Financial costs	**122**	**1.9**
Total capital expenditures	**1,462**	**22.8**

Because of CapEx variability among projects, we established estimates for the turbine component costs using the NREL 2015 CSM. In this year's report, we estimate BOS costs using the recently developed LandBOSSE model (Eberle et al. 2019), as opposed to NREL's Land-Based-Wind BOS model used in the prior version of this report. Construction financing was estimated assuming a 3-year construction duration and distributing the capital and interest over the 3 years. We estimated the project contingency at 6% of CapEx, which is consistent with industry reporting. Total installed project CapEx for U.S. projects in 2020 averaged $1,462/kW (Wiser and Bolinger 2021) and has remained relatively stable over the last 3 years.

4.3 Land-Based Technology Characteristics and Annual Energy Production

4.3.1 Wind Turbine Parameters

For this report, the turbine parameters are specific to the wind turbine and independent of the wind resource characteristics. These parameters include not only turbine size (such as rated power, rotor diameter, and hub height), but also turbine operating characteristics (such as coefficient of power, maximum tip speed, maximum tip-speed ratio, and drivetrain design). Because the three-stage planetary/helical gearbox with a high-speed asynchronous generator-style drivetrain topology dominates the U.S. market, we selected this type of drivetrain for the baseline wind turbines used in this analysis. The power curve for the 2.8-MW land-based wind turbine is derived from NREL's System Advisor Model. A summary of the turbine parameters is shown in Table 5. For specific approaches regarding additional turbine parameters (e.g., power curves), see the "2010 Cost of Wind Energy Review" (Tegen et al. 2012).

Table 5. Reference Land-Based Wind Turbine Parameters

Turbine Parameters	
Turbine rated power (MW)	2.8
Turbine rotor diameter (m)	125
Turbine hub height (m)	90
Maximum rotor tip speed (meters per second [m/s])	80
Tip-speed ratio at maximum coefficient of power (C_p)	8
Drivetrain design	Geared
Cut-in wind speed (m/s)	3
Cut-out wind speed (m/s)	25
Maximum coefficient of power	0.47

4.3.2 Wind Resource

The average wind speed varies from project to project across the United States. The annual average wind speed chosen for the reference project analysis, which is consistent with prior reports, is 7.25 meters per second (m/s) at 50 meters (m) above ground level (7.89 m/s at a hub height of 90 m). This wind speed is intended to be generally indicative of the wind regime for projects installed in moderate-quality sites (i.e., IEC wind class IIb). We applied an elevation of 450 m above sea level based on this concept of using a representative site that would have a similar altitude to a project located within the interior of the country. The representative elevation defines the air density used for calculating the project AEP. A summary of the wind resource assumptions for the 2020 representative site is included in Table 6.

Table 6. Reference Land-Based-Wind Resource Assumptions

Wind Resource Characteristics	
Annual average wind speed at a 50-m height (m/s)	7.25
Annual average wind speed at a 90-m hub height (m/s)	7.89
Weibull k	2.0
Shear exponent	0.143
Turbine elevation (meters above sea level)	450

4.3.3 Losses and Availability

Although some losses can be affected by turbine design or wind resource characteristics, they are treated as independent of any other input in this simplified analysis. Types of losses accounted for here include array wake losses, electric collection system and transmission losses (from the substation to the point of interconnection), and blade soiling losses, totaling 15%. A wind power plant availability of 98% is assumed, indicating the plant is ready to produce power 98% of the time that the wind speed falls within the operational range (i.e., between the wind turbine's cut-in and cut-out wind speeds). Wind power plant availability accounts for any unplanned downtime the plant may experience, such as unplanned maintenance activities. The net average AEP is then calculated by applying all losses and availability to the gross AEP. Table 7 shows the estimated losses and availability for the land-based reference wind power plant.

Table 7. Reference Land-Based-Wind Losses and Availability Assumptions

Losses	
Losses (i.e., array, energy conversion, and line)	15%
Availability	98%

4.3.4 Annual Energy Production

We computed the AEP for this analysis using the System Advisor Model. The model uses an idealized power curve based on the wind turbine configuration and computes annual energy capture for a wind project that is specified by the wind resource and the wind power plant's assumed losses and availability. The result of these calculations yields a net energy capture of 3,707 MWh/MW/year (yr), which corresponds to a 42.3% net capacity factor assuming 8,760 hours in a year. For reference, the average capacity factor reported by Wiser and Bolinger (2021) among recently built projects was over 40%. The net energy capture and net capacity factor for the reference wind plant are shown in Table 8.

Table 8. Reference Land-Based-Wind Power Plant AEP and Capacity Factor Summary

AEP and Capacity Factors	
	7.25 m/s at 50 m
Net energy capture (MWh/MW/year [yr])	3,703
Net capacity factor (%)	42.3%

4.4 Land-Based Operation and Maintenance Expenditures

OpEx costs are generally organized into two categories: 1) fixed O&M costs (e.g., scheduled plant maintenance or land lease costs) and 2) variable O&M costs (e.g., unscheduled plant maintenance). For simplicity, annual OpEx can be converted to a single term and expressed as either dollars per kilowatt per year ($/kW/yr) or dollars per megawatt-hour ($/MWh). This analysis uses the dollars-per-kilowatt-per-year convention. O&M market data are not widely available; therefore, the recent U.S. wind industry survey, "Assessing wind power operating costs in the United States: Results from a survey of wind industry experts" (Wiser et al. 2019) is used to inform the O&M cost estimates for the representative wind power plant. For recently installed projects, entering commercial operations from 2015 through 2018, the survey results anticipate an average range of O&M costs between $33 and $59/kW/yr. The average across respondents was ~$43/kW/yr and is assumed to be the all-in levelized OpEx for the representative project.[12] The annual O&M cost from the expert survey and the calculated O&M cost on an energy basis for the representative wind power plant is shown in Table 9.

Table 9. Land-Based-Wind Reference Project OpEx

	2.8-MW Land-Based Wind Turbine ($/kW/yr)	2.8-MW Land-Based Wind Turbine $/MWh
OpEx	43	11.5

4.5 Land-Based-Wind Finance

This section describes the financing assumptions for the report's representative land-based-wind reference project in the United States in 2020. It is important to distinguish between financing assumptions and financial costs. Financial costs, which are part of CapEx according to the system cost breakdown structure, include items such as insurance, contingency, and reserve accounts. Financing assumptions, on the other hand, refer to the cost of interest and other carrying charges, corporate taxes, and depreciation (represented by the FCR in this report), applied to the total CapEx. To capture the financing structure and costs, we use a fixed charge rate, detailed in Section 4.5.2, for the LCOE equation.

4.5.1 Discount Rate

Typically, various financial terms, such as the cost of debt or equity, are captured in the discount rate, which is in turn used to estimate the cost of energy. For this analysis, we calculate the discount rate as the after-tax weighted-average cost of capital (WACC), and we presume that the reported yields for equity are after-tax yields and can be used directly in the WACC calculation. The cost of debt (as a value) is also reported, but because interest on debt is tax deductible, we use an effective corporate marginal tax rate to determine an after-tax cost of debt for the discount rate calculation. The cost of capital data collected by Lawrence Berkeley National Laboratory (Wiser and Bolinger 2021) gives a basis for WACC assumptions for the representative wind project in 2020 and results in a nominal WACC of 5.23%. This WACC was derived assuming a debt fraction of 47.9%, nominal debt interest rate of 2.61%, nominal return on equity of 8.25%,

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[12] Given the scarcity and varying quality of the data, OpEx may vary substantially among projects, and the data included here may not fully represent the challenges that OpEx present to the wind energy industry.

and a 25.7% tax rate.[13] Each actual project, however, has a unique risk profile, financing terms, and ownership structure. For this reason, a single WACC representing the entire fleet of 2020 wind energy installations should be viewed cautiously and used to illustrate general market trends and conditions only.

In financial modeling, corporate tax rates are often presented as a composite, or effective, tax rate. This rate is calculated from a blend of the highest marginal corporate tax rate of 21% and an approximate typical state corporate tax rate. Because state taxes are normally deductible expenses on federal tax returns, the blended rate is represented as 25.7%, as reported in NREL's ATB. Wind projects are often organized as disregarded entities for tax purposes (i.e., no taxes are paid by the project entity) and taxes are paid further up the organizational structure at some corporate level.

The inflation rate has been set to 2.5%. This rate aligns with the inflation rate provided in NREL's ATB. Discount rates are initially calculated in nominal after-tax USD, and an estimate of inflation is used to calculate a discount rate in real after-tax USD.

Although the PTC is a critical component for wind energy projects installed in 2020, it is expected to phase out in future years.[14] Research shows that one likely outcome of the termination of the PTC is increased project leverage, which will reduce the higher-cost tax-equity portion of project finance. This shift of capital structure is expected to partially offset the impact of the lack of PTC (Bolinger 2014). There continues to be active discussions among lawmakers surrounding possible additional PTC extensions, which could have a significant impact on the project finance market in years to come (Wiser and Bolinger 2021).

4.5.2 Economic Evaluation Metrics

In the economic evaluation of wind energy investments there are two important metrics: the capital recovery factor (CRF) and FCR. The FCR represents the amount of annual revenue required to pay the carrying charge[15] as applied to the CapEx on that investment during the expected project economic life.[16] The FCR is based on the capital recovery factor but also reflects corporate income taxes and depreciation. The ATB methodology is used to calculate the FCR.

The CRF is defined as "the uniform periodic payment, as a fraction of the original investment cost that will fully repay a loan including all interest, over the term of the loan" (Short et al. 1995). The CRF can be thought of as the recurring fixed payment over the life of a loan common to most types of mortgages. Note, the CRF ignores the impact of corporate income taxes, thus it applies to a no-tax investment scenario, such as from a government investment.

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[13] Because these data are derived from installed wind energy projects in 2020, they include the impact of the PTC on the debt ratio even though the LCOE estimates do not include the PTC.

[14] "In December 2020, Congress extended the PTC for yet another year (i.e., projects must start construction by the end of 2021) at the 60% level, while in June 2021, the IRS extended the safe-harbor window yet again, to six years for projects that started construction in 2016–2019 and to five years for projects that started construction in 2020" (Wiser and Bolinger 2021).

[15] Carrying charges include the return on debt, return on equity, taxes, and depreciation.

[16] The FCR does not allow for detailed analysis of specific financing structures; however, these structures can be represented through the use of a WACC as the discount rate input.

A reasonable assumption for land-based wind energy projects is that 95% of the project capital cost is eligible for 5-year (Modified Accelerated Cost Recovery System [MACRS]) depreciation, and the balance of the project capital cost is eligible for 15-year MACRS. In this work, the MACRS assumption is further simplified by assuming that 100% of the wind project cost basis is eligible for 5-year MACRS.

Table 10 presents the estimated WACC, CRF, and FCR in nominal and real terms using the after-tax WACC discount rate of 6.32% and 3.72%, respectively, a project design lifetime of 25 years, and a net present value depreciation factor of 84.6% (assuming a 5-year MACRS depreciation schedule). The nominal and real CRF are estimated at 8.06% and 6.21%, respectively. The nominal FCR is estimated at 8.49% and the real FCR is estimated at 6.55%. As noted in Short et al. (1995), comparisons of two or more capital investments should be on a consistent tax treatment basis (i.e., both investments using a before-tax method or an after-tax method).

Table 10. Summary of Land-Based-Wind Reference Project Economic Evaluation Metrics

	Nominal	Real
Weighted-average cost of capital (%)	5.23%	2.66%
Capital recovery factor (%)	7.26%	5.53%
Fixed charge rate (%)	7.59%	5.78%

4.6 Land-Based-Wind Levelized Cost of Energy

The levelized cost of energy for the 2020 representative land-based wind power plant is calculated using the formulation presented in NREL's ATB and the representative wind turbine technology parameters, site conditions, wind resource, and cost estimates (i.e., CapEx, FCR, OpEx, and AEP). The LCOE value for the 2020 representative plant is estimated at $34/MWh. Table 11 summarizes the costs for the primary components on a per-kilowatt and per-megawatt-hour basis. The graphic in Figure 2 illustrates the LCOE breakdown for the primary components of the representative wind power plant, whereas Figure 3 depicts the absolute LCOE values for each of the components.

Table 11. Summary of Inputs and Reference Project LCOE for 2020 Land-Based-Wind Installations

	2.8-MW Land-Based Wind Turbine ($/kW)	2.8-MW Land-Based Wind Turbine ($/MWh)
Turbine capital cost	1,030	16.1
Balance of system	322	5.0
Financial costs	110	1.7
CapEx	**1,462**	**22.8**
OpEx ($/kW/yr)	**43**	**11.5**
FCR (real) [%]	5.78%	
Net annual energy production (MWh/MW/yr)	3,703	
Net capacity factor (%)	42.3%	
TOTAL LCOE ($/MWh)	**34**	
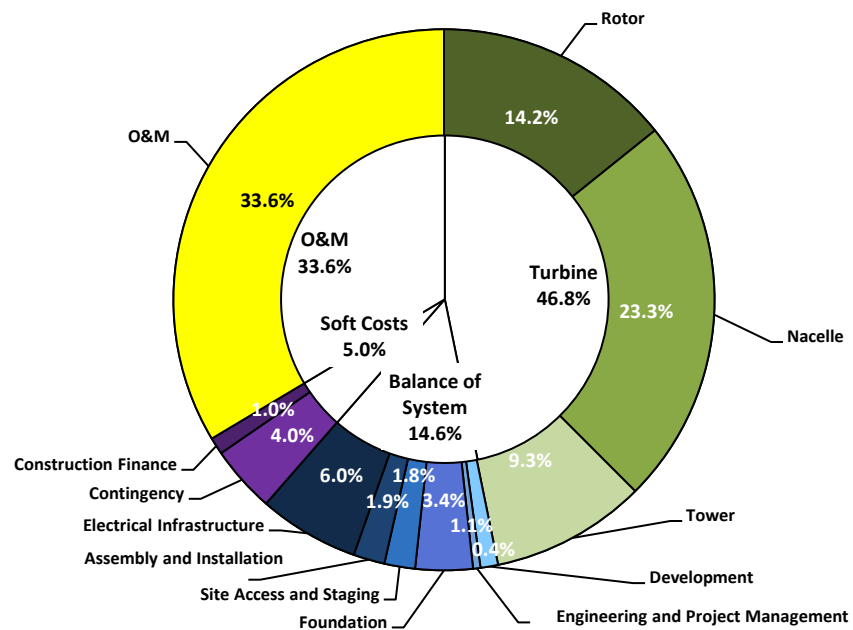
Figure 2. Component-level LCOE contribution for the 2020 land-based-wind reference project operating for 25 years
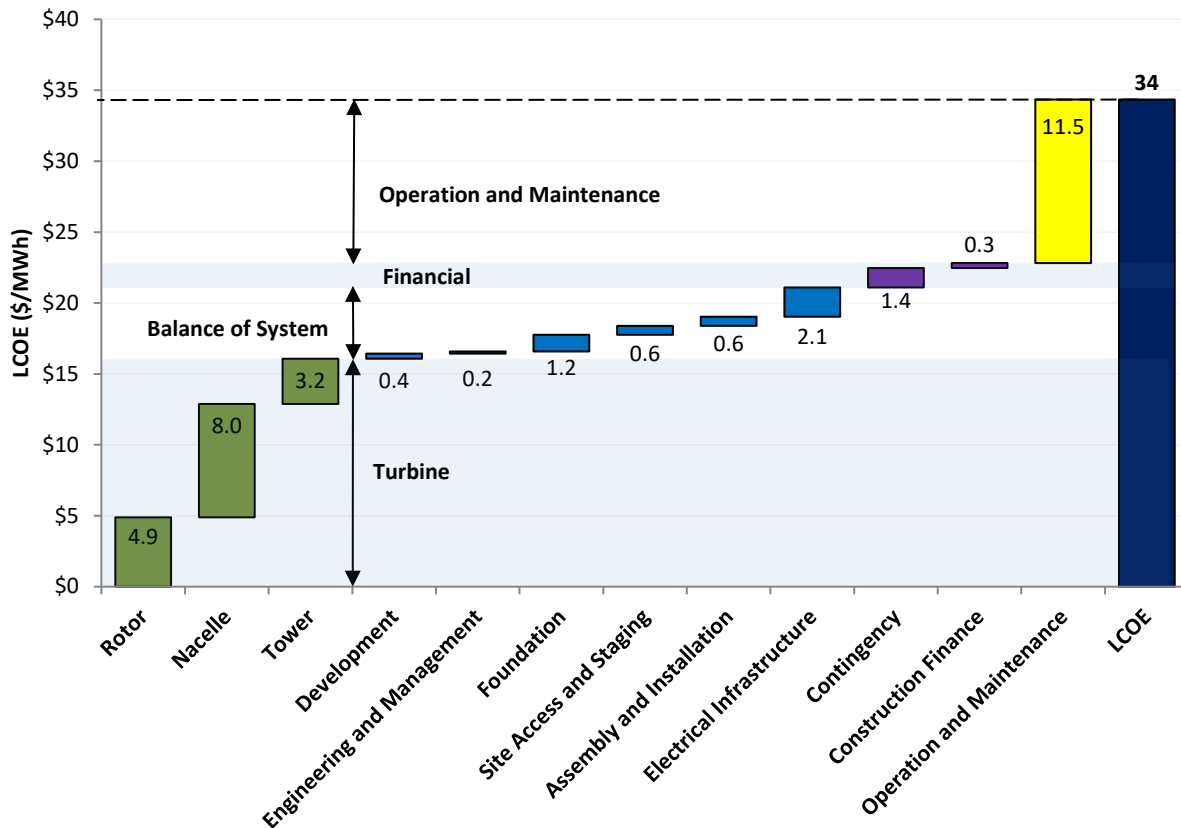
Figure 3. Component-level LCOE breakdown for the 2020 land-based-wind reference project

4.7 Land-Based-Wind Levelized Cost of Energy Sensitivities

The input parameters described earlier reflect the land-based reference wind project; however, input parameters for a near-term wind energy project are subject to considerable uncertainty. As a result, it is beneficial to investigate how this variability may impact the LCOE. The sensitivity analysis shown in Figure 4 focuses on the basic LCOE inputs: CapEx, OpEx, capacity factor, and FCR, which is broken into its principal elements: discount rate and economic operational lifetime.

Sensitivity analyses are conducted by holding all reference project assumptions constant and altering only the variable in question. Sensitivity ranges for all parameters except for project design life are pulled from representative industry data or analysis contained in the "Wind Energy Technology Data Update" (Wiser and Bolinger 2021). This selection provides insight into how real-world ranges influence LCOE. Keeping the same 200-MW project size, the sensitivity analysis yields ranges in LCOE from a low of $26/MWh to a high of $60/MWh—a
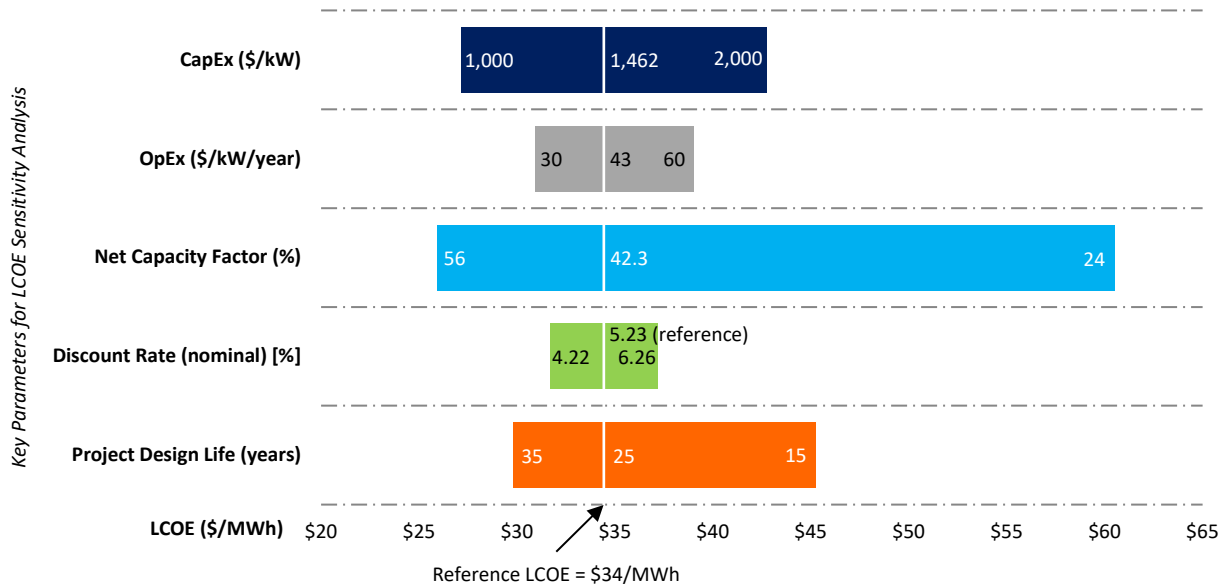
Figure 4. Sensitivity of land-based-wind LCOE to key input parameters

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).

low-to-high delta of $35/MWh. Within the ranges shown, net capacity factor has the greatest impact on land-based-wind LCOE followed by impacts from CapEx and then project design life. Net capacity factor appears to have the greatest influence with respect to decreasing the LCOE relative to the reference project.

4.8 Land-Based Supply Curve

The land-based supply curve illustrates LCOE across the contiguous United States using the 2020 market data from Wiser and Bolinger (2021) and the Wind Integration National Dataset Toolkit (https://www.nrel.gov/grid/wind-toolkit.html). The toolkit provides meteorological conditions for more than 126,000 sites in the continental United States for the years 2007 to 2013. The LCOE for each of the potential wind power plant locations is computed using a site-specific CapEx and net AEP using a geographic-information-system-based algorithm (Maclaurin et al. 2019). The estimated theoretical capacity for the United States is calculated to be over 9,000 gigawatts (GW), assuming a wind power plant density of 3 MW/square kilometer (km^2). The LCOE calculated for this theoretical capacity ranges from $24/MWh for the best sites in the United States and extends beyond $175/MWh for nonideal sites. Figure 5 shows this supply curve. For illustrative purposes, the LCOE is calculated for the land-based wind energy projects installed in 2020 using the same site-specific methodology for 109 project locations, which are shown on the supply curve (marked by green circles). In the figure, most of the installed projects in 2020 are grouped near the left side of the supply curve, where LCOE values are lowest, with fewer scattered when moving toward the right of the supply curve with higher LCOE values. Also shown is the calculated LCOE for the reference land-based wind project (indicated by the

orange diamond), which is based on the 2020 market data from Wiser and Bolinger (2021) and the representative wind site characteristics.

It is important to note that the potential wind power plant capacity available over a range of LCOE varies by geographic region primarily because of the available wind resource characteristics. Incremental costs associated with labor rates, material costs, logistical or siting challenges, and distance to existing transmission infrastructure also contribute to regional differences. This range of costs is illustrated in the supply curve (Figure 5), wherein the cluster of installed wind energy projects in 2020 is toward the lower LCOE end of the supply curve and reflects projects built in the interior region of the United States where the wind resource is favorable. On the other side of the spectrum, the higher LCOE values on the supply curve reflect sites with a relatively lower-quality wind resource and may occur in many regions of the country depending on local meteorological and terrain features.
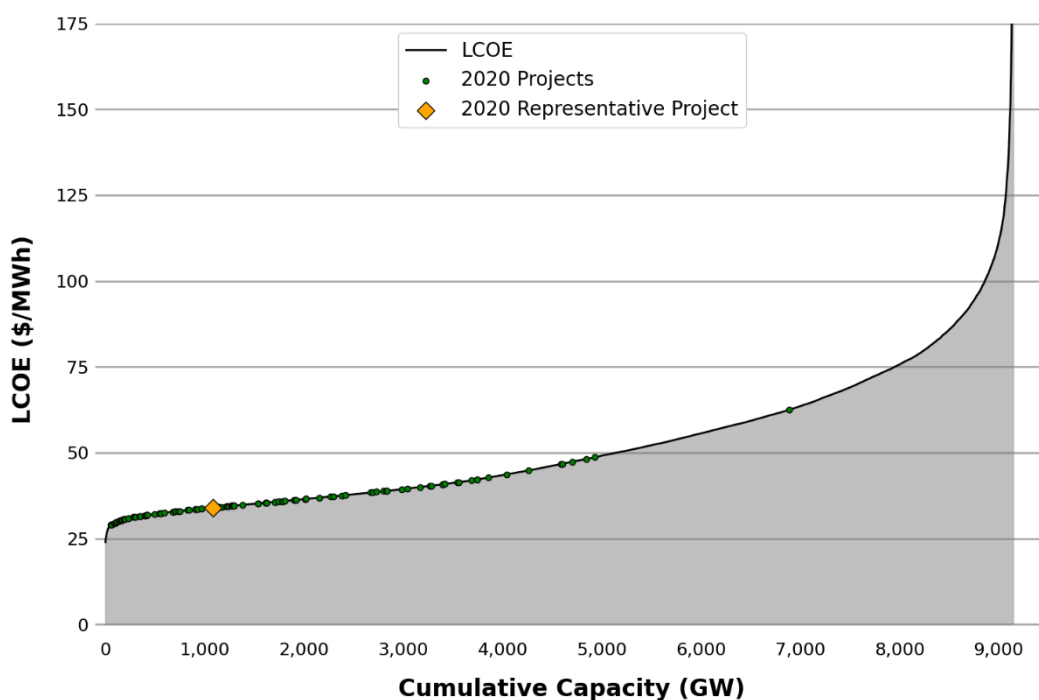
Figure 5. National land-based-wind resource supply curve with 2020 U.S. installed projects

4.9 Land-Based-Wind Discussion of Results in Context of DOE Goals

In this section, we present the official land-based-wind GPRA levelized cost of energy end-point target in FY 2030. The 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 GPRA target is projected to $23/MWh (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 pathway for LCOE reduction from the FY 2016 baseline to the FY 2030 target is primarily driven by the increase in AEP through turbine scaling, enhanced control strategies, and reducing wind power plant losses ($20/MWh [in 2015 USD]). The secondary driver in decreasing LCOE is through reductions in CapEx from wind power plant economies of scale, turbine scaling, and efficient manufacturing capabilities ($8/MWh [in 2015 USD]). The

remaining LCOE reductions are derived from decreasing OpEx through advanced O&M strategies ($4/MWh [in 2015 USD]) and lowering the cost of capital from increased certainty of future plant performance and reduced risk ($1/MWh [in 2015 USD]). This LCOE reduction pathway is illustrated in Figure 6.
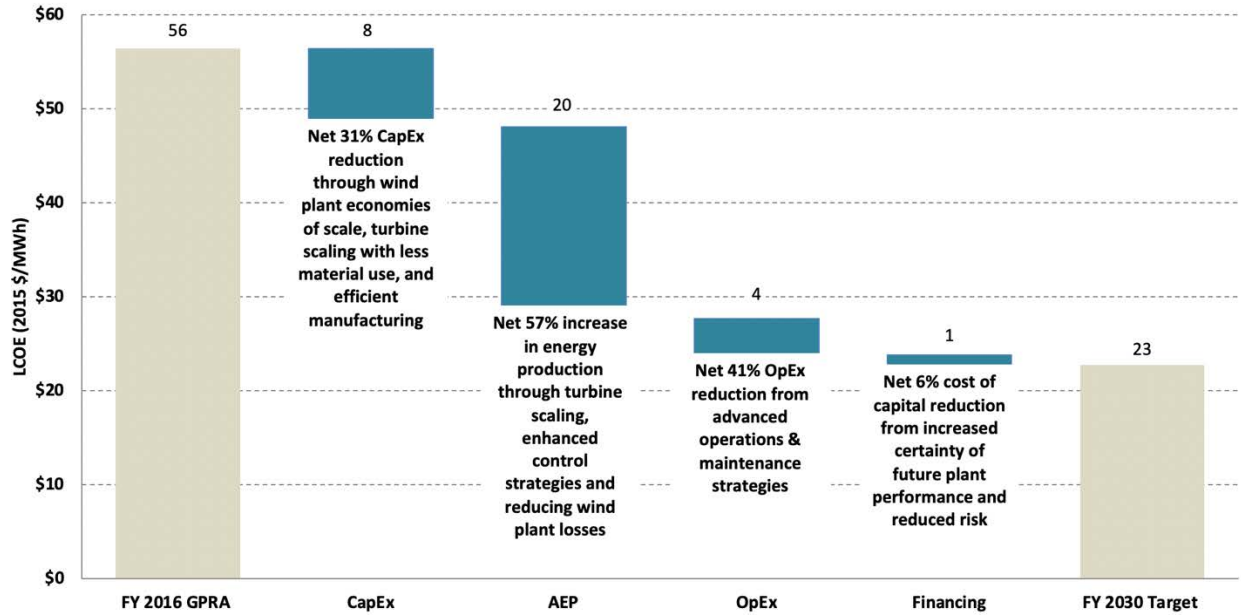
Figure 6. Pathway to LCOE reduction in 2030 by LCOE parameter

The GPRA trajectory and FY 2030 target are shown in Figure 7. To track LCOE progress against the GPRA trajectory, the historical LCOE (starting from FY 2016) and the current LCOE value (in FY 2021) assessed in this year's report are plotted. The GPRA baseline and target levelized cost of energy are reported in 2015 USD for land-based wind energy because WETO will report land-based wind values in 2015 USD. The current and historical LCOE values are labeled as "Actuals" in Figure 7. In the figure, the FY 2021 actual LCOE is reported as $31/MWh instead of $34/MWh, as it was converted from 2020 USD to 2015 USD to compare against the GPRA trajectory.[17]

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[17] The 2020 USD to 2015 USD was calculated assuming a -8.4% cumulative rate of inflation from the Bureau of Labor and Statistics (undated).
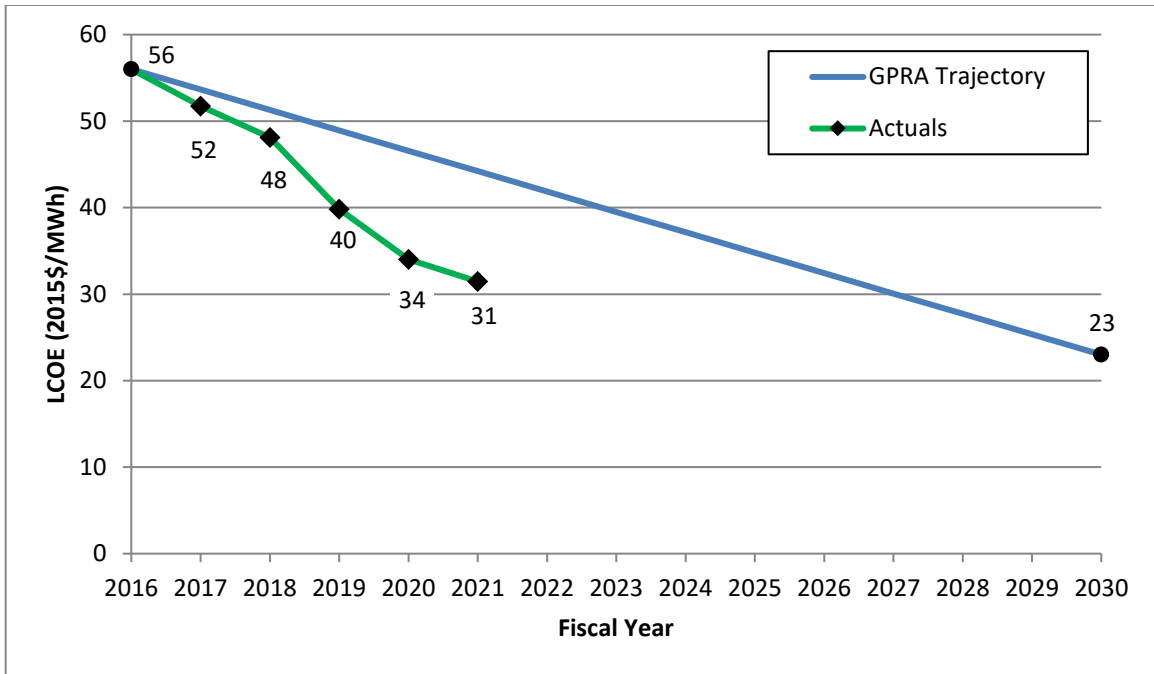
Figure 7. Land-based-wind GPRA cost trajectories for LCOE (in 2015 USD)

5   Offshore Wind Energy

In this section, we outline our methodology and core assumptions for calculating LCOE at representative U.S. projects at the offshore wind reference sites introduced in the "2018 Cost of Wind Energy Review" (Stehly and Beiter 2019). These reference sites reflect spatial conditions that are intended to represent near- to medium-term U.S. project development (see Appendix A for details). During this writing, Vineyard Wind 1 became the first U.S. commercial-scale offshore wind power plant to reach financial close and start construction, so we still rely on global offshore wind market and cost trends to serve as the basis for modeling and U.S. offshore wind costs (Vineyard Wind 2021). In this report, we updated costs and financial parameters to conform with the most recent industry and market developments based on data from NREL's internal offshore wind database, the 2021 ATB, and the "Offshore Wind Market Report: 2021 Edition" (NREL 2021; Musial et al. 2021).

5.1   Offshore Wind Energy Reference Projects

For the purposes of this study, we assessed two offshore wind energy technology categories: fixed bottom and floating. The two substructure technologies are used in different site conditions and correspond to separate offshore reference sites used to calculate LCOE (one for fixed bottom and one for floating). Only the fixed-bottom site is used for GPRA reporting purposes.

The offshore wind energy projects we assessed at the fixed-bottom and floating sites consist of 75 wind turbines rated at 8.0 MW, yielding a total plant capacity of 600 MW. The turbine capacity is estimated from NREL's global offshore wind project database for calendar year 2020. We assume wind turbines are oriented in a grid layout and operate for 25 years without any catastrophic O&M events. Turbines at the fixed-bottom reference site are assumed to be supported by a monopile substructure 50 km from cable landfall at a water depth of 34 m, which is representative of characteristics of the wind energy areas located in the North Atlantic region. At the floating reference site, we assume semisubmersible substructure technology is anchored 36 km from cable landfall at a water depth of 739 m, which is analogous to features of the Pacific Coast. Additional information on the types of fixed-bottom and floating wind substructures can be found in Musial et al. (2021).

The array cable system and electrical line that connects to the offshore substation is a 66-kilovolt collection system design. The export cable from the offshore substation that is used to transfer the power to landfall assumes a 220-kilovolt export system. Specific to the floating reference site, we applied cost premiums to the array and export cable systems to account for the use of dynamic cables. A summary of the two offshore reference site characteristics is provided in Table 12. Further details on the development of the fixed-bottom and floating reference sites are presented in Appendix A.

Table 12. Offshore Wind Reference Project Parameters (Fixed-Bottom and Floating Substructures)

Project Parameters		
	Fixed Bottom	**Floating**
Region	North Atlantic	Pacific Coast
Turbine rated power (MW)	8.0	8.0
Number of wind turbines	75	75
Wind power plant capacity (MW)	600	600
Water depth (m)	34	739
Substructure type	Monopile	Semisubmersible
Distance from shore (km)	50	36
Project design life (yr)	25	25

5.2 Offshore Wind Capital Expenditures

We estimated CapEx using ORBIT for balance-of-system costs. Soft costs are estimated based on the methodology from ORCA (Nunemaker et al. 2020; Beiter et al. 2016). Turbine CapEx is assumed to remain constant with the "2019 Cost of Wind Energy Review" based on industry data analyzed in the "Offshore Wind Market Report: 2021 Edition" (Stehly et al. 2020; Musial et al. 2021). The representative wind turbine characteristics (i.e., turbine capacity, rotor diameter, and hub height) used as inputs to the model were obtained from NREL's global offshore wind database. The capacity-weighted average turbine installed globally (excluding China) in 2020 was 8.0 MW, with a 159-m rotor diameter at a 102-m hub height. This choice to exclude China from the global capacity weighted average is informed by the fact that the average turbine capacity installed in China in 2020 was 4.0 MW (compared with 8.12 MW in Europe). We expect projected wind turbine technology choices in the U.S. market to follow European market trends in the near-term; therefore, the Chinese data were excluded. We used these turbine parameters in combination with the spatial parameters presented in Table 12 for the fixed-bottom and floating reference sites to calculate CapEx.

The ORBIT and ORCA modeling effort yields a total installed CapEx value of $3,756/kW for the fixed-bottom reference site and $5,351/kW for the floating reference site. It should be noted that the CapEx estimates for floating offshore wind energy in this analysis assume an 8.0-MW turbine and are not necessarily optimized for floating offshore wind applications; therefore, they may negatively impact the floating CapEx estimates. Note a change from the 2019 COE Review—the Port, Logistics, Staging, and Transportation cost category has been removed from pie charts and summary tables because ORBIT represents these costs during respective installation processes for the wind turbine, substructure, and electrical system, rather than as a unique line item in ORCA.

A breakdown of the CapEx for the fixed-bottom offshore reference project is shown in Figure 8. The shades of green represent the turbine cost, shades of blue represent BOS costs, and shades of purple represent financial costs. Further details on the BOS cost breakdown are provided in Nunemaker et al. (2020). The dollar-value component cost breakdown is shown in Table 13. Figure 9 and Table 14 describe the same breakdown for the floating offshore wind reference project.
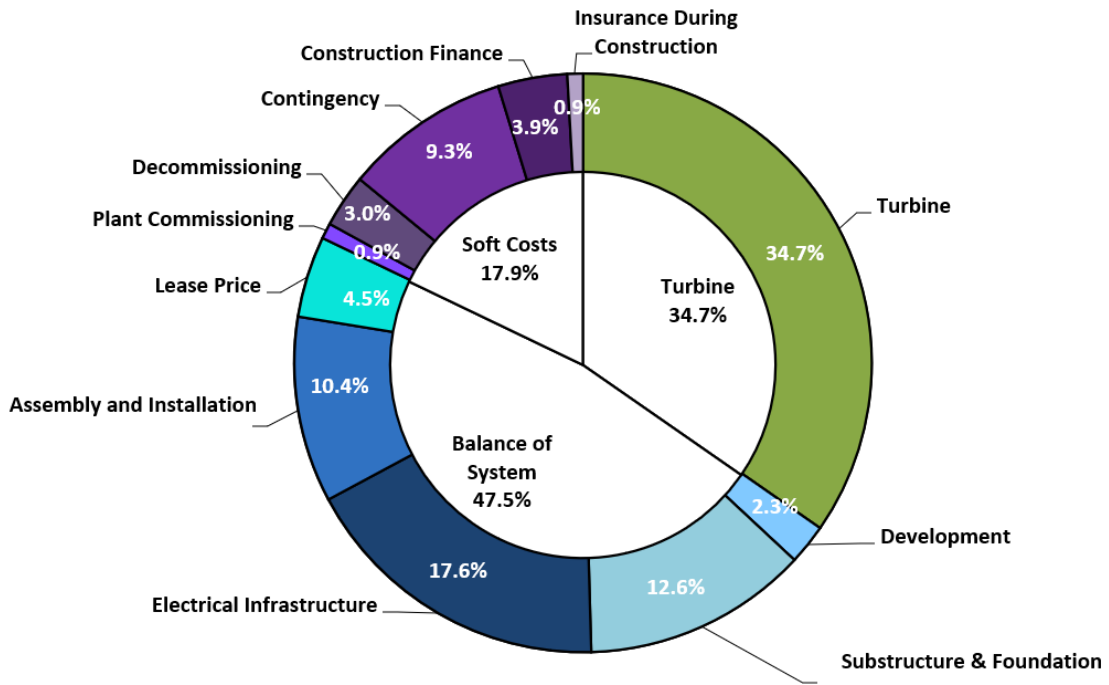
Figure 8. Capital expenditures for the fixed-bottom offshore wind reference project

Table 13. Fixed-Bottom Offshore CapEx and LCOE Breakdown

	8.0-MW Fixed-Bottom Offshore Wind Turbine ($/kW)	8.0-MW Fixed-Bottom Offshore Wind Turbine ($/MWh)
TURBINE CAPITAL COST	**1,301**	**17.7**
Development cost	85	1.2
Engineering and management	2	0.0
Substructure and foundation	474	6.4
Electrical infrastructure	662	9.0
Assembly and installation	390	5.3
Lease price	170	2.3
BALANCE OF SYSTEM	**1,782**	**24.2**
Insurance during construction	33	0.4
Decommissioning bond	111	1.5
Construction financing	145	2.0
Contingency	350	4.8
Plant commissioning	33	0.4
SOFT COSTS	**672**	**9.1**
TOTAL CAPITAL EXPENDITURES	**3,756**	**51.0**

Note: Values rounded to the nearest dollar. The electrical infrastructure cost category includes construction and fabrication costs of both the land-based and offshore substations and does not include installation costs for the electrical system, as they are included in the assembly and installation costs.
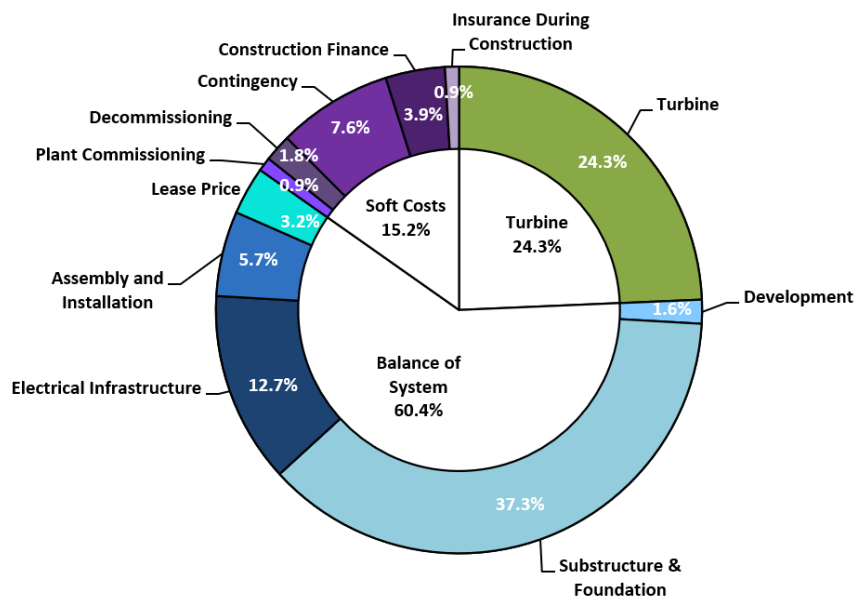
Figure 9. Capital expenditures for the floating offshore wind reference project

Table 14. Floating Offshore CapEx and LCOE Breakdown

	8.0-MW Floating Offshore Wind Turbine ($/kW)	8.0-MW Floating Offshore Wind Turbine ($/MWh)
TURBINE CAPITAL COST	**1,301**	**22.7**
Development cost	85	1.5
Engineering and management	2	0.0
Substructure and foundation	1,996	34.9
Electrical infrastructure	679	11.9
Assembly and installation	302	5.3
Lease price	170	3.0
BALANCE OF SYSTEM	**3,234**	**56.5**
Insurance during construction	49	0.9
Decommissioning bond	97	1.7
Construction financing	211	3.7
Contingency	409	7.1
Plant commissioning	49	0.9
SOFT COSTS	**816**	**14.3**
TOTAL CAPITAL EXPENDITURES	**5,328**	**93.1**

Notes:
- The electrical infrastructure cost category includes construction and fabrication costs of both the land-based and offshore substations; this category does not include installation costs for the electrical system, as they are included in the assembly and installation costs.
- Take caution if comparing fixed-bottom and floating offshore wind project costs because there are significant differences in spatial parameters between the representative sites selected for each technology.

There is a notable difference between the cost components that make up the land-based and offshore projects. In the land-based project, 70% of the cost is related to the wind turbine. For the offshore project, the turbine makes up approximately 24% and 34% of the fixed-bottom offshore and floating offshore reference project costs, respectively. The substructure and foundation portion of the BOS costs is the primary cause for the cost differences between the fixed-bottom and floating offshore projects. The analysis indicates that the fixed-bottom substructure is about 24% of the cost of the floating substructure (assuming a monopile for fixed bottom and a semisubmersible for floating). The other differences in the BOS and financial costs are related to the empirically-based cost and scaling relationships—some of which are a calculated as a percentage of total costs.

5.3 Offshore Technology Characteristics and Annual Energy Production

Offshore wind turbines have increased in size in the recent past and manufacturer announcements suggest that this trend will continue (Shields and Nunemaker 2020). For example, 9.5-MW turbines have been installed, with larger turbines currently in different phases of market and technology development (REVE 2019). As mentioned earlier, we exclude the Chinese market from informing U.S. market technology assumptions because they are more likely to reflect European market trends in the near-term. General Electric is testing a prototype 12- to 14-MW turbine currently, which is scheduled to be available for commercial deployment in 2021 (GE Renewable Energy 2018). Siemens Gamesa (2020) announced a 2024 target for the commercial release of a 14-MW turbine model, with a power boost feature that increases the capacity to 15 MW. Vestas also announced a 15-MW platform with the same 2024 serial production target (Vestas 2021). The Chinese manufacturer, MingYang Smart Energy, announced a 16-MW platform with a target prototype in 2023 and commercial production in 2024, which represents a step change over the 2020 average scale of offshore wind turbine technology deployed in China (MingYang 2021). Incorporating larger turbines in a project's design contributes to LCOE reductions via reduced balance-of-plant and O&M costs (Shields et al. 2021). Larger turbine sizes are made possible in offshore applications, partly because there are fewer transportation and installation limits than for land-based wind energy projects.

5.3.1 Wind Turbine Parameters

The offshore wind turbine technology characteristics for this analysis are calculated using a capacity-weighted average of the global offshore wind projects installed in 2020 (excluding China). The results of this calculation yield a turbine rating of 8.0 MW, rotor diameter of 159 m, and a hub height of 102 m, as reported in Musial et al. (2021). These values and additional assumptions for the offshore turbine characteristics are summarized in Table 15.

Table 15. Reference Offshore Wind Turbine Parameter Input Assumptions

Wind Turbine Parameters	
Turbine rated power (MW)	8.0
Turbine rotor diameter (m)	159
Turbine hub height (m)	102
Drivetrain design	Geared
Cut-in wind speed (m/s)	3
Cut-out wind speed (m/s)	25

5.3.2 Wind Resource

In this report, we assessed the wind resource for the fixed-bottom and floating reference sites located on the North Atlantic and Pacific Coast, respectively. The details of this analysis and its results are presented in Appendix A. The annual average wind speed in the North Atlantic region was assessed to be 8.43 m/s at 50 m (9.12 m/s at a hub height of 102 m), and 7.67 m/s at 50 m (8.30 m/s at a hub height of 102 m) for the Pacific Coast. Note that the same wind resources are used for the 2020 study as were used in 2018. Hub-height wind speeds have been extrapolated

from the 2018 hub height of 93.8 m up to the corresponding 2020 hub height of 102 m using the power law and a wind shear exponent of 0.1. The wind resource parameters are summarized in Table 16.

Table 16. Reference Offshore Wind Resource Input Assumptions

Wind Resource Characteristics		
	North Atlantic	Pacific Coast
Annual average wind speed at a 50-m height (m/s)	8.43	7.67
Annual average wind speed at a 102-m hub height (m/s)	9.12	8.3
Weibull k	2.1	2.1
Shear exponent	0.1	0.1

5.3.3 Losses and Availability

The U.S. offshore wind reference project considers losses from wind power plant array wake impacts, inefficiencies in power collection and transmission (export cable), and losses from wind power plant availability. These losses and availability estimates are determined using ORCA (Beiter et al. 2016), which performs calculations based on a specific wind power plant layout and site-specific meteorological ocean conditions. The total system losses for the fixed-bottom technology in the North Atlantic region are 15.7%, whereas the system losses for the floating offshore technology in the Pacific Coast region are 20.8%. The primary differences in loss between these offshore technologies are the additional electrical cable losses for floating wind in deeper waters (i.e., 34 m versus 739 m), and wake losses from the different reference sites. Table 17 summarizes the losses and availability estimates for the fixed-bottom and floating offshore wind technologies.

Table 17. Reference Offshore Wind Total Losses

Losses		
	North Atlantic (Fixed Bottom)	Pacific Coast (Floating)
Total system losses (%)	15.7%	20.8%

5.3.4 Annual Energy Production

The net AEP is calculated using the wind turbine technology parameters and wind resource inputs, and by applying the appropriate losses and availability estimates. The net AEP is calculated for the offshore wind reference project for both fixed-bottom and floating offshore applications using ORCA. The resulting net AEP for the fixed-bottom configuration in the North Atlantic region is 4,283 MWh/MW/year, with a 48.9% net capacity factor, and 3,332 MWh/MW/year for the floating configuration in the Pacific Coast region, with a 38.0% net capacity factor. These values are summarized in Table 18.

Table 18. Reference Offshore Wind Net Annual Energy Production

Net Annual Energy Production		
	North Atlantic (Fixed Bottom)	Pacific Coast (Floating)
Net energy capture (MWh/MW/year)	4,283	3,332
Net capacity factor (%)	48.9%	38.0%

Capacity factors in the United States are expected to vary widely depending on the project location and wind turbine technology. Improving the performance of offshore wind turbines and arrays has been a continued focus of industry and research activities. More information on the global trends for offshore wind power plant performance can be found in Musial et al. (2017).

5.4 Offshore Wind Operation and Maintenance Expenditures

OpEx can vary greatly between projects; however, the two largest cost drivers are the distance from the project to the maintenance facilities and the meteorological ocean climate at the site (Maples et al. 2013; Pietermen et al. 2011). Beiter et al. (2016) evaluated the O&M for fixed-bottom and floating substructures located at sites with various wave heights, water depths, and distances from ports informed by parametric studies using the Energy Research Centre of the Netherlands O&M Tool.[18] The North Atlantic fixed-bottom and Pacific Coast floating offshore reference projects assume the same operational costs (e.g., annual leases and fees) of $30/kW/yr, whereas the maintenance expenditures differ between the two because they each use a different maintenance strategy (i.e., in situ versus tow to shore) and have distinctive site characteristics (i.e., distance from operations port, meteorological ocean conditions, and water depth), resulting in $110/kW/yr for the fixed-bottom project and $118/kW/yr for the floating project. These O&M costs and the LCOE component breakdown are shown in Table 19.

Table 19. Offshore Wind Reference Project OpEx

	North Atlantic (Fixed Bottom)		Pacific Coast (Floating)	
	($/kW/yr)	($/kilowatt-hour [kWh])	($/kW/yr)	($/kWh)
Operation	30	7.1	30	9.1
Maintenance	80	18.7	88	26.3
OpEx	**110**	**25.8**	**118**	**35.4**

5.5 Offshore Finance

This section describes the financing assumptions for the report's representative offshore wind (both fixed bottom and floating) reference projects in the United States in 2020. In this report, the offshore financing assumptions are consistent with those developed for NREL's ATB (Feldman et al. 2020).

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[18] Operation and maintenance costs for offshore wind energy projects are assumed to include labor, vessels, equipment, scheduled maintenance, unscheduled maintenance, land-based support, and administration.

5.5.1 Discount Rate

An individual project's financing terms reflect its specific risk profile, assumptions, and ranges of nominal discount rates for offshore wind energy. The generic assumptions used for this report are consistent with NREL's 2021 ATB (Feldman et al. 2020), which were derived from industry interviews and a literature review. For this analysis, we assumed the discount rate and other economic evaluation metrics to be similar for the North Atlantic and Pacific Coast representative projects. The updated nominal WACC for 2021 is 5.29%, which corresponds to a real WACC of 2.72%, assuming a 2.5% inflation rate. Underlying assumptions for marginal tax rate and inflation are consistent with those presented in Section 4.5.1.

5.5.2 Economic Evaluation Metrics

To determine the LCOE for the 2020 representative offshore wind projects, a similar FCR methodology that was used for the land-based representative wind project is applied (see Section 4.5) and informed by the 2021 ATB (NREL 2021). The FCR includes the present value of the accumulated depreciation benefit and ignores bonus depreciation. Assuming a project life of 25 years and discount rates and depreciation benefits as calculated, the offshore reference project nominal and real FCR for fixed-bottom and floating technologies is 7.64% and 5.82%, respectively. Table 20 presents a summary of nominal and real WACC, CRF, and FCR that is used throughout the offshore analysis.

Table 20. Summary of Offshore Reference Project Economic Evaluation Metrics

	North Atlantic and Pacific Coast (Fixed Bottom and Floating)	
	Nominal	Real
WACC (%)	5.29%	2.72%
CRF (%)	7.30%	5.60%
FCR (%)	7.64%	5.82%

5.6 Offshore Reference Project Levelized Cost of Energy

Based on the offshore wind turbine technology parameters, site conditions, wind resource, and cost estimates, we used the CapEx, FCR, OpEx, and AEP to calculate LCOE for the 2020 offshore reference wind power plant for fixed-bottom and floating technologies. LCOE for the fixed-bottom North Atlantic representative project is calculated at $77/MWh and $129/MWh for the representative floating project on the Pacific Coast. Table 21 summarizes the fixed-bottom costs for the primary components (including their contribution to LCOE) in the North Atlantic region. The graphic in Figure 10 illustrates the LCOE breakdown for the primary components of the North Atlantic wind power plant, whereas Figure 11 provides a graphical representation of LCOE by line item. Table 22, Figure 12, and Figure 13 show the cost values, LCOE breakdown, and LCOE values for the floating project in the Pacific Coast region.

Table 21. Fixed-Bottom Offshore Wind LCOE and Reference Projects Cost Breakdown

	8.0-MW Fixed-Bottom Offshore Wind Turbine ($/kW)	8.0-MW Fixed-Bottom Offshore Wind Turbine ($/MWh)
Turbine capital cost	1,301	17.7
Balance of system	1,782	24.2
Financial costs	672	9.1
CapEx	**3,756**	**51.0**
OpEx ($/kW/yr)	**110**	**25.8**
FCR (real) [%]	5.8%	
Net AEP (MWh/MW/yr)	4,283	
Net capacity factor (%)	48.9%	
Total LCOE ($/MWh)	**77**	
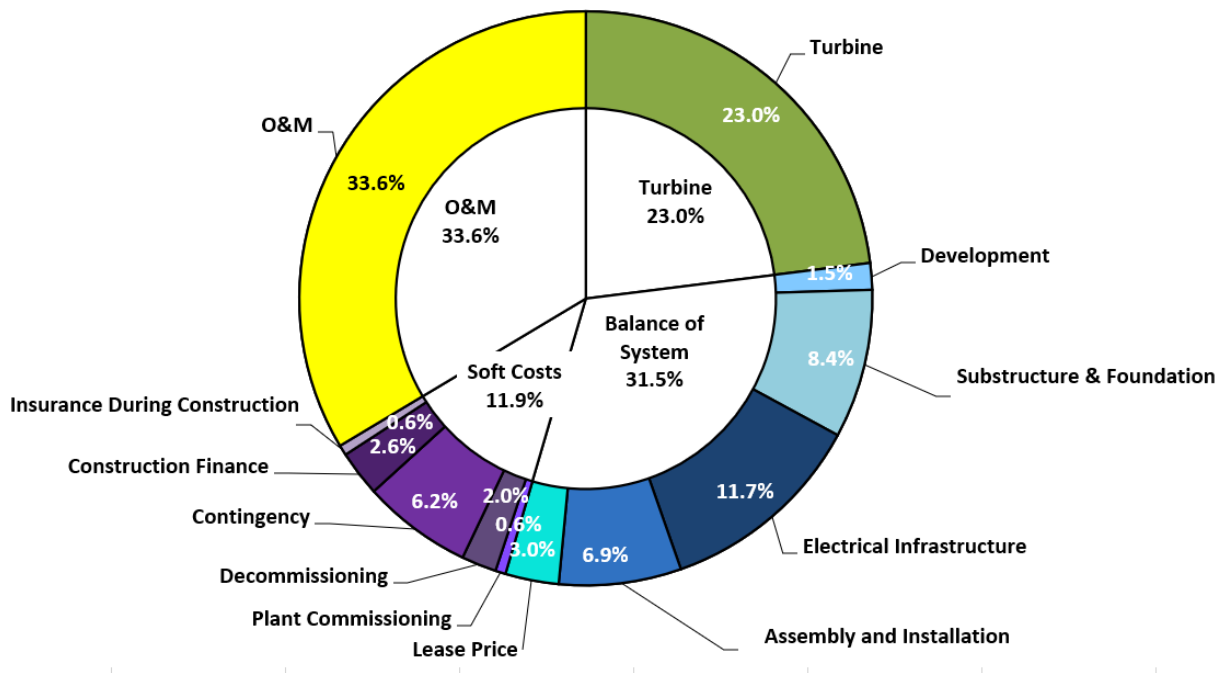
Figure 10. Component-level LCOE contribution for the 2020 fixed-bottom offshore wind reference project operating for 25 years
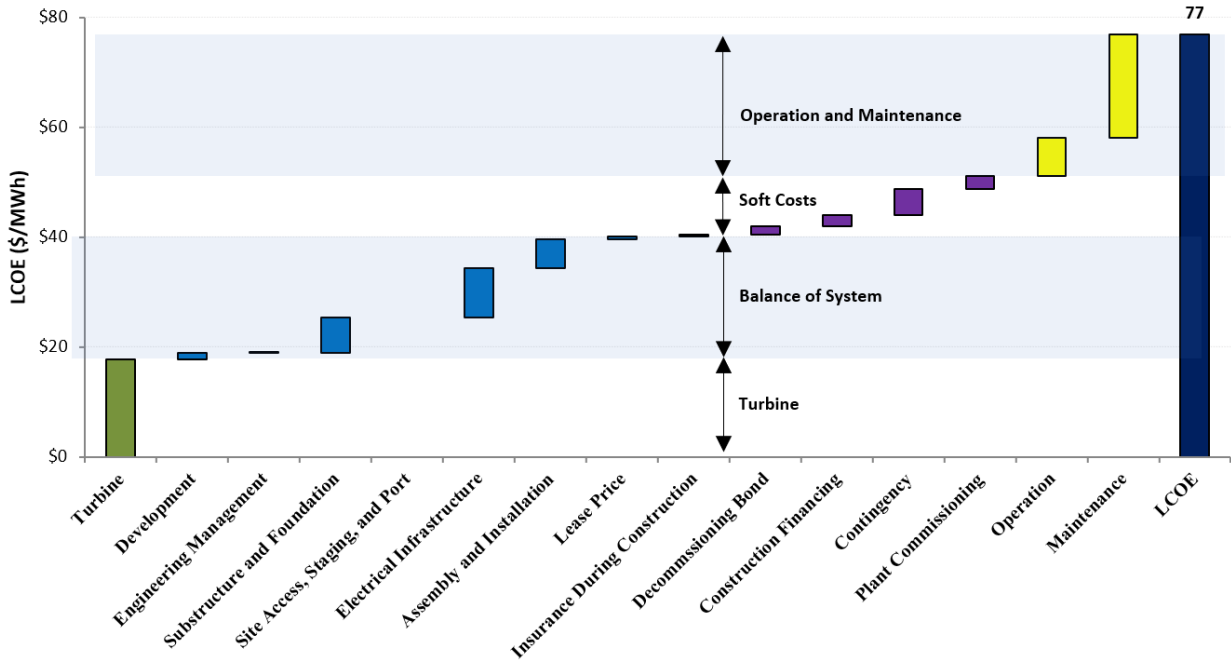
Figure 11. Component-level cost breakdown for the 2020 fixed-bottom offshore wind reference project

Table 22. Floating Offshore Wind LCOE and Reference Projects Cost Breakdown

	8.0-MW Floating Offshore Wind Turbine ($/kW)	8.0-MW Floating Offshore Wind Turbine ($/MWh)
Turbine capital cost	1,301	22.7
Balance of system	3,234	56.5
Financial costs	816	14.3
CapEx	**5,351**	**93.5**
OpEx ($/kW/yr)	**118**	**35.4**
FCR (real) [%]	5.8%	
Net AEP (MWh/MW/yr)	3,332	
Net capacity factor (%)	38.0%	
Total LCOE ($/MWh)	**129**	
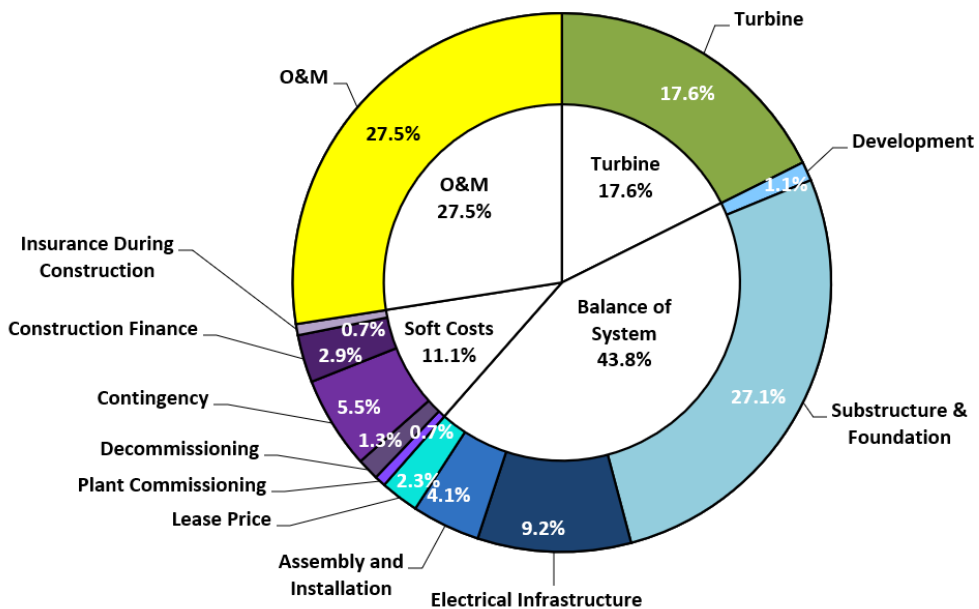
Figure 12. Component-level LCOE contribution for the 2020 floating offshore wind reference project operating for 25 years
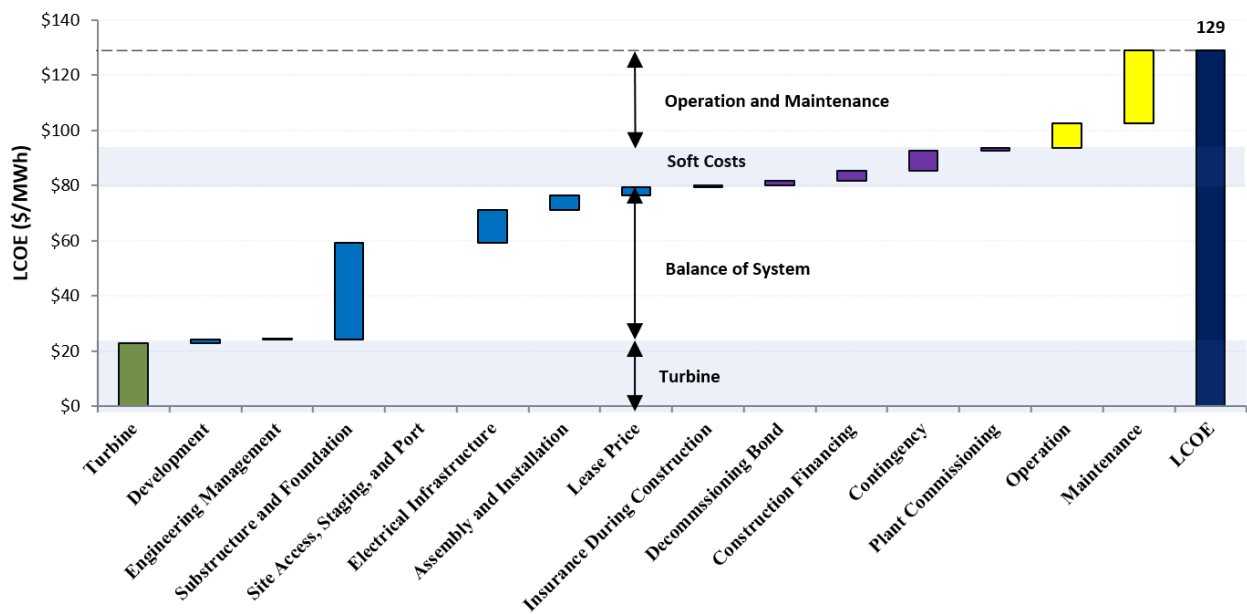
Figure 13. Component-level cost breakdown for the 2020 floating offshore wind reference project

5.7 Offshore Levelized Cost of Energy Sensitivities

The LCOE parameters described earlier represent the fixed-bottom and floating offshore reference wind projects; however, input parameters for a near-term wind project are subject to considerable uncertainty. Hence, it is beneficial to investigate how this variability may impact

the LCOE. The sensitivity analysis shown in Figure 14 (for the North Atlantic fixed-bottom site) and Figure 15 (for the Pacific Coast floating site) focuses on the basic LCOE inputs: CapEx, OpEx, net capacity factor, and FCR, which are broken into two principal elements—discount rate and economic operational lifetime. We determined the sensitivity ranges for the LCOE inputs by examining the globally installed offshore wind projects in 2020 reported in the "Offshore Wind Market Report: 2021 Edition" (Musial et al. 2021) and NREL's offshore wind database.
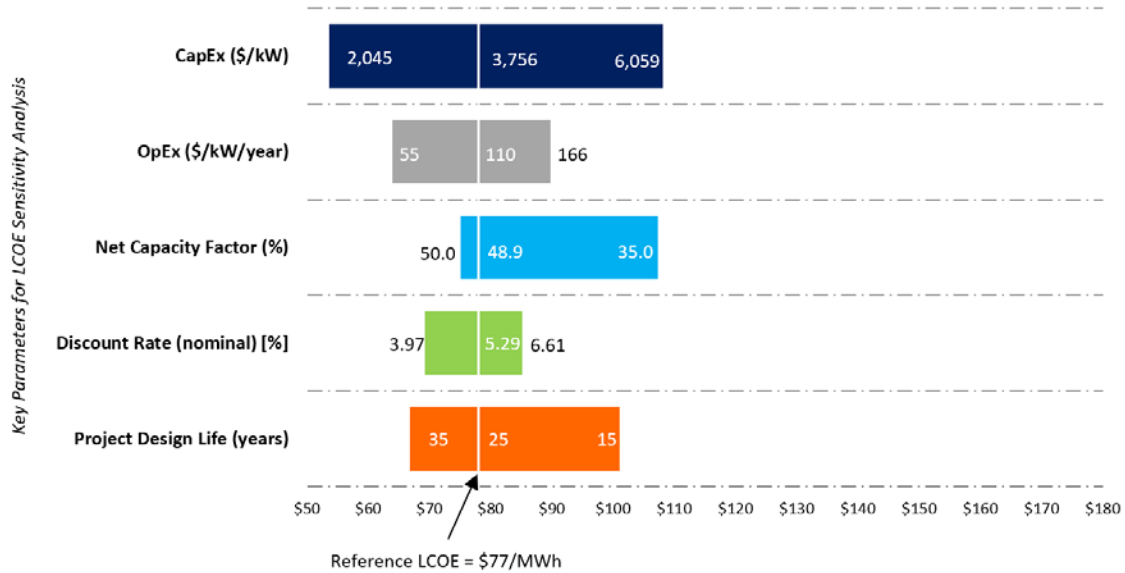
Figure 14. Sensitivity of fixed-bottom offshore wind LCOE to key input parameters
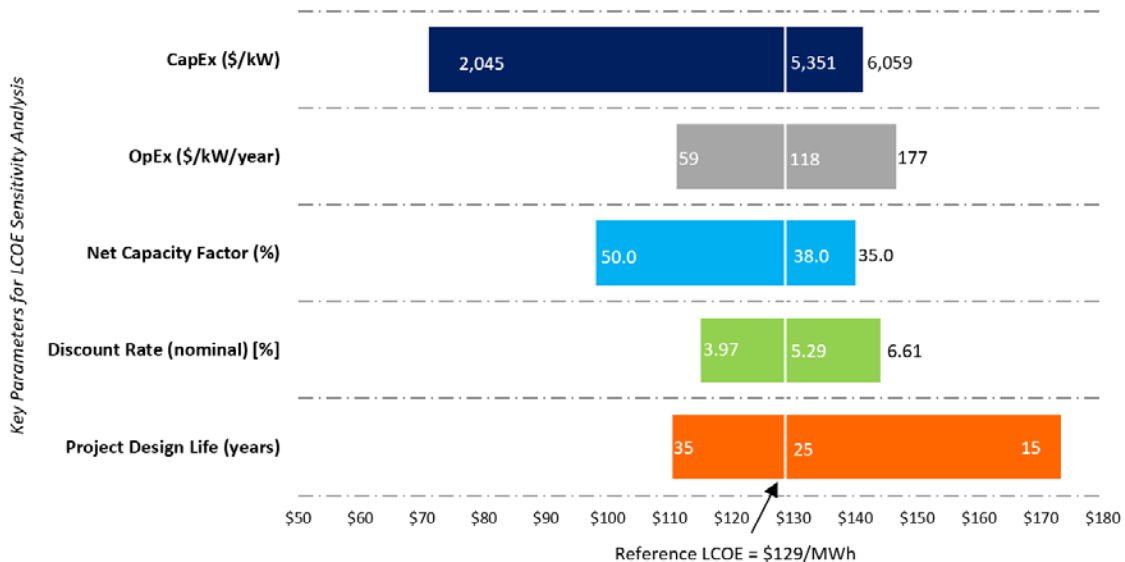
Figure 15. Sensitivity of floating offshore wind LCOE to key input parameters

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).

Sensitivity analyses are conducted by holding all reference project assumptions constant and altering only the variable in question. Sensitivity ranges are selected to represent the highs and lows observed in the industry and from the data in the "Offshore Wind Market Report: 2021 Edition" (Musial et al. 2021). This selection provides insight into how real-world ranges influence LCOE. Keeping the same 600-MW project size, the sensitivity analysis yields ranges in LCOE from a low of $54/MWh to a high of $108/MWh for fixed-bottom configurations (Figure 14), and a low of $71/MWh to a high of $173/MWh for floating configurations (Figure 15). Within the ranges shown, CapEx and project design life are the two factors that are shown to have the greatest impact on offshore wind LCOE, with CapEx having the greatest influence on decreasing LCOE relative to the reference projects.

5.8 Offshore Wind Energy Supply Curve

Nearly 5,500 GW of offshore wind +gross resource potential has been estimated for the "2020 Cost of Energy Review" covering the continental United States (excluding Alaska and Hawaii). This gross resource potential does not exclude any areas of competing use or exclusion areas[19] and was calculated using a geographic-information-system-based algorithm documented in Beiter et al. (2017). For the offshore wind supply curve, the LCOE for each of the potential wind power plant locations is computed using CapEx, OpEx, and net AEP. LCOE varies by offshore geographic region primarily because of the available wind resource, distance from port, and water depth. Incremental costs associated with labor rates, material costs, logistical or siting challenges, and distance to existing transmission infrastructure also contribute to regional differences.

LCOE, which includes the cost of export cables and onshore spur lines and was calculated for this gross resource area, ranged from $67/MWh to $233/MWh. Figure 16 illustrates the supply curve of the gross offshore wind resource potential and highlights the 2020 fixed-bottom (marked with an orange diamond) and floating (marked with a blue diamond) offshore wind reference sites.

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[19] This gross resource potential compares to nearly 2,060 GW of "technical resource capacity" when considering various competing use and exclusion areas (Musial et al. 2016).
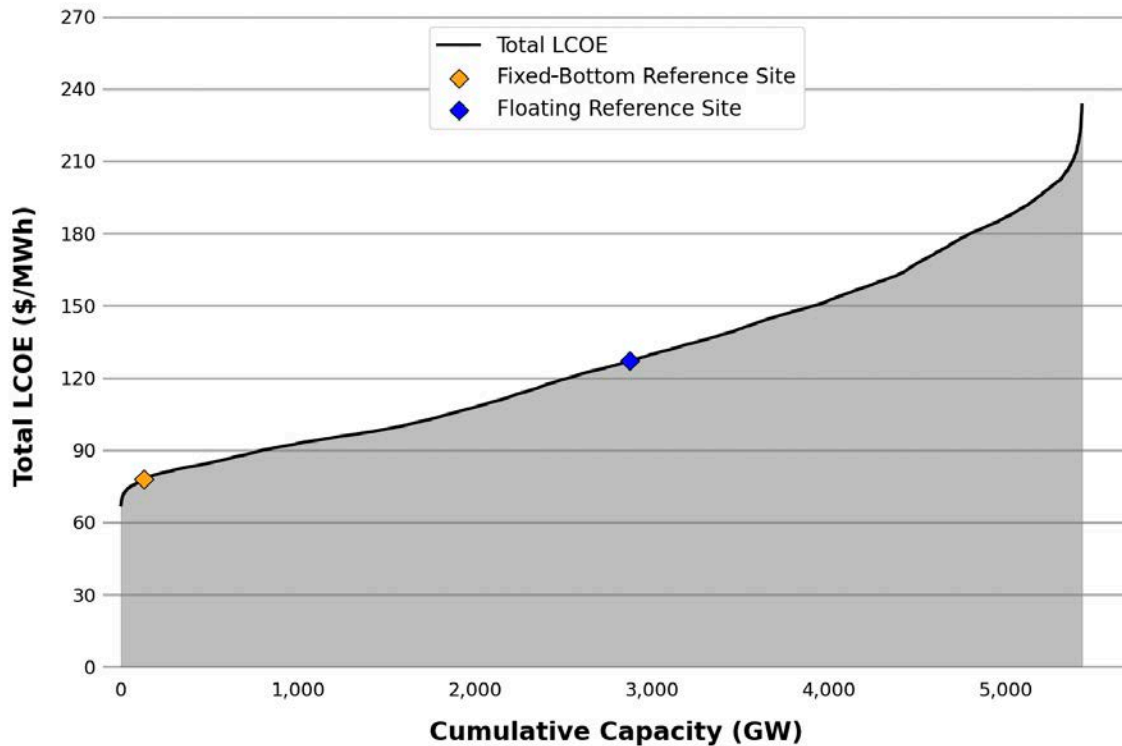
Figure 16. National fixed-bottom and floating offshore wind supply curve

5.9 Offshore Discussion of Results in Context of DOE Goals

In this section, we present the fixed-bottom offshore wind GPRA levelized cost of energy 2030 target. The GPRA trajectory was baselined in FY 2019 using 2018 reference project data reported in Stehly et al. (2019). The baseline LCOE starts at $89/MWh (in 2018 USD) and is projected to reach the FY 2030 GPRA target of $51/MWh (in 2018 USD). The GPRA baseline and target LCOE are reported in 2018 USD because WETO will report fixed-bottom offshore wind values to Congress in 2018 USD.

The FY 2030 target analysis estimates the future CapEx and O&M costs using ORCA (Beiter et al. 2016) and assuming a wind power plant comprising 15-MW wind turbines placed in the North Atlantic reference site. The cost reduction trajectory is also informed by technology innovations considered in the spatial economic analysis by Beiter et al. (2016). This future technology assessment estimates the wind power plant's CapEx to be $3,476/kW, with an O&M cost of $60/kW/yr operating at a 58% net capacity factor. The future financial assumptions are informed by NREL's 2019 ATB, with an operation life of 25 years for a 5.7% real FCR. The 2030 LCOE calculated from this analysis is $51/MWh and is designated as the FY 2030 GPRA target. To track LCOE progress against the GPRA trajectory, historical LCOE values and the FY 2021 LCOE value assessed in this year's report are plotted in Figure 17. The reported LCOE value for FY 2021 is calculated in Section 5.6 of this report.
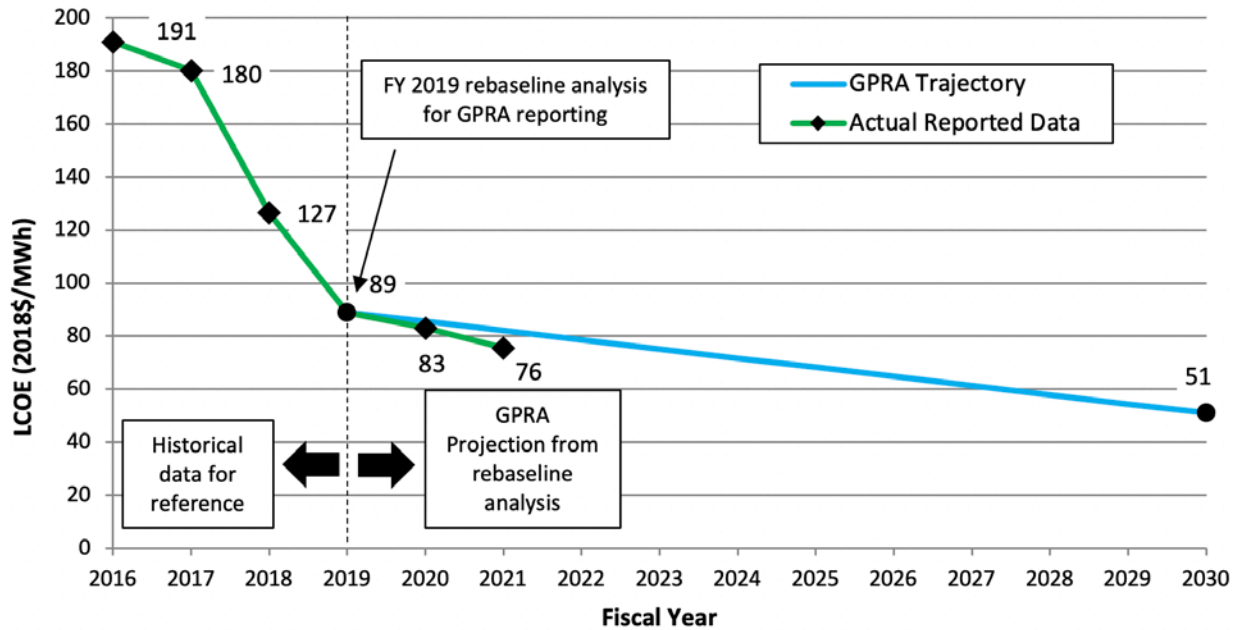
Figure 17. Fixed-bottom wind GPRA cost trajectories for LCOE

The reduction in the estimated LCOE ("GPRA goal") between FY 2019 and FY 2030 is categorized as various cost components: O&M expenditures ($17/MWh), CapEx components (i.e., wind turbine, electric system, and support structure; $12/MWh), and improvements in AEP ($9/MWh). These categories and their respective cost reductions are shown in Figure 18.
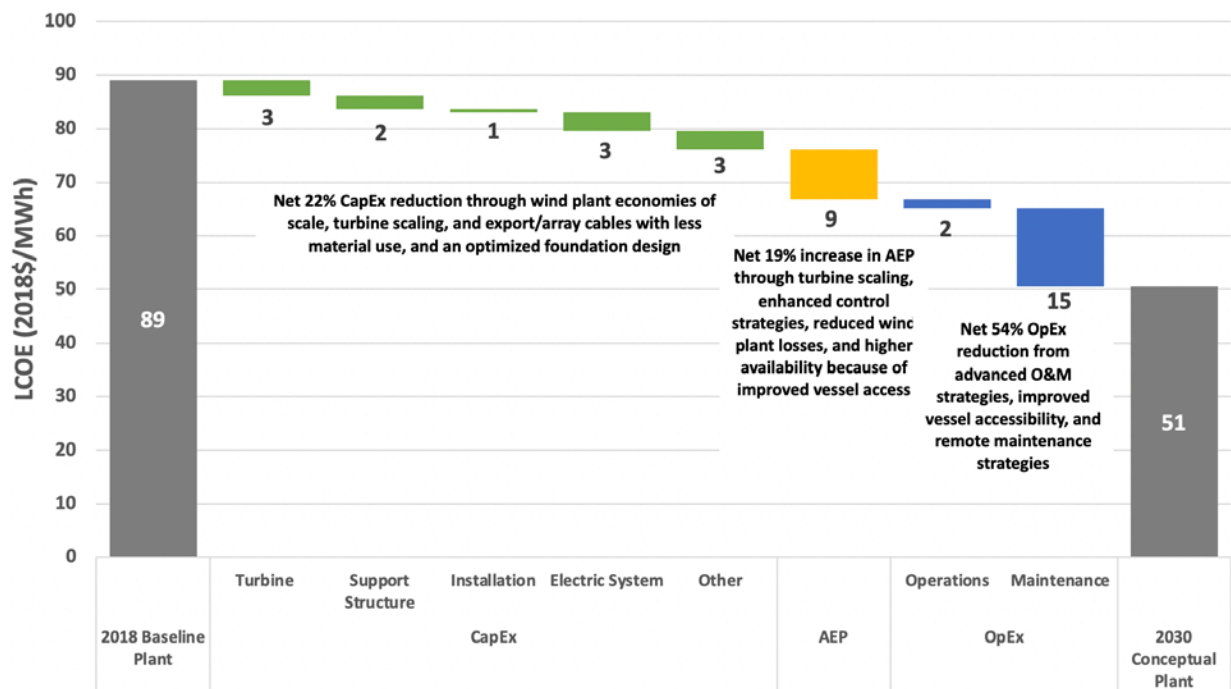
Figure 18. Fixed-bottom cost reductions in GPRA cost trajectories for LCOE

Although DOE had no official GPRA reporting requirement for floating offshore wind energy costs at the time of this writing, we still include a value for 2030 floating LCOE obtained in the same manner as the 2030 target for fixed-bottom offshore wind costs. Figure 19 illustrates the projected cost reduction potential for floating offshore wind relative to a 2018 baseline.
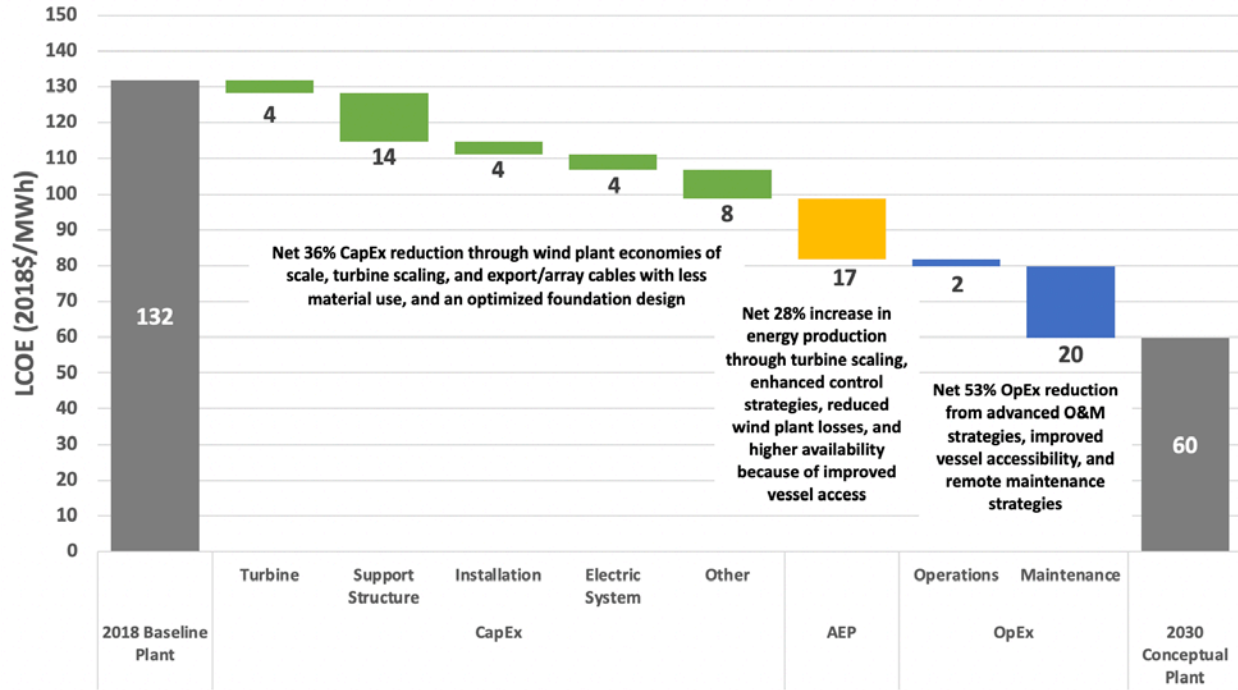
Figure 19. Floating cost reduction trajectories for LCOE

6 Distributed Wind Energy

The distributed wind energy reference projects are intended to represent wind sites suitable for residential and commercial-scale wind turbines found in the United States. For the purposes of this report, distributed wind technology size classes are binned into discrete representations: 20 kW for residential and 100 kW for commercial (Lantz et al. 2016). The representative project size for the residential and commercial classes assumes the installation of a single wind turbine. In this year's report, the residential and commercial distributed wind reference project LCOE estimates are primarily informed by the 2019 market data from Orrell et al. (2020) because the market data for distributed wind energy projects in 2020 only comprised retrofits or upgrades (Orrell et al. 2021). With the absence of newly installed project data in 2020, we had to assume the CapEx, O&M, and net energy production estimates using the "2019 Cost of Wind Energy Review" (Stehly et al. 2020). However, this report incorporates financial changes experienced in 2020 that are used to calculate LCOE. A summary of the financial changes and LCOE values are summarized in this section with additional reference project details presented in Appendix B.

6.1 Distributed Wind Finance

Financing assumptions refer to the cost of interest and other carrying charges, corporate taxes, and depreciation (represented by the FCR in this report) that are applied to the total CapEx. To capture the financing structure and costs, we used a fixed charge rate for the LCOE equation. Additional details describing FCR are presented in Section 4.5. Distributed wind finance is the single LCOE input parameter changed from last year's distributed wind cost assumptions by applying a change to the nominal debt interest rate from 3.6% reported in the "2019 Cost of Wind Energy Review" (Stehly et al. 2020) to 2.61%.

6.1.1 Discount Rate

Typically, various financial terms, such as the cost of debt or equity, are captured in the discount rate, which is in turn used to estimate the cost of energy. For this analysis, the discount rate is calculated as the after-tax WACC, and it is presumed that the reported yields for equity are after-tax yields and can be used directly in the WACC calculation. The cost of debt (as a value) is also reported, but because interest on debt is tax deductible, an effective corporate marginal tax rate is used to determine an after-tax cost of debt for the discount rate calculation. The cost of capital gives a basis for WACC assumptions for the representative wind projects and results in a nominal WACC of 5.16%. This WACC was derived assuming a debt fraction of 60% from Lantz et al. (2016), a nominal debt interest rate of 2.61%, a nominal return on equity of 10%, and a 25.7% tax rate. Further details on the blended tax rate are presented in Section 4.5.1. Each actual project, however, has a unique risk profile, financing terms, and ownership structure. For this reason, a single WACC representing the distributed wind energy installations should be viewed cautiously and used to illustrate general market trends and conditions only.

The inflation rate has been set to 2.5% and aligns with the inflation rate provided in NREL's Annual Technology Baseline. Discount rates are initially calculated in nominal after-tax USD, and an estimate of inflation is used to calculate a discount rate in real after-tax USD.

6.1.2 Economic Evaluation Metrics

In the economic evaluation of wind energy investments there are two important metrics: the CRF and FCR, with details provided in Section 4.5.2. For the economic evaluation of the residential and commercial projects, analysts assumed the residential host-owned representative project uses a 20-year straight-line depreciation schedule and the commercial/industrial host-owned project uses a 5-year MACRS depreciation schedule.

Table 23 presents the estimated WACC, CRF, and FCR in nominal and real terms using a project design lifetime of 25 years, and a net present value depreciation factor of 59.9% for the residential project (assuming a 20-year straight-line depreciation schedule) and 87.1% for the commercial project (assuming a 5-year MACRS depreciation schedule).

Table 23. Summary of Distributed Wind Reference Projects' Economic Evaluation Metrics

	Residential (20 kW)		Commercial (100 kW)	
	Nominal	Real	Nominal	Real
WACC (%)	5.16%	2.60%	5.16%	2.60%
CRF (%)	7.21%	5.49%	7.21%	5.49%
FCR (%)	8.21%	6.25%	7.53%	5.73%

6.2 Distributed Wind Levelized Cost of Energy

We calculated the LCOE for the representative distributed wind projects using the formulation presented in NREL's Annual Technology Baseline and the representative turbine technology parameters, site conditions, wind resource, and cost estimates (i.e., CapEx, FCR, OpEx, and AEP). The LCOE value for the representative 2020 residential project is estimated at $151/MWh and $99/MWh for the representative commercial project.

Table 24 and Table 25 summarize the costs for the primary components on a per-kilowatt and per-megawatt-hour basis for the residential and commercial projects, respectively. The graphics in Figure 20 illustrate the LCOE breakdown for the primary LCOE components (i.e., turbine CapEx, BOS CapEx, and O&M) of the representative residential and commercial wind energy projects.

Table 24. Summary of Inputs and Reference Project LCOE for 2020 Residential Distributed Wind

	20-kW Residential Wind Turbine ($/kW)	20-kW Residential Wind Turbine ($/MWh)
Turbine CapEx	2,575	62.4
Balance-of-system CapEx	3,100	75.1
Total CapEx	**5,675**	**137.5**
OpEx ($/kW/yr)	**35**	**13.6**
FCR (real) [%]	6.2%	
Net AEP (kWh/kW/yr)	2,580	
Net capacity factor (%)	29.5%	
TOTAL LCOE ($/MWh)	**151**	

Table 25. Summary of Inputs and Reference Project LCOE for 2020 Commercial Distributed Wind

	100-kW Commercial Wind Turbine ($/kW)	100-kW Commercial Wind Turbine ($/MWh)
Turbine CapEx	2,530	51.0
Balance-of-system CapEx	1,770	35.7
Total CapEx	**4,300**	**86.6**
OpEx ($/kW/yr)	**35**	**12.3**
FCR (real) [%]	5.7%	
Net AEP (kWh/kW/yr)	2,846	
Net capacity factor (%)	32.5%	
TOTAL LCOE ($/MWh)	**99**	
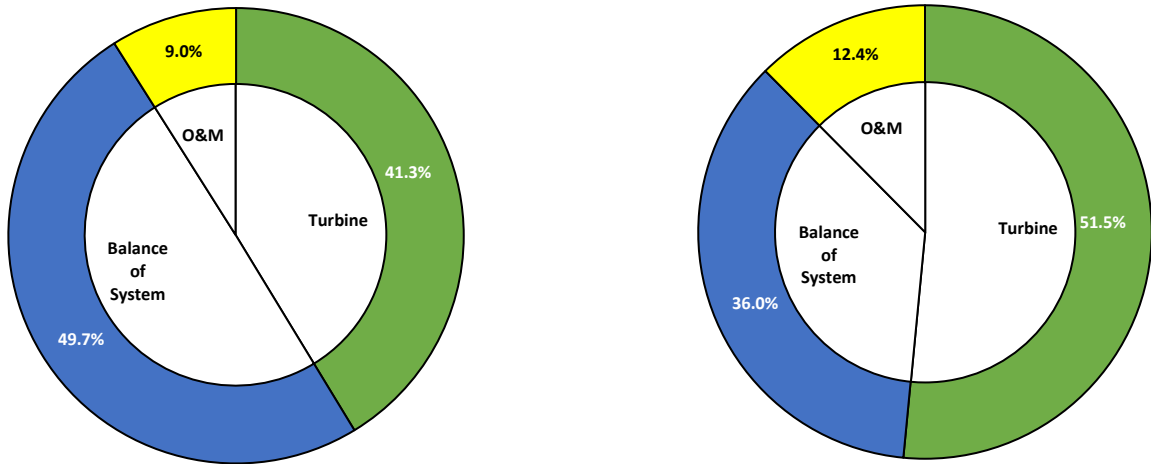
Figure 20. Component-level LCOE contribution for the 2020 residential (left) and commercial (right) distributed wind reference projects operating for 25 years

Note: Empirical data and cost model representation for residential and commercial distributed wind energy projects are limited; hence, detailed component-level LCOE contributions are not presented in this report.

7 Conclusions and Future Work

This report presents a snapshot of the levelized cost of land-based, offshore, and distributed wind energy using empirically derived and modeled data representative of 2020 market conditions. Scenario planning and modeling activities often focus on one number (or cost) for land-based, offshore, and distributed wind LCOE. In reality, the cost of these wind energy technologies varies regionally across the United States and other parts of the world (Table 26).

Notably, the LCOE analysis presented is only one way to measure the cost of wind energy. It does not include other costs and price issues that influence a given wind project's viability, such as regional transmission upgrades and interconnection costs, environmental impacts, military constraints, or other areas of consideration (e.g., public policy, consumer costs, energy prices, or public acceptance). In addition, these LCOE estimates do not reflect the value of electricity, incentives, or other policy mechanisms (such as production tax credits or investment tax credits) that affect the sales price of electricity produced from wind energy projects.

Table 26. Range of LCOE for U.S. Land-Based and Offshore Wind in 2020

	Land-Based Wind			Offshore Wind		
	Low	**Reference**	**High**	**Low**	**Reference**	**High**
CapEx ($/kW)	1,000	1,462	2,000	2,045	3,756	6,059
OpEx ($/kW/year)	30	43	60	59	117	176
Net capacity factor (%)	24%	42%	56%	35%	49%	50%
Discount rate (nominal) [%]	4.2%	5.2%	6.3%	4.0%	5.3%	6.6%
Operational life (years)	15	25	35	15	25	35
LCOE ($/MWh)	**26**	**34**	**60**	**70**	**127**	**172**

The analysis and findings in this report helped generate the following conclusions:

- LCOE estimates continue to show a downward trend from the "2010 Cost of Wind Energy Review" (Tegen et al. 2012) to 2020. Compared to the 2010 report, LCOE has decreased by 59% for land-based wind and 71% for fixed-bottom offshore wind.[20]

- We observed the reference project LCOE for land-based installations to be $34/MWh; the full range of single-variable, land-based sensitivity estimates cover $26–$60/MWh.

- The reference offshore LCOE project estimates are $77/MWh for fixed-bottom substructures and $129/MWh for floating substructures, with a single-variable sensitivity range of $54–$108/MWh for fixed bottom and $71–$173/MWh for floating. This range is mostly influenced by the large variation in CapEx ($2,045–$6,059/kW) reported by project developers and is partly a function of differences in water depth and distance to shore.

- The residential distributed wind reference system LCOE was evaluated at $151/MWh and $99/MWh for the commercial distributed wind reference system. The single-variable sensitivity analysis was not performed in this year's report because new distributed wind project data were not available in 2020, but indicative LCOE ranges can be found in the "2019 Cost of Wind Energy Review" (Stehly et al. 2020).

- The range of LCOE calculated for the more than 9,000 GW of theoretical land-based wind capacity ranges from $24/MWh to beyond $175/MWh, with an estimated LCOE range of $29–$62/MWh for the projects installed in 2020. For fixed-bottom and floating offshore wind technology, an LCOE range between $67/MWh and $233/MWh is estimated for approximately 5,430 GW of theoretical capacity for all major U.S. coastal regions (excluding Alaska and Hawaii). The fixed-bottom representative offshore site is on the lower end of this range at $77/MWh, whereas the floating representative site is near the middle of the range at $129/MWh.

- The 2021 GPRA target for land-based wind energy, set in 2015, is $44/MWh compared to the actual LCOE estimate of $31/MWh in 2015 USD.[21] For fixed-bottom offshore wind, the GPRA target for 2021 is $82/MWh compared to the actual LCOE estimate of $76/MWh in 2018 USD.[22]

NREL continues to strive for a better understanding of costs associated with many components of wind turbines and their related systems. Ongoing collaboration with industry, growing data sets, and enhanced modeling capabilities are expected to continue, leading to better insights and increased awareness of current and future wind power system and component costs. Future updates to this report are anticipated to help maintain a perspective on costs that is grounded in real-time market changes and offer greater insight into the costs and performance of individual components related to the wind electric generation system. In addition, these reports are intended

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[20] The LCOE values reported in the "2010 Cost of Wind Energy Review" were inflated from 2010 USD to 2020 USD assuming a 18.7% cumulative rate of inflation from the Bureau of Labor and Statistics (undated) for comparison.

[21] The 2021 GPRA target and actual levelized cost of energy values for land-based wind energy are reported in 2015 USD because WETO will report land-based wind values in 2015 USD.

[22] The 2021 GPRA target and actual levelized cost of energy values for offshore wind are reported in 2018 USD because WETO will report offshore wind values in 2018 USD.

to provide greater clarity regarding wind energy costs and the effects of changes in specific variables on LCOE. The data and tools developed from this work will be used to help inform projections, goals, and improvement opportunities. As the industry evolves and matures, these data provide current representative project costs and LCOE estimates for scenario planning, modeling, and goal setting.

Future work entails three primary objectives: 1) continuing to enhance data representing market-based costs, performance, and technology trends to reflect actual wind industry experience, 2) enhancing the fidelity of LandBOSSE, ORBIT, and scaling cost models to estimate individual wind power plant components, and 3) understanding sensitivities to factors, such as regional differences, site characteristics, and technology choices. In 2022 and beyond, NREL will continue to work with industry and national laboratory partners to obtain project-specific data to validate and improve models.

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Appendix A. Offshore Wind Reference Site Development

In this report, we define reference sites for fixed-bottom and floating offshore wind technology. These reference sites are intended to reflect site conditions that represent near- to medium-term U.S. project development and are based on a replicable methodology.

We conducted the following steps to identify a reference site for fixed-bottom and floating offshore wind technology, respectively:

1. For each offshore wind region (as specified in Gilman et al. 2016), a 600-megawatt (MW) cohesive area within each Bureau of Ocean Energy Management lease and Call Area delineation (Bureau of Ocean Energy Management 2019) that is closest to shore (measured by direct distance) was identified, while:

   o Only considering lease area(s) if at least one is available within an offshore wind region

   o Consider Call Area(s) if there is no designated lease area

   o Assuming a wind turbine spacing of 3 MW/square kilometer (Musial et al. 2016).

2. Define "reference site" parameters by averaging key spatial parameters across the areas defined in step #1 for each offshore wind region:

   o Water depth

   o Wind speed

   o Gross and net capacity factor

   o Array efficiency

   o Distance from site to cable landfall

   o Distance from cable landfall to onshore substation

   o Distance from site to construction port

   o Distance from site to operation and maintenance port

   o Wave height.

3. Designated the "North Atlantic" offshore wind region to be the reference site for fixed bottom and the "Pacific Coast" to represent floating offshore wind technology. This determination was made because these regions experience the highest commercial activity for these technology types (Musial et al. 2019).

4. Specify the spatial parameters from step #2 in the Offshore Wind Cost Model to determine the levelized cost of energy.

Results for the spatial parameters calculated for each regional reference sites are shown in Table A1.

Table A1. Spatial Parameters for Regional Reference Sites

	Depth	Wind Speed	GCF (6 MW)	NCF	Array Efficiency	Site to Cable Landfall	Distance Cable Landfall to Substation	Site to CP	Site to OP	Average HS
Units	*m*	*m/s*	*%*	*%*	*%*	*km*	*km*	*km*	*km*	*m*
North Atlantic	34	9.03	58%	48%	92%	50	9	116	114	1.2
South Atlantic	30	8.58	53%	44%	92%	51	7	118	118	1.2
Pacific Coast	739	8.22	48%	38%	93%	36	8	189	189	2.4
Hawaii	764	8.59	52%	43%	94%	18	10	36	36	1.6

Note: The "North Atlantic" serves as fixed bottom and the "Pacific Coast" serves as the floating offshore wind technology reference site. The "South Atlantic" and "Hawaii" are included for reference only.

Acronyms in Table A1: CP: construction port; GCF: gross capacity factor; HS: significant annual average wave height; km: kilometer(s); m: meter(s); m/s: meters per second; NCF: net capacity factor; OP: operations port.

Appendix B. Summary of Assumptions for 2020 Reference Projects

A summary of the capital expenditures, technology characteristics, annual energy production, operation and maintenance expenditures, and finance assumptions for each of the reference projects presented in this report is provided in this appendix. The information appears in separate tables for land-based wind (Table B1), fixed-bottom offshore wind (Table B2), floating offshore wind (Table B3), residential distributed wind (Table B4), and commercial distributed wind (Table B5) reference projects.

Table B1. Land-Based-Wind Reference Project Levelized Cost of Energy Assumptions

Assumption	Units	Value	Notes
Wind power plant characteristics			
Wind plant capacity	megawatts (MW)	200	Representative of commercial-scale projects
Number of wind turbines		73	
Turbine rating	MW	2.76	
Rotor diameter	meters (m)	124.9	"Land-Based Wind Market Report: 2021 Edition" (Wiser and Bolinger 2021)
Hub height	m	90.2	
Specific power	watts (W)/square meter (m²)	225	Calculation
Cut-in wind speed	meters per second (m/s)	3	Typical wind turbine characteristics
Cut-out wind speed	m/s	25	
Annual average wind speed at 50 m	m/s	7.25	Reference site wind speed
Annual average wind speed at hub height	m/s	7.89	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	megawatt-hour (MWh)/ MW/year (yr)	3,703	System Advisor Model calculation
Net capacity factor	%	42.3%	
Capital Expenditures (CapEx)			
Total CapEx	dollars ($)/kilowatt (kW)	1,462	"Land-Based Wind Market Report: 2021 Edition" (Wiser and Bolinger 2021)
Wind turbine	$/kW	1,030	
Rotor module	$/kW	313	2015 Cost and Scaling Model
Blades	$/kW	203	

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Assumption	Units	Value	Notes
Pitch assembly	$/kW	63	
Hub assembly	$/kW	48	
Nacelle module	$/kW	512	
Nacelle structural assembly	$/kW	103	
Drivetrain assembly	$/kW	205	
Nacelle electrical assembly	$/kW	166	
Yaw assembly	$/kW	38	
Tower module	$/kW	204	
Balance of system	$/kW	322	
Development	$/kW	23	
Engineering and project management	$/kW	10	Land-based Balance of System Systems Engineering [LandBOSSE] (Eberle et al. 2019)
Foundation	$/kW	75	
Site access and staging	$/kW	40	
Assembly and installation	$/kW	41	
Electrical infrastructure	$/kW	132	
Soft costs	$/kW	110	
Construction finance	$/kW	22	Project construction over 3 years
Contingency	$/kW	88	6% of total CapEx
Operational Expenditures (OpEx)			
Total OpEx	$/kW/yr	43	"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 Results Act (GPRA) reporting
Tax rate (combined state and federal)	%	25.7%	2021 Annual Technology Baseline (NREL's Annual Technology Baseline and Standard Scenarios web page: atb.nrel.gov)
Inflation rate	%	2.5%	
Interest during construction (nominal)	%	2.61%	"Land-Based Wind Market Report: 2021 Edition" (Wiser and Bolinger 2021)
Construction finance factor	%	102%	Calculation
Debt fraction	%	47.9%	"Land-Based Wind Market Report: 2021 Edition" (Wiser and Bolinger 2021)
Debt interest rate (nominal)	%	2.61%	
Return on equity (nominal)	%	8.25%	
Weighted-average cost of capital (WACC) (nominal; after-tax)	%	5.23%	Calculation
WACC (real; after-tax)	%	2.66%	
Capital recovery factor (nominal; after-tax)	%	7.26%	
Capital recovery factor (real; after-tax)	%	5.53%	
Depreciable basis	%	100%	Simplified depreciation schedule

Assumption	Units	Value	Notes
Depreciation schedule		5-year Modified Accelerated Cost Recovery System (MACRS)	MACRS is standard for U.S. wind energy projects
Depreciation adjustment (net present value [NPV])	%	86.9%	Calculation
Project finance factor	%	105%	
Fixed charge rate (FCR) (nominal)	%	7.59%	
FCR (real)	%	5.78%	
Levelized cost of energy	$/MWh	34	Calculation

Table B2. Fixed-Bottom Offshore Wind Reference Project Levelized Cost of Energy Assumptions

Assumption	Units	Value	Notes
Wind power plant characteristics			
Wind plant capacity	MW	600	Representative of commercial-scale projects
Number of wind turbines	Number	75	Calculation
Turbine rating	MW	8	"Offshore Wind Market Report: 2021 Edition" (Musial et al. 2021)
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 Cost of Energy Review
Substructure type		Monopile	
Distance from shore	kilometers (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	%	15.7%	ORCA (based on Beiter et al. 2016)
Gross energy capture	MWh/MW/year	5,081	Calculation
Net energy capture	MWh/MW/year	4,283	
Gross capacity factor	%	58.0%	ORCA (based on Beiter et al. 2016)
Net capacity factor	%	48.9%	
CapEx			
Total CapEx	$/kW	3,756	
Wind turbine	$/kW	1,301	"Offshore Wind Market Report: 2021 Edition" (Musial et al. 2021)
Rotor nacelle assembly	$/kW	1,119	
Tower	$/kW	182	

Assumption	Units	Value	Notes
Balance of system	$/kW	1,782	Balance of system (BOS) costs computed with ORBIT (Nunemaker et al. 2020)
Development	$/kW	85	
Project management	$/kW	2	
Substructure and foundation	$/kW	474	
Substructure	$/kW	185	
Foundation	$/kW	289	
Electrical infrastructure	$/kW	662	
Array cable system	$/kW	112	
Export cable system	$/kW	370	
Grid connection	$/kW	180	
Assembly and installation	$/kW	390	
Turbine installation	$/kW	212	
Substructure and foundation installation	$/kW	178	
Lease price	$/kW	170	
Soft costs	$/kW	672	Soft costs computed using same methodology as ORCA (Beiter et al. 2016)
Insurance during construction	$/kW	33	
Decommissioning bond	$/kW	111	
Construction finance	$/kW	145	
Sponsor contingency	$/kW	350	
Procurement contingency	$/kW	127	
Installation contingency	$/kW	223	
Project completions/commissioning	$/kW	33	
OpEx			
Total OpEx	$/kW/year	110	ORCA (based on Beiter et al. 2016)
Operations (pretax)	$/kW/year	30	
Maintenance	$/kW/year	80	
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
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

Assumption	Units	Value	Notes
Depreciation schedule		5-year MACRS	Standard for U.S. wind projects
Depreciation adjustment (NPV)	%	86.8%	Calculation
Project finance factor	%	105%	Calculation
FCR (nominal)	%	7.6%	Calculation
FCR (real)	%	5.8%	Calculation
Levelized cost of energy	$/MWh	77	Calculation

Table B3. Floating Offshore Wind Reference Project LCOE Assumptions

Assumption	Units	Value	Notes
Wind power plant characteristics			
Wind plant capacity	MW	600	Representative of commercial-scale projects
Number of wind turbines	Number	75	Calculation
Turbine rating	MW	8	"Offshore Wind Market Report: 2021 Edition" (Musial et al. 2021)
Rotor diameter	m	159	"Offshore Wind Market Report: 2021 Edition" (Musial et al. 2021)
Hub height	m	102.1	"Offshore Wind Market Report: 2021 Edition" (Musial et al. 2021)
Specific power	W/m²	403	Calculation
Water depth	m	739	Representative floating site for Cost of Wind Energy Review
Substructure type		Semisubmersible	Representative floating site for Cost of Wind Energy Review
Distance from shore	km	36	Representative floating site for Cost of Wind Energy Review
Cut-in wind speed	m/s	3	Representative floating site for Cost of Wind Energy Review
Cut-out wind speed	m/s	25	Representative floating site for Cost of Wind Energy Review
Average annual wind speed at 50 m	m/s	7.7	Representative floating site for Cost of Wind Energy Review
Average annual wind speed at hub height	m/s	8.2	Representative floating site for Cost of Wind Energy Review
Shear exponent		0.10	Representative floating site for Cost of Wind Energy Review
Weibull k		2.1	Representative floating site for Cost of Wind Energy Review
Total system losses	%	20.8%	ORCA (based on Beiter et al. 2016)
Gross energy capture	MWh/MW/yr	4,205	Calculation
Net energy capture	MWh/MW/yr	3,332	
Gross capacity factor	%	48.0%	ORCA (based on Beiter et al. 2016)
Net capacity factor	%	38.0%	ORCA (based on Beiter et al. 2016)
CapEx			
Total CapEx	$/kW	5,351	
Wind turbine	$/kW	1,301	"Offshore Wind Market Report: 2021 Edition" (Musial et al. 2021)
Rotor nacelle assembly	$/kW	1,119	"Offshore Wind Market Report: 2021 Edition" (Musial et al. 2021)
Tower	$/kW	182	"Offshore Wind Market Report: 2021 Edition" (Musial et al. 2021)
Balance of system	$/kW	3,234	

Assumption	Units	Value	Notes
Development	$/kW	85	
Project management	$/kW	2	
Substructure and foundation	$/kW	1,996	
Substructure	$/kW	1,293	
Foundation	$/kW	703	BOS costs computed with ORBIT (Nunemaker et al. 2020)
Electrical infrastructure	$/kW	679	
Array cable system	$/kW	174	
Export cable system	$/kW	323	
Grid connection	$/kW	182	
Assembly and installation	$/kW	302	
Lease price	$/kW	170	
Soft costs	$/kW	816	
Insurance during construction	$/kW	49	
Decommissioning bond	$/kW	97	
Construction finance	$/kW	211	Soft costs computed using same methodology as ORCA (Beiter et al. 2016)
Sponsor contingency	$/kW	409	
Procurement contingency	$/kW	215	
Installation contingency	$/kW	194	
Project completions/commissioning	$/kW	49	
OpEx			
Total OpEx	$/kW/year	118	
Operations (pretax)	$/kW/year	30	ORCA (based on Beiter et al. 2016)
Maintenance	$/kW/year	88	
Financials			
Project design life	Years	25	Offshore wind energy project life for GPRA reporting
Tax rate (combined state and federal)	%	26%	
Federal	%	21%	
State	%	4.7%	Feldman et al. (2020) and NREL's Annual Technology Baseline
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%	
WACC (real; after-tax)	%	2.7%	Calculation
Capital recovery factor (nominal; after-tax)	%	7.3%	

Assumption	Units	Value	Notes
Capital recovery factor (real; after-tax)	%	5.6%	
Depreciable basis	%	100%	Simplified depreciation schedule
Depreciation schedule		5-year MACRS	Standard for U.S. wind energy projects
Depreciation adjustment (NPV)	%	86.8%	Calculation
Project finance factor	%	105%	
FCR (nominal)	%	7.6%	
FCR (real)	%	5.8%	
Levelized cost of energy	$/MWh	129	Calculation

Table B4. Residential Distributed Wind Reference Project LCOE Assumptions

Assumption	Units	Value	Notes
Wind power plant characteristics			
Wind plant capacity	kW	20	Representative of residential distributed wind projects
Number of wind turbines		1	
Turbine rating	kW	20	"Assessing the Future of Distributed Wind: Opportunities for Behind-the Meter Projects" (Lantz et al. 2016)
Rotor diameter	m	12.4	
Hub height	m	30	
Specific power	W/m^2	166	Calculation
Cut-in wind speed	m/s	3	Typical turbine characteristics
Cut-out wind speed	m/s	20	
Annual average wind speed at 50 m	m/s	6.00	Reference site wind speed
Annual average wind speed at hub height	m/s	5.58	IEC class IV
Weibull k factor		2.0	
Shear exponent		0.143	Shear for neutral stability conditions
Altitude above mean sea level	m	0	Altitude at turbine foundation
Losses	%	7%	Informed by https://www.nrel.gov/wind/competitiveness-improvement-project.html
Availability	%	95%	
Net energy capture	kWh/kW/yr	2,580	Calculation in Openwind (UL website (undated) https:/aws-dewi.ul.com/software/openwind/)
Net capacity factor	%	29.5%	
CapEx			
Total CapEx	$/kW	5,675	
Wind turbine	$/kW	2,575	"2019 Distributed Wind Data Summary" (Orrell et al. 2020)
Balance of system	$/kW	3,100	"NREL's Balance-of-System Cost Model for Land-Based Wind" (Eberle et al. 2019)
OpEx			

Assumption	Units	Value	Notes
Total OpEx	$/kW/year	35	"Assessing the Future of Distributed Wind: Opportunities for Behind-the Meter Projects" (Lantz et al. 2016)
Financials			
Project design life	Years	25	Project life for GPRA reporting
Tax rate (combined state and federal)	%	25.7%	2021 Annual Technology Baseline (NREL's Annual Technology Baseline and Standard Scenarios web page: atb.nrel.gov)
Inflation rate	%	2.5%	
Debt fraction	%	60%	"Assessing the Future of Distributed Wind: Opportunities for Behind-the Meter Projects" (Lantz et al. 2016)
Debt interest rate (nominal)	%	2.61%	"Land-Based Wind Market Report: 2021 Edition" (Wiser and Bolinger 2021)
Return on equity (nominal)	%	10%	"2019 Cost of Wind Energy Review" (Stehly et al. 2020)
WACC (nominal; after-tax)	%	5.16%	Calculation
WACC (real; after-tax)	%	2.60%	
Capital recovery factor (nominal; after-tax)	%	7.21%	
Capital recovery factor (real; after-tax)	%	5.49%	
Depreciable basis	%	100%	Simplified depreciation schedule
Depreciation schedule	20-yr straight line	20-yr straight line	
Depreciation adjustment (NPV)	%	59.9%	Calculation
Project finance factor	%	114%	
FCR (nominal)	%	8.21%	
FCR (real)	%	6.25%	
Levelized cost of energy	$/MWh	151	Calculation

Table B5. Commercial Distributed Wind Reference Project LCOE Assumptions

Assumption	Units	Value	Notes
Wind power plant characteristics			
Wind plant capacity	kW	100	Representative of residential distributed wind energy project
Number of wind turbines		1	
Turbine rating	kW	100	"Assessing the Future of Distributed Wind: Opportunities for Behind-the Meter Projects" (Lantz et al. 2016)
Rotor diameter	m	27.6	
Hub height	m	40	
Specific power	W/m²	167	Calculation
Cut-in wind speed	m/s	3	Typical wind turbine characteristics
Cut-out wind speed	m/s	25	
Annual average wind speed at 50 m	m/s	6.00	Reference site wind speed

Assumption	Units	Value	Notes
Annual average wind speed at hub height	m/s	5.81	IEC class IV
Weibull k factor		2.0	
Shear exponent		0.143	Shear for neutral stability conditions
Altitude above mean sea level	m	0	Altitude at wind turbine foundation
Losses	%	7%	Informed by NREL's Competitiveness Improvement Project website: https://www.nrel.gov/wind/competitiveness-improvement-project.html
Availability	%	95%	
Net energy capture	kWh/kW/yr	2,846	Calculation in Openwind (UL website (undated): https://aws-dewi.ul.com/software/openwind/)
Net capacity factor	%	32.5%	
CapEx			
Total CapEx	$/kW	4,300	
Wind turbine	$/kW	2,530	"2019 Distributed Wind Data Summary" (Orrell et al. 2020)
Balance of system	$/kW	1,770	"NREL's Balance-of-System Cost Model for Land-Based Wind" (Eberle et al. 2019)
OpEx			
Total OpEx	$/kW/yr	35	"Assessing the Future of Distributed Wind: Opportunities for Behind-the Meter Projects" (Lantz et al. 2016)
Financials			
Project design life	Years	25	Project life for GPRA reporting
Tax rate (combined state and federal)	%	25.7%	2021 Annual Technology Baseline (NREL's Annual Technology Baseline and Standard Scenarios web page: atb.nrel.gov)
Inflation rate	%	2.5%	
Debt fraction	%	60%	"Assessing the Future of Distributed Wind: Opportunities for Behind-the Meter Projects" (Lantz et al. 2016)
Debt interest rate (nominal)	%	2.61%	"Land-Based Wind Market Report: 2021 Edition" (Wiser and Bolinger 2021)
Return on equity (nominal)	%	10%	"2019 Cost of Wind Energy Review" (Stehly et al. 2020)
WACC (nominal; after-tax)	%	5.16%	
WACC (real; after-tax)	%	2.60%	Calculation
Capital recovery factor (nominal; after-tax)	%	7.21%	
Capital recovery factor (real; after-tax)	%	5.49%	
Depreciable basis	%	100%	Simplified depreciation schedule
Depreciation schedule	5-year MACRS	5-year MACRS	MACRS assumed for commercial project
Depreciation adjustment (NPV)	%	87.1%	
Project finance factor	%	104%	Calculation
FCR (nominal)	%	7.53%	
FCR (real)	%	5.73%	
Levelized cost of energy	$/MWh	99	Calculation