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NOWRDC DEEPFARM R&D PROJECT

D6.1 Cost Trade-offs of Open-source Mooring Systems

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Levelized Cost of Energy Comparison of Floating Wind Farms With and Without Shared Anchors

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National Renewable Energy Laboratory

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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

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1 Introduction

As part of the Innovative Deep-Water Mooring Systems for Floating Wind Farms (DeepFarm) research and development (R&D) project, led by Principle Power Inc., the National Renewable Energy Laboratory (NREL) performed a levelized cost of energy (LCOE) analysis to compare the changes in LCOE between floating wind farms with individual anchors versus shared anchors. Shared anchors—sometimes called multiline anchors—are anchors with multiple mooring line attachments that serve multiple floating wind turbines, allowing fewer anchors to be used in a given floating wind farm. This report presents a comparative analysis of the LCOE of two different wind farms with different mooring systems: one with taut mooring lines each connected to individual suction pile anchors and one with taut mooring lines connected to shared anchors. A brief description of the methodology employed to conduct the LCOE comparison is given, including the underlying assumptions. Then results are presented with a compilation of key findings.

2 Methodology

The objective of the study is to provide a comparative analysis of capital expenditures (CapEx) and LCOE between wind farms with and without shared anchors. Each wind farm under analysis has a constant water depth of 850 meters (m), consists of 15-megawatt (MW) wind turbines and semisubmersible platforms, has three mooring lines per platform, and has either individual or shared anchors. The DeepFarm project originally considered four prospective reference sites on the U.S. West Coast, but a single reference site is used for the LCOE comparison: near the Humboldt Bay Wind Energy Area, centered on 40.13330 degrees north latitude, 124.73094 degrees west longitude. These locations and assumptions are used as inputs to a set of modeling tools developed by NREL to calculate the LCOE of a floating offshore wind farm.

2.1 Modeling Tools

LCOE is a metric used to assess and compare the lifetime cost of generating electricity from different sources of energy. The units are typically expressed in terms of dollars per megawatt-hour ($/MWh). In this report, LCOE provides a standardized way to compare the economic competitiveness between two floating offshore wind farms—one with shared anchors and one with individual anchors.

LCOE can be calculated primarily as a function of the CapEx, the operational expenditures (OpEx), and the annual energy production (AEP). These values are calculated by a coupled suite of open-source modeling tools:

- Offshore Renewables Balance-of-System and Installation Tool (ORBIT): Balance-of-system and installation costs and logistics
- Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT): Operations and maintenance (O&M) costs, wind farm availability, and logistics
- FLOw Redirection and Induction in Steady State (FLORIS): Annual energy production and wake losses.

ORBIT provides medium-fidelity modeling of installation logistics and the associated costs of wind farm development using a discrete-event simulation framework, allowing for the effects of weather delays and vessel interactions (Nunemaker et al. 2020). Costs and sizes of offshore wind components are either calculated using a suite of engineering design modules or taken as user-defined inputs. Underlying cost data used by ORBIT is maintained by NREL using industry and market trends. ORBIT's installation modules are designed to break down construction logistics into discrete subprocesses, effectively mirroring the time and complexity inherent in real-world installation scenarios. In addition, certain development and installation processes have wind speed and/or wave height limits, which ORBIT includes to account for possible weather delays. With the capabilities offered by ORBIT, we can compare the CapEx of two wind farms that employ different mooring system components and installation sequences.

WOMBAT is an O&M scenario-based tool that calculates the costs associated with component failures, scheduled maintenance tasks, and mobilization of equipment to carry out repairs within a discrete-event simulation framework that (Hammond and Cooperman, 2022). WOMBAT does not optimize O&M costs but quantifies the impacts of new technologies, maintenance strategies, and site conditions on the costs of operating a wind power plant. We input major failure and replacement costs into WOMBAT to quantify the impacts of the unit-cost reduction of the shared-anchor farm design compared to a conventional, individual-anchor farm design.

FLORIS estimates energy production and wake losses given a set of specific wind farm characteristics and site-specific conditions (NREL 2022). We combine the availability results from WOMBAT with the annual energy production from FLORIS to estimate the net capacity factor of both wind farms.

Using these tools, we can estimate CapEx, OpEx, and AEP, which can then be used to calculate the LCOE in the following equation, using the fixed charge rate (FCR) method.

$$LCOE = \frac{FCR \times CapEx + OpEx}{AEP} \tag{1}$$

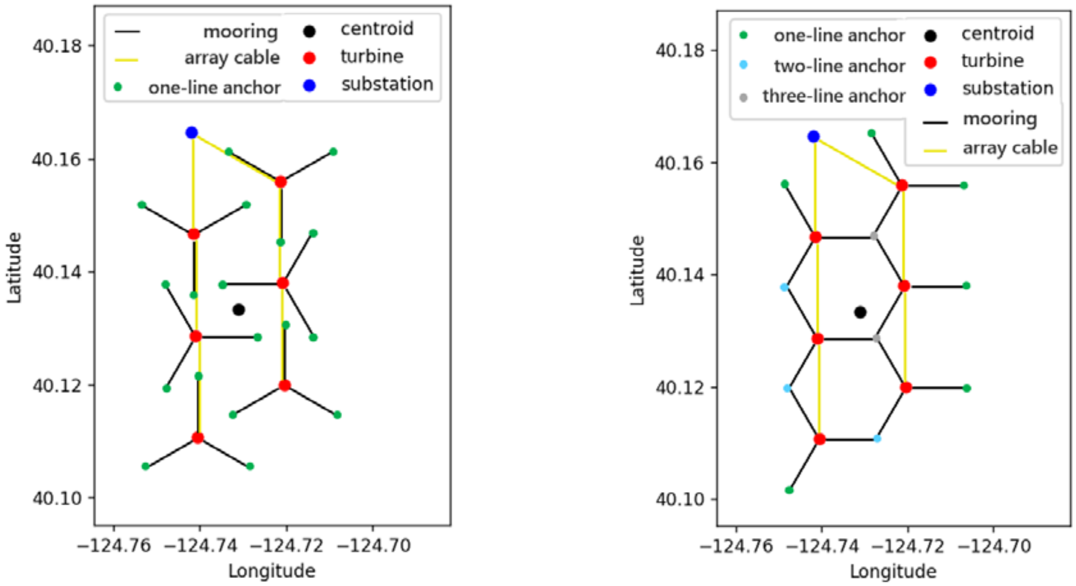
FCR is a financial metric derived from tax, project lifetime, depreciation, and other financial assumptions to annualize a project's initial investment (CapEx). We assume a FCR of 5.82%—in line with the FCR used in the 2021 Cost of Wind Energy Review (Stehly 2023).

Most of the inputs to these LCOE modeling tools use the default values provided in each tool's documentation. However, the following sections detail the changes made to the default assumptions in the modeling tools to model shared-anchor mooring systems.

2.2 Layout

Two sizes of floating wind farms are considered in this analysis: a pilot-scale project of six floating wind turbines, and a gigawatt-scale project of 100 floating wind turbines. For each floating wind farm size, two layouts are compared: an individual-anchor layout and a shared-anchor layout. Figure 1a shows the individual-anchor layout of the pilot-scale wind farm, Figure 1b shows the shared-anchor layout of the pilot-scale wind farm, Figure 2 shows the individual-anchor layout of the gigawatt-scale wind farm, and Figure 3 shows the shared-anchor layout of the gigawatt-scale wind farm. These four cases are used to compare the LCOE impacts between two different farm capacities and between individual- and shared-anchor farms.

The layouts for the pilot-scale wind farms were chosen so that both individual- and shared-anchor configurations could be created without any overlapping mooring lines and the inclusion of shared anchors with three mooring line attachments. The layout of the individual-anchor, gigawatt-scale wind farm was chosen to be a 10-by-10 grid of 100 wind turbines to represent a simple large-scale layout. The layout of the shared-anchor, gigawatt-scale wind farm also consists of 100 turbines but staggers their positions in order to create shared anchor positions. The differences in the gigawatt-scale wind farms will create differences in the array cable layouts and in wake losses, which will be accounted for in the LCOE analysis.



(a) Individual anchors (b) Shared anchors

Figure 1. Pilot-scale floating wind farm layouts of mooring lines and either individual or shared anchors

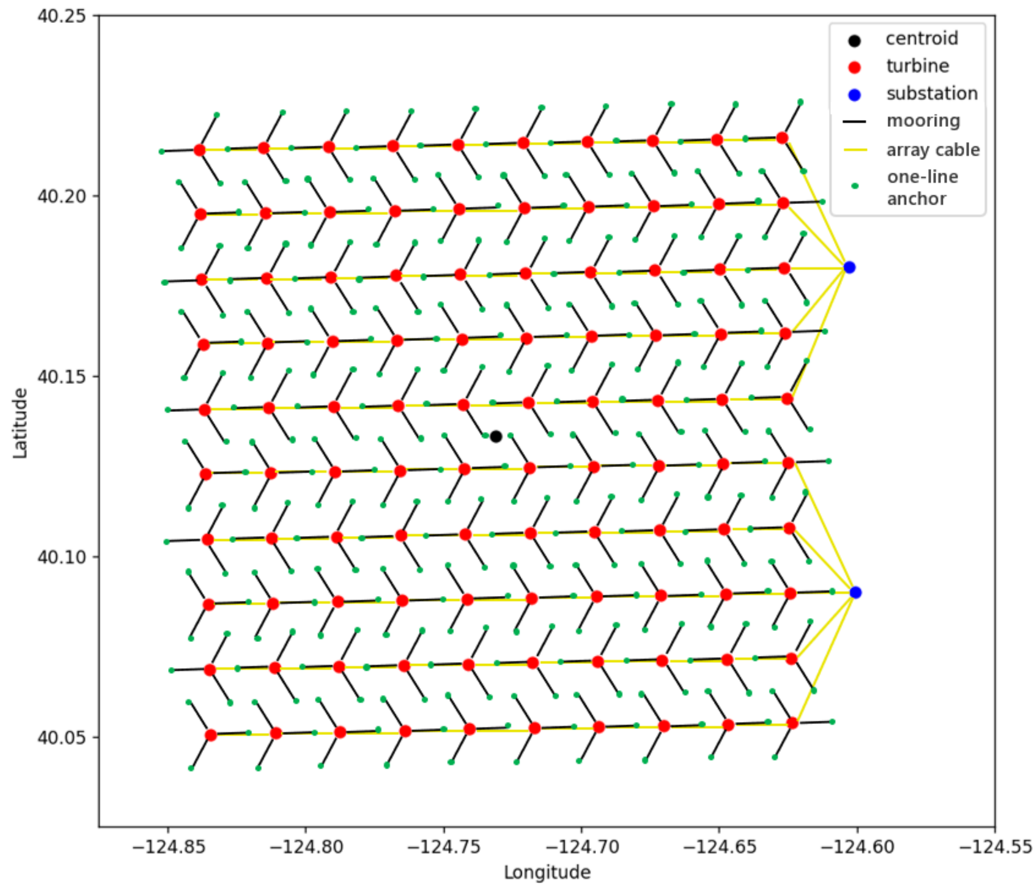


Figure 2. Gigawatt-scale floating wind farm layout of mooring lines and individual anchors

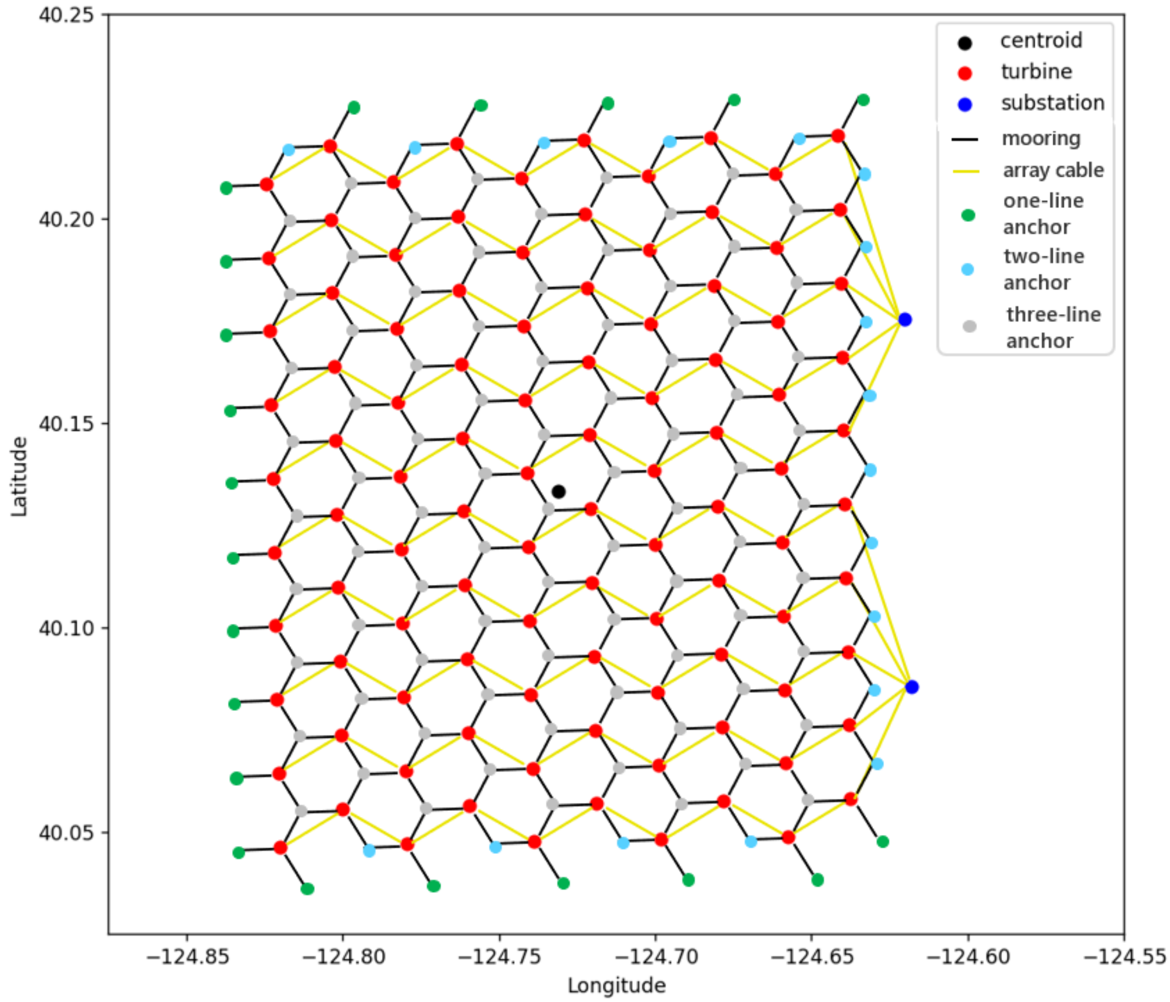


Figure 3. Gigawatt-scale floating wind farm layout of mooring lines and shared anchors

One offshore substation is included in the pilot-scale floating wind farms and two offshore substations are included in the gigawatt-scale floating wind farms. The offshore substations for the gigawatt-scale farms are located on the east side of the farm, closest to export cable landfall. For modeling purposes, it is assumed that these substations can support each wind farm and that the export cables have enough capacity to transmit the power to shore. Specific details on offshore substations and export cables are not required for this comparative analysis.

Mooring lines are attached to a turbine and platform on one end, signified by red circles and to either an individual or a shared anchor on the other end, signified by either green, light blue, or gray circles depending on if it has only one mooring line attachment, two attachments, or three attachments, respectively. In the gigawatt-scale shared-anchor wind farm configuration, the turbine layout is adjusted to accommodate the connection of mooring lines to shared anchors, which also changes the array cable layout, but maintains the same turbine spacing. Specific details about each floating wind farm are provided in Table 1.

Table 1. Layout Assumptions and Details for Each Floating Wind Farm

	Pilot-Scale		Gigawatt-Scale	
Parameter	**Individual**	**Shared**	**Individual**	**Shared**
Water Depth (meters [m])	850	850	850	850
Distance to Shore (m)	44.4	44.4	44.4	44.4
Distance to Landfall (m)	44.4	44.4	44.4	44.4
Turbine Rating (megawatts [MW])	15	15	15	15
Number of Turbines (-)	6	6	100	100
Plant Capacity (MW)	90	90	1,500	1,500
Turbine Spacing (m)	2,000	2,000	2,000	2,000
Number of Offshore Substations	1	1	2	2
Number of One-Line Anchors	18	6	300	21
Number of Two-Line Anchors	0	3	0	18
Number of Three-Line Anchors	0	2	0	81
Total Number of Anchors	18	11	300	120
Number of Mooring Lines	18	18	300	300
Floating Substructure Type	Semi-Submersible	Semi-Submersible	Semi-Submersible	Semi-Submersible
Mooring System Type	Taut	Taut	Taut	Taut
Anchor Type	Suction Pile	Shared Suction Pile	Suction Pile	Shared Suction Pile

The site is assumed to have a constant water depth of 850 m so that all mooring system designs can be assumed to be identical. Each farm is centered around the same centroid with a distance to shore (and landfall) of 44.4 kilometers (km). Each turbine platform has a 15-MW wind turbine on a semisubmersible platform. Details on the individual- and shared-anchor mooring systems are in the following subsections.

2.3 Mooring System Design

In this analysis, each mooring line is modeled as a taut mooring system (Figure 4a) comprising all polyester rope. In practice, there would typically be a short length of chain near both the anchor and fairlead, but this small amount of chain was not included to simplify the analysis.

(a) Taut mooring system (b) Suction pile anchor

Figure 4. Taut mooring system and suction pile anchor depictions used in the modeling tools.
Illustrations by Josh Bauer, NREL

Each anchor in the farm is modeled as a suction pile anchor (Figure 4b), but the anchors that support more than one mooring line attachment are modeled as "shared suction piles," which look like regular suction piles, but can support loads from multiple mooring lines. They are assumed to be slightly heavier than regular suction piles. Details on the mooring system specifics are found in Table 2.

Table 2. Mooring System Design Specifications and Assumptions Between the Individual and Shared Configurations (Aker Solutions, unpublished data; Principle Power, unpublished data)

Stationkeeping Inputs		Individual-Anchor Farms	Shared-Anchor Farms
Anchor	**Type**	Suction Pile	Shared Suction Pile
	Mass per Unit (tons [t])	65	87
Mooring	**Type**	Taut	Taut
	Line Material	Polyester	Polyester
	Line Diameter (millimeters)	183	183
	Mass per Meter of Chain (kg/m)	26.72	26.72
	Minimum Breaking Load (meganewtons)	5.71	5.71

2.4 Mooring System Installation

The mooring system installation procedure is the largest difference between the individual- and shared-anchor wind farms when modeling LCOE. Conventionally, anchors and mooring lines are loaded onto a vessel at port and installed on site by lowering an anchor (with a mooring line attached) to the seabed and ensuring the mooring line can hookup to a floating platform. This process is repeated for each individual anchor. For shared anchors, this process may look different. In this section, we present the assumptions we used to model the installation of individual- and shared-anchor mooring systems, even though these processes may look different in practice.

We assume that one anchor installation vessel can perform all of the mooring system installation processes for both the individual- and shared-anchor mooring systems. In practice, there could be more than one vessel or a fleet of vessels that can perform the various installation processes, but for simplicity, we only use one vessel. The specifications of the vessel used for both the individual- and shared- wind farms are detailed below in Table 3, which is based off a representative support vessel in ORBIT.

Table 3. Mooring System Installation Vessel Specifications (Nunemaker et al. 2020)

Parameter	Value
Default Mooring System Installation Vessel (U.S. dollars/day)	100,000
Maximum Cargo Mass (t)	5,000
Maximum Occupied Deck Space (square meters [m^2])	1,000
Maximum Wave Height for Operation (m)	3
Maximum Wind Speed for Operation (meters per second)	20
Transit Speed (km/hour [h])	10

To efficiently run through the LCOE modeling tools, we define an "individual mooring system" as three polyester mooring lines and three suction pile anchors, where each mooring line is attached to only anchor, and we define a "shared anchoring system" as one of three collections: one shared anchor and three mooring lines that attach to it, one shared anchor and two mooring lines that attach to it, or one shared anchor and one mooring line that attaches to it. The shared-anchor wind farms have varying numbers of anchors with different amounts of attached mooring lines, as shown in Table 1. The specifications of each mooring and anchoring system as they relate to the vessel capacity are detailed in Table 4.

Table 4. Mooring System Design Specifications Relating to Vessel Capacity

Stationkeeping Inputs	Individual-Anchor Farms	Shared-Anchor Farms
Mooring Line Mass (t)	33.75	33.75
Mooring Line Deck Space (m^2)	0	0
Anchor Type	Suction Pile	Shared Suction Pile
Anchor Mass (t)	65	87
Anchor Deck Space (m^2)	125.0	150.0
Mooring System Mass (t)	296.3	-
Mooring System Deck Space (m^2)	375.0	-
Mooring System (Three-Line) Mass (t)	-	188.3

Stationkeeping Inputs	Individual-Anchor Farms	Shared-Anchor Farms
Mooring System (Three-Line) Deck Space (m^2)	-	150.0
Mooring System Mass (t)	-	154.5
Mooring System (Two-Line) Deck Space (m^2)	-	150.0
Mooring System Mass (t)	-	120.8
Mooring System (One-Line) Deck Space (m^2)	-	150.0

We assume that only the anchors contribute to the deck space available, and the mooring lines can be stored somewhere else on the vessel away from the allowable deck space. It is also assumed that each suction pile anchor takes up 125 m^2 of deck space and the larger shared suction piles take up 150 m^2, where these areas are based on rough estimates of anchor dimensions that are derived from anchor mass. These deck space values are crucial properties, as they determine how many mooring system components can be loaded onto a vessel at one time, which determines how many total trips the vessel needs during installation of the entire wind farm. Actual deck space and mass amounts for mooring lines and anchors in these scenarios could be significantly different; it will eventually depend on the available vessels and mooring system designs.

Using these assumptions, only a maximum of 2 individual mooring systems (6 anchors and 6 mooring lines) or 6 shared anchoring systems (6 shared anchors and either 18, 12, or 6 mooring lines) loaded onto the vessel at a time, due to the vessel's deck space limits. The anchors drive the amount of mooring system components that can be loaded onto a vessel at a time. During the installation trips with 6 shared anchors and 6 mooring lines, for example, the vessel would have capacity to transport additional mooring lines, but those mooring lines would have no anchors to attach to, rendering them unnecessary. Also, for modeling simplicity, only complete individual mooring systems can be loaded at a time; a third set of 3 individual anchors and 3 mooring lines would exceed the deck space limits of the vessel, even though the vessel has the capacity for one more individual anchor and mooring line. Table 5 tabulates the assumed mooring system installation processes for the gigawatt-scale floating wind farm with and without shared anchors.

Table 5. Mooring System Installation Process for the Gigawatt-Scale Individual- and Shared-Anchor Wind Farms*

	Gigawatt-Scale Individual-Anchor Farm		Gigawatt-Scale Shared-Anchor Farm	
Load Mooring Lines and Anchors to Vessel Deck				
	Times per Trip	Time per Unit (h)	Times per Trip	Time per Unit (h)
Load Anchor	6	1	6/6/6	1
Load Mooring Line	6	0.5	18/12/6	0.5
Total Time To Load One Trip (h)		9		15/12/9
Transit to Lease Area				
Transit to Farm Centroid (h)	-	4.44	-	4.44

Install Mooring Systems at Site				
	Times per Trip	Time per Unit (h)	Times per Trip	Time (h)
Position On-site	6	2	6	2
Perform Mooring Site Survey	6	4	6	4
Install Anchor	6	15.25	6	20.41
Install Mooring Line	6	4.25	18/12/6	4.25
Total Time To Install One Trip (h)		153		235.0/209.5/184.0
Transit Back to Port				
Transit to Port (h)	-	4.44	-	4.44
Totals				
Total Time per Trip (h)	170.9		258.9/233.4/207.9	
Number of Trips	50		13.5/3/3.5	
Total Hours To Install (h)	8,454		4,923	
Total Days To Install (days)	356		205.2	
*Slashes indicate different amounts depending on the number of shared-anchor mooring systems remain at port or on the vessel.				

The individual mooring system installation process is assumed to load 2 mooring systems (3 anchors and 3 mooring lines each) at port, transit to site, and then go through the process of positioning on-site, performing a mooring site survey, installing an anchor, and installing the mooring line attached to that anchor for as many anchors there are on the vessel (6). The shared anchoring system installation process is assumed to load 6 shared anchoring systems (6 anchors and either 18, 12, or 6 mooring lines depending on how many systems have already been installed); transit to site; and then go through the process of positioning on-site, performing a mooring site survey, installing an anchor, and then installing either 3, 2, or 1 mooring line(s) to that anchor depending on where the anchor is located within the farm.

For modeling simplicity, the shared anchoring system installation process first installs all the shared anchors with three mooring line attachments, moves on to the shared anchors with two mooring line attachments, and then installs the anchors with only one mooring line attachment until all anchors and mooring lines are installed.

For the gigawatt-scale wind farm, the installation process involves 50 trips to and from port for the individual-anchor configuration, whereas it involves only 20 trips to and from port for the shared-anchor configuration. For the individual-mooring configuration, each trip installs two individual mooring systems (6 anchors and 6 mooring lines). For the shared-anchor configuration, the first 13.5 trips (with 6 anchors and 18 mooring lines per trip) install all the shared anchors with 3 mooring line attachments; the next 3 trips (with 6 anchors and 12 mooring lines per trip) install all the shared anchors with 2 mooring line attachments; and the last 3.5 trips (with 6 anchors and 6 mooring lines per trip) install the remaining anchors with 1 mooring line attachment. The thirteenth trip, for example, has 6 anchors and 15 mooring lines—9 mooring lines for the last 3 shared anchors with 3 mooring line attachments, and 6 mooring lines for the first 3 shared anchors with 2 mooring line attachments.

Many other assumptions were made to produce reasonable mooring system installation results:

- The shared-anchor installation time is made proportional to the weight of the anchor—the shared suction piles are 34% heavier than individual suction piles, and so the shared suction pile installation time is 34% longer than the individual suction pile installation time.
- All mooring system components are always ready to be loaded at port with no delays.
- The load times at port for suction pile anchors and mooring lines are 1 hour and 0.5 hours, respectively.
- The processes listed in Table 5 are the only main processes involved in a mooring system installation, even though there is likely to be others, such as mooring line tensioning procedures.
- The vessel transits from port to the centroid of the farm during every trip, whereas in practice, the vessel will transit to different points within the farm every trip, which can be kilometers away from the farm centroid.

In the context of this comparative analysis, it is important to highlight that the ORBIT discrete-event processes have been designed to accommodate weather-related delays arising from the exceedance of maximum wind speeds and wave heights, which can affect the timelines of construction and installation activities. However, Table 5 lists the installation times as if they could all be completed sequentially without any weather delays. For the purposes of this assessment, we did not consider the determination of specific installation windows.

2.5 Operations and Maintenance

In this comparative LCOE analysis between an individual- and shared-anchor wind farm, the O&M aspects and procedures are assumed to be the same for every component of the wind farm except the mooring system. This section aims to show the main differences in assumptions taken for OpEx modeling of a wind farm with and without shared anchors.

The main factors that affect OpEx, in general, are the repair and replacements costs and the failures per year. Assumptions regarding repair and replacement costs were initially made for individual anchors and mooring lines, which were all sourced from Schwartzkopf et al. (2021). For shared anchors, only the failure and replacement rates were adjusted to account for the higher likelihood of failure in shared anchors, shown in results from Hallowell et al. (2018). Due to limited available data, it is assumed that the replacement cost of shared anchors is the same as the replacement cost of individual anchors, even though they have different masses. In practice, these costs would likely change and could impact the final results. Table 6 details the major failure costs, replacement costs, inspection costs, and number of failures or replacements per year of the individual anchors, shared anchors, and mooring lines.

Table 6. Mooring Line and Anchor Repair and Replacement Data

Stationkeeping Inputs		Individual Anchor	Shared Anchor	Source(s)
Anchor	**Type**	Suction Pile	Shared Suction Pile	-
	Major Failure Cost ($)	75,000	75,000	Schwartzkopf et al. (2021)
	Replacement Cost ($)	512,000	512,000	Schwartzkopf et al. (2021)
	Major Failure/year	0.015	0.0423	Schwartzkopf et al. (2021); Hallowell et al. (2018)
	Replacement/year	0.0125	0.0352	Schwartzkopf et al. (2021); Hallowell et al. (2018)
Mooring	**Type**	Taut	Taut	-
	Major Failure Cost ($)	20,000	20,000	Schwartzkopf et al. (2021)
	Replacement Cost ($)	135,000	135,000	Schwartzkopf et al. (2021)
	Major Failure/Year	0.015	0.015	Schwartzkopf et al. (2021)
	Replacement/Year	0.0125	0.0125	Schwartzkopf et al. (2021)
	Subsea Inspection Cost ($)	500	500	Schwartzkopf et al. (2021)

All mooring line-specific costs and failure assumptions are assumed to be the same between individual- and shared-anchor wind farms. The major failure and replacement costs of mooring lines and individual anchors are based on data gathered from the COREWIND project (Schwartzkopf et al. 2021) and are assumed to be the same between the individual- and shared-anchor wind farms. The number of major failures and replacements of mooring lines and individual anchors are also gathered from the COREWIND project, but only the failure and replacement rates of the mooring lines are assumed to be the same between individual- and shared-anchor wind farms—we assign shared anchors different failure and replacement rates.

The number of major failures and replacements of shared anchors is adjusted from the individual failure and replacement rates based on the reliability of shared anchors. Hallowell et al. (2018) investigates the reliability of multiline anchors and finds that they are 2.82 times more likely to fail than individual anchors when designed for the same 500-year storm conditions (a difference in probability between reliability factors of 1.9 and 1.4 for single-line and multiline anchors, respectively). In the shared-anchor wind farms, these adjusted failure and replacement rates are applied to the shared anchors with two or three mooring line attachments, whereas the anchors with one mooring line attachment in the shared-anchor wind farm will continue to have the same failure and replacement rates as the anchors in the individual-anchor wind farm.

3 Results

Having established the underlying inputs and assumptions to the modeling tools, we can present the CapEx and LCOE results between the two sizes of wind farms. The CapEx estimation was derived through the use of ORBIT, whereas the OpEx estimation and wind farm availability were obtained via WOMBAT. Furthermore, the AEP was determined using FLORIS and WOMBAT. These tools collectively facilitated the comparative techno-economic analysis of all wind farms in consideration.

3.1 Pilot-Scale Wind Farm

3.1.1 Capital Expenditures

For the pilot-scale wind farm, the CapEx analysis for both the individual- and shared- anchor configurations was conducted using ORBIT, and the corresponding outcomes are presented in Table 7 and Figure 5. This table and figure provide an overview of the main CapEx components that varied from the individual-anchor configuration to the shared-anchor configuration of the pilot-scale wind farm.

Table 7. Change in CapEx Component ($/kilowatt [kW]) of the Pilot-Scale Shared-Anchor Wind Farm With Respect to the Individual-Anchor Wind Farm

CapEx Component	Pilot-Scale Individual Wind Farm ($/kW)	Pilot-Scale Shared Wind Farm ($/kW)	Difference ($/kW)	Change With Respect to Individual Wind Farm CapEx Component (%)
Array System	111.60	111.60	0.00	0.00
Export System	444.58	444.58	0.00	0.00
Substructure	979.53	979.53	0.00	0.00
Offshore Substation	290.66	290.66	0.00	0.00
Array System Install	82.79	82.79	0.00	0.00
Export System Install	75.14	75.14	0.00	0.00
Substructure Install	106.47	106.47	0.00	0.00
Substation Install	35.49	35.49	0.00	0.00
Turbine Install	182.42	182.42	0.00	0.00
Turbine	1,500.00	1,500.00	0.00	0.00
Soft	543.16	543.16	0.00	0.00
Project	1,680.56	1,680.56	0.00	0.00
Mooring System	55.80	49.84	**-5.97**	**-10.69**
Mooring System Install	58.13	51.04	**-7.09**	**-12.20**
Total	6,146.32	6,133.26	**-13.06**	**-0.21**

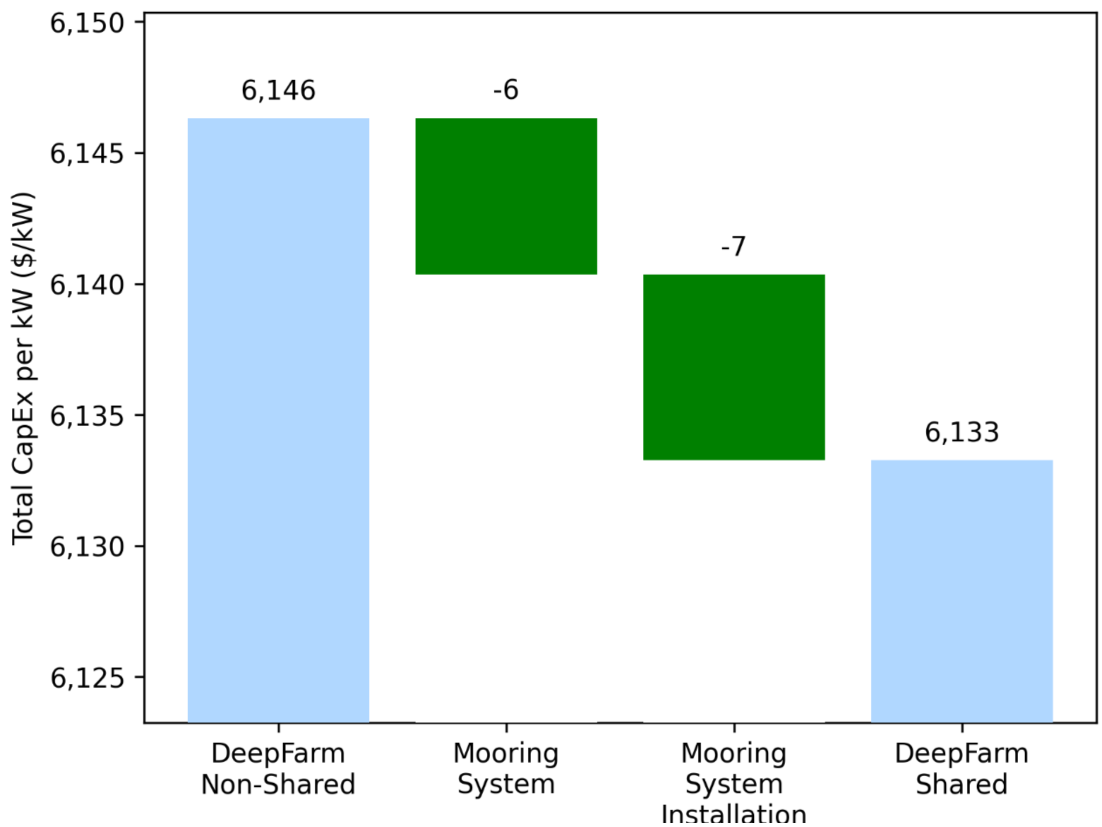


Figure 5. Change in CapEx by CapEx component in the pilot-scale wind farm

The total CapEx of the shared-anchor, pilot-scale wind farm is slightly lower when compared to the individual-anchor, pilot-scale wind farm. The shared-anchor configuration saves 13 $/kilowatt (kW) in CapEx, or 0.21%, relative to the individual-anchor configuration. The only components that had cost differences in the pilot-scale comparison were the mooring system design and the mooring system installation. The mooring system employed in the shared-anchor case features the same number of mooring lines (18) but requires seven fewer anchors than the individual-anchor wind farm. The installation of the mooring system with shared anchors also follows the same methodology outlined in Section 2.4, which takes slightly more than half the time of the individual-anchor configuration installation. This reduction in the number of anchors and installation time leads to a cost decrease of 13 $/kW, or 0.21%, between the shared- and individual-anchor configurations. This cost reduction shows the slight impact shared anchors have on a wind farm with only six wind turbines.

3.1.2 Levelized Cost of Energy

In Table 8, the principal inputs and outputs from ORBIT, WOMBAT, and FLORIS are displayed for both wind farm designs. We conducted five runs per wind farm and averaged the results, as the failures in estimating OpEx and wind farm availability are drawn from a Weibull distribution, which varies for each model run.

Table 8. Summary of Average LCOE Modeling Results for the Pilot-Scale Wind Farm by Mooring System Type

Wind Farm Input/Output	Individual-Anchor Wind Farm	Shared-Anchor Wind Farm
Number of Turbines	6	6
Turbine Rating (MW)	15	15
Project Capacity (MW)	90	90
Number of Substations	1	1
Total Export Cable Length (km)	47.07	47.07
Total Array Cable Length (km)	20.09	20.09
FCR (%)	5.82	5.82
CapEx per kW ($/kW)	6,146.32	6,133.26
Annual OpEx per kW ($/kW)	235.58	214.12
Energy Availability (%)	89.63	89.70
AEP per kW (megawatt-hour [MWh]/kW)	3.6666	3.6694
LCOE ($/MWh)	**161.81**	**155.63**

Figure 6 shows the results of the LCOE comparison, offering a quantification (in $/megawatt-hour [MWh]) of the variations in the CapEx and OpEx.

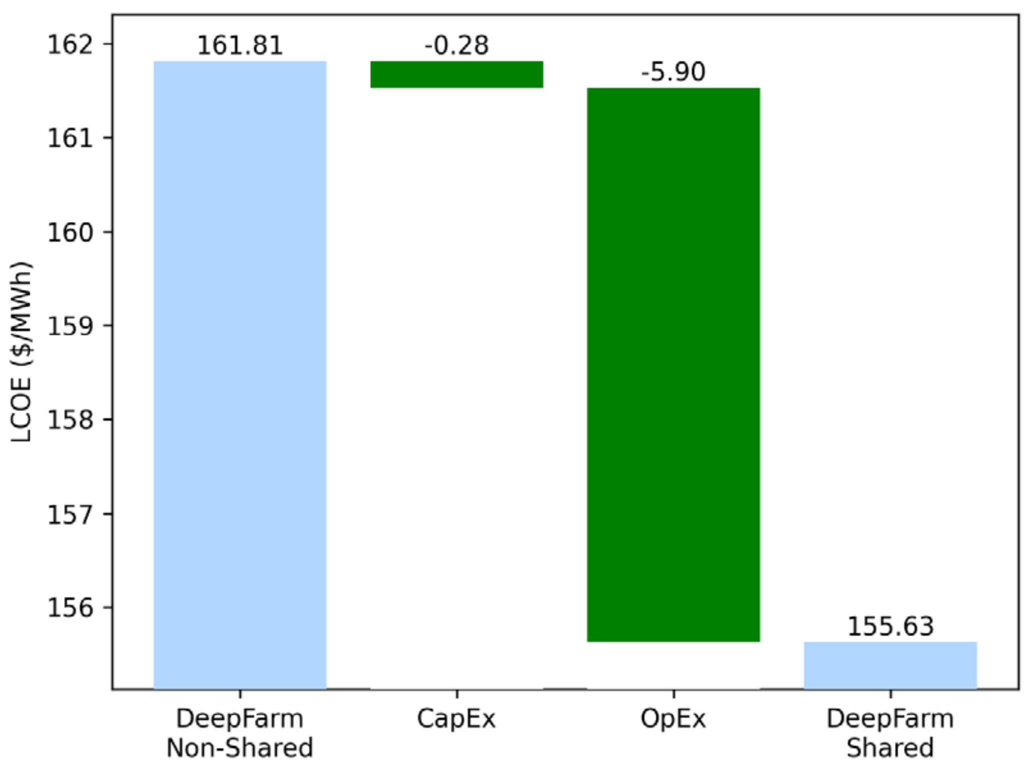


Figure 6. LCOE change by cost component in the pilot-scale wind farm

The OpEx of the pilot-scale, shared-anchor wind farm decreased by 9.1% and contributed to a reduction in LCOE of 5.9 $/MWh (3.6% relative to the LCOE of the pilot-scale, individual-anchor wind farm). Even though failure rates increased for shared anchors, the total OpEx decreased. The number of total anchors was reduced by 39% (18 to 11), where 45% of anchors (5 out of 11) are shared. The reduction in number of total anchors appears to have a larger influence on reducing OpEx than the addition of shared anchors with higher failure rates. The total CapEx of the pilot-scale wind farm decreased in the shared-anchor configuration compared to the individual-anchor configuration and contributed to a decrease of 0.28 $/MWh (0.17%) in LCOE. With its decrease in OpEx and slight decrease in CapEx, the shared-anchor configuration of the pilot-scale wind farm produced a 3.8% reduction (6.2 $/MWh) in LCOE.

3.2 Gigawatt-Scale Wind Farm

3.2.1 Capital Expenditures

For the gigawatt-scale wind farm, the CapEx analysis for the individual- and shared-anchor configurations was conducted using ORBIT, and the corresponding outcomes are presented in Table 9 and Figure 7. This table and figure provide an overview of the main CapEx components that varied from the individual- anchor configuration to the shared-anchor configuration of the gigawatt-scale wind farm. We assume that this wind farm is an idealized commercial-scale wind farm, assuming to have well-developed supply chains.

Table 9. Change in CapEx Component ($/kW) of the Gigawatt-Scale Shared-Anchor Wind Farm With Respect to the Individual-Anchor Wind Farm

CapEx Component	Gigawatt-Scale Individual Wind Farm ($/kW)	Gigawatt-Scale Shared Wind Farm ($/kW)	Difference ($/kW)	Change With Respect to Individual Wind Farm CapEx Component (%)
Export System	133.37	133.37	0.00	0.00
Substructure	979.53	979.53	0.00	0.00
Offshore Substation	133.24	133.24	0.00	0.00
Export System Install	13.54	13.54	0.00	0.00
Substructure Install	99.51	99.51	0.00	0.00
Substation Install	5.58	5.58	0.00	0.00
Turbine Install	134.93	134.93	0.00	0.00
Turbine	1,500.00	1,500.00	0.00	0.00
Soft	543.16	543.16	0.00	0.00
Project	100.83	100.83	0.00	0.00
Array System Install	61.76	54.36	**-7.39**	**-11.97**
Mooring System	55.80	40.84	**-14.96**	**-26.81**
Array System	171.88	115.59	**-56.29**	**-32.75**
Mooring System Install	43.34	25.06	**-18.28**	**-42.18**
Total	**3,976.48**	**3,879.55**	**-96.93**	**-2.44**

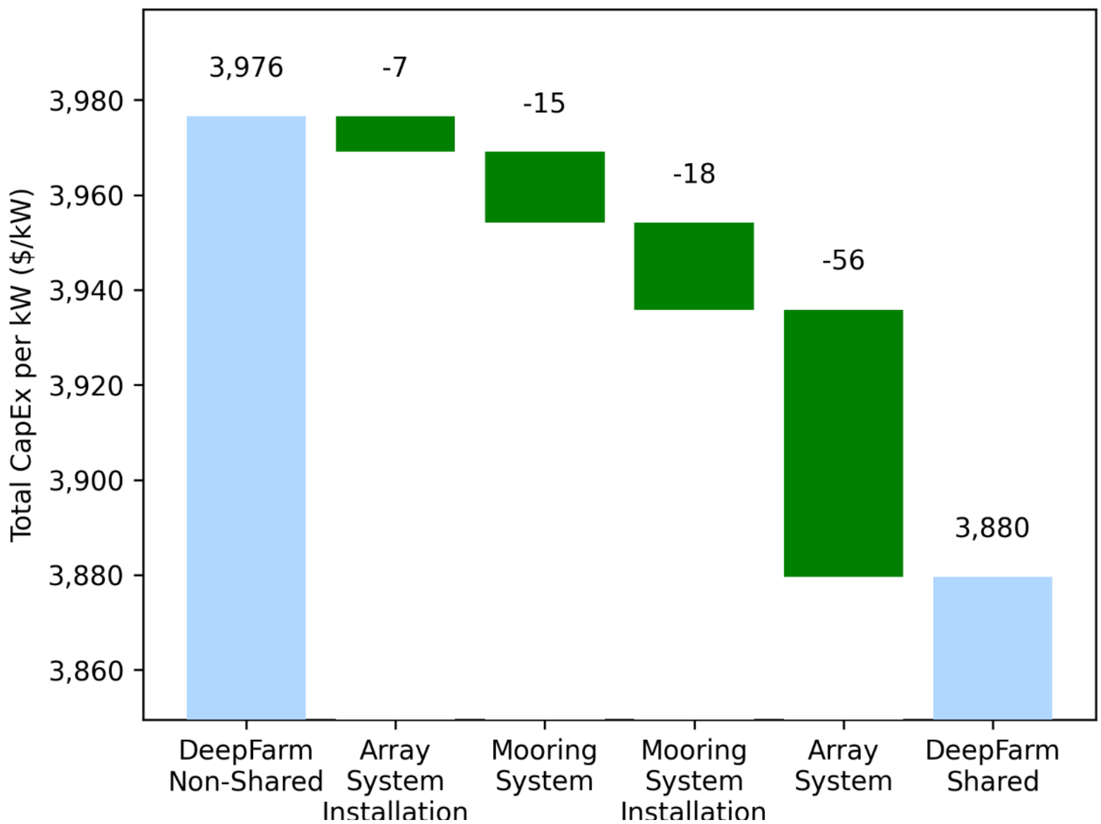


Figure 7. Total change in CapEx by CapEx component in the gigawatt-scale wind farm

The total CapEx costs for the shared-anchor wind farm are notably lower when compared to the individual-anchor wind farm. This cost advantage is primarily attributed to the shared-anchor wind farm's turbine positions, which are on average closer to each other. This proximity reduces the amount of cable required, resulting in a reduction of 63 $/kW in array cable procurement and installation costs. Additionally, the mooring system employed in the shared-anchor case features the same number of mooring lines (300) but requires 180 fewer anchors than the individual-anchor wind farm. The installation of the mooring system with shared anchors also takes slightly more than half the time relative to the installation of the mooring system with individual anchors. This reduction in the number of anchors and installation time leads to a cost decrease of 33 $/kW compared to the individual case. Consequently, the shared-anchor wind farm contributes to a 2.44% reduction in the overall CapEx. This cost reduction underscores the significant impact and cost-effectiveness associated with the implementation of shared anchors in larger wind farms.

3.2.2 Levelized Cost of Energy

In Table 10, the principal inputs and outputs from ORBIT, WOMBAT, and FLORIS are displayed for both wind farm designs. We conducted five runs per wind farm and averaged the results, as the failures in estimating OpEx and wind farm availability are drawn from a Weibull distribution, which varies for each model run.

Table 10. Summary of Average LCOE Modeling Results for the Gigawatt-Scale Wind Farm by Mooring System Type

Wind Farm Input/Output	Individual Wind Farm	Shared Wind Farm
Number of Turbines	100	100
Turbine Rating (MW)	15	15
Project Capacity (MW)	1,500	1,500
Number of Substations	2	2
Total Export Cable Length (km)	235.36	235.36
Total Array Cable Length (km)	515.65	346.78
FCR (%)	5.82	5.82
CapEx per kW ($/kW)	3,976.48	3,879.55
Annual OpEx per kW ($/kW)	62.51	64.34
Energy Availability (%)	94.14	94.00
AEP per kW (MWh/kW)	3.6852	3.6701
LCOE ($/MWh)	**79.76**	**79.05**

Figure 8 shows the results of the LCOE comparison, offering a quantification (in $/MWh) of the variations in the CapEx and OpEx.

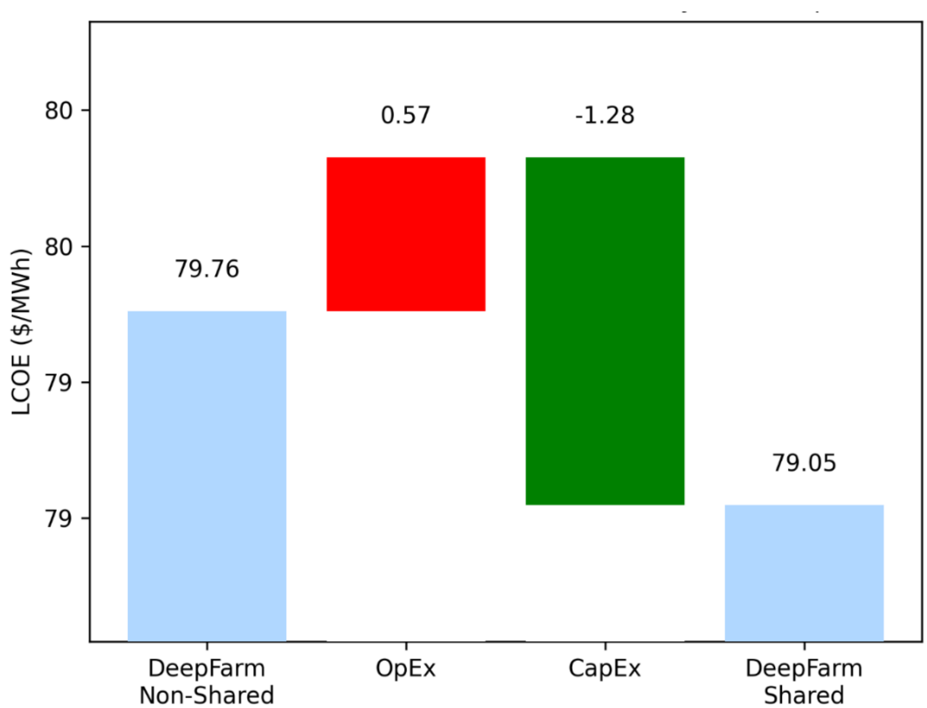


Figure 8. LCOE change by cost component in the gigawatt-scale wind farm

The OpEx of the gigawatt-scale, shared-anchor wind farm increased by 2.9% and contributed to an increase in LCOE of 0.57 $/MWh (0.71% relative to the LCOE of the gigawatt-scale, individual-anchor wind farm. An increase was expected due to the increase in failure rates for the shared anchors and could increase or decrease further depending on changes to the input failure rate for shared anchors. However, the OpEx for the pilot-scale wind farm decreased. The number of total anchors in the gigawatt-scale wind farm was reduced by 60% (300 to 120), where 83% of anchors (99 out of 120) are shared. These ratios, and the absolute number of anchors in the gigawatt-scale wind farm, suggest that the increase in OpEx due to increased failure rates of anchors is more apparent in larger wind farms or in wind farms with higher amounts of shared anchors. There is likely a critical point in the number of total anchors and shared anchors in a shared-anchor wind farm where OpEx may not contribute to an increase or decrease in the LCOE relative to an individual-anchor wind farm. This critical point would also change for different anchor failure rates.

The total CapEx of the gigawatt-scale, shared-anchor wind farm decreased by 1.28 $/MWh, or 1.6% relative to its individual-anchor configuration. With its increase in OpEx but larger decrease in CapEx, the shared-anchor configuration of the gigawatt-scale wind farm produced a reduction of 0.89% (0.71 $/MWh) in LCOE. Even though this change in LCOE between mooring configurations is less than the change in LCOE of the pilot-scale wind farm, the LCOE of the gigawatt-scale wind farm is slightly greater than one half the LCOE of the pilot-scale wind farm, showing the advantages of installing at larger scales.

4 Conclusion

In this task, we compared the costs and performance of two sizes of wind farms with two different anchor types: individual anchors and shared anchors. Many assumptions were made to model the layout, design, installation logic, and failure rates of shared anchors. Adjustments to these assumptions could result in significantly different results. The following are the main takeaways of the difference in LCOE, CapEx, and OpEx between individual- and shared-anchor wind farms for two different sizes of wind farms:

- The use of shared anchors for both the pilot-scale and gigawatt-scale wind farms contributed to an overall decrease in LCOE. (0.89% reduction in LCOE, from 79.8 to 79.1 $/MWh for the gigawatt-scale wind farm; 3.8% reduction in LCOE, from 161.8 to 155.6 $/MWh for the pilot-scale wind farm).
    - Even though the pilot-scale wind farm had a higher decrease in LCOE percentage, its total LCOE in $/MWh was almost two times the LCOE of the gigawatt-scale wind farm.
    - This finding highlights not only the general cost savings of developing at larger scales but also the higher relative cost savings of using shared anchors at smaller scales.
- Considering only the effects of the shared-anchor mooring system design and installation, the gigawatt-scale wind farm had a 33 $/kW decrease in CapEx (0.83%) and the pilot-scale wind farm had a 13 $/kW decrease in CapEx (0.21%) compared to the CapEx of the same wind farms with individual anchors. Total CapEx reductions contributed to 1.6% decrease in LCOE for the gigawatt-scale wind farm and a 0.17% decrease in LCOE for the pilot-scale wind farm.
    - Higher CapEx reductions by using shared anchors can be a result of either larger wind farm sizes, or wind farms with a higher ratio of shared anchors to total anchors (83% of anchors in the gigawatt-scale wind farm had more than one mooring line attached, whereas only 45% of anchors in the pilot-scale wind farm had more than one mooring line attached).
- The OpEx increased in the gigawatt-scale shared-anchor configuration by 2.93% relative to the individual-anchor configuration, which contributed to a 0.71% increase in LCOE. The OpEx decreased in the pilot-scale shared-anchor configuration by 9.1% relative to the individual-anchor configuration, which contributed to a 3.6% decrease in LCOE.
    - The increase in OpEx from the increase in failure rates of shared anchors was larger than the decrease in OpEx from the reduction in total number of anchors in the gigawatt-scale wind farm (60%), whereas the decrease in OpEx from the reduction in total number of anchors in the pilot-scale wind farm (39%) was larger than the increase in OpEx from the increase in failure rates of shared anchors.
    - The ratio of shared anchors to total anchors in the gigawatt-scale wind farm was greater than the same ratio in the pilot-scale wind farm (83% versus 45%, respectively), which suggests that there are less anchors that fail more often in the pilot-scale wind farm.

It is important to emphasize that the cost-estimation tools used throughout this report—ORBIT and WOMBAT—aim to represent the costs associated with the procurement, installation, and operation of an offshore wind farm at a specific point in time. Although the models employed by NREL are periodically updated to capture changes in cost trends, they are not designed to incorporate variations over time in exogenous factors such as commodity prices, inflation, or limitations within the supply chain.

It is essential to note that many assumptions have been made throughout this analysis to produce the given results. The following assumptions had the highest influence on the LCOE between the individual- and shared-anchor wind farms and should be carefully considered in any follow-on analysis.

- The overall wind farm layout using shared anchors greatly influences LCOE, as this determines the number of shared anchors within the farm and the number of mooring lines attached to each one. It also influences the array cable procurement and installation costs, as well as the AEP due to differences in wake losses.
- The physical design of mooring lines and anchors affects the initial procurement costs of the mooring systems.
- The deck space and masses of individual and shared anchors determine how many mooring system components can be loaded onto a vessel at one time, which determines how many trips the vessel takes to and from port, which greatly impacts the overall mooring system installation cost.
- The vessel capacity—or the maximum occupied deck space and cargo mass—also determines how many mooring system components can be loaded onto the vessel at one time.
- The installation logic of shared-anchor mooring systems, which contained different numbers of mooring lines that were transported each trip depending on the number of anchors already installed, can influence the number of trips taken to and from port.
- The replacement costs and failure rates of shared anchors have a direct influence on how many maintenance trips are required throughout the lifetime of the wind farm and the cost to perform that maintenance.

In general, using the given assumptions, the use of shared anchors in a floating offshore wind farm likely reduces LCOE by a few percent depending on the wind farm size and layout. Any adjustments to the above assumptions will likely impact the resulting change in LCOE. This work successfully developed an initial assessment of LCOE between wind farms with and without shared anchors, which could be further refined with adjustments and updates to the modeling assumptions.

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