OSW Consortium 1 - Floating Structure Moorings

Cooperative Research and Development Final Report

CRADA Number: CRD-19-16314

NREL Technical Contacts: Senu Sirnivas, Matthew Hall, and Stein Housner

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Technical Report
NREL/TP-5000-96769
September 2025

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NOTICE

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Cooperative Research and Development Final Report

Report Date: August 13, 2025

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: New York State Energy Research and Development Authority (NYSERDA) (Under the National Offshore Wind Research & Development Consortium, NOWRDC)

CRADA Number: CRD-19-16314

CRADA Title: OSW Consortium 1 - Floating Structure Moorings

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Wind Energy Technologies Office

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources Government In-Kind
Year 1 Year 2, Modification #1 Year 3, Modification #2	$200,000.00 $100,000.00 $.00
TOTALS	$300,000.00

Executive Summary of CRADA Work:

The National Renewable Energy Laboratory will cooperate with NYSERDA to improve the economic feasibility of floating offshore wind plants by researching shared mooring systems that require fewer anchors and cables.

CRADA benefit to DOE, Participant, and US Taxpayer:

- Adds new capability to the laboratory's core competencies
- Enhances the laboratory's core competencies
- Enhances U.S. competitiveness by utilizing DOE developed intellectual property and/or
- capabilities.

Purpose

In September 2019, the National Offshore Wind Research and Development Consortium awarded the first project selected for funding under this RFP: the National Renewable Energy Laboratory will receive $300,000 to improve the economic feasibility of floating offshore wind plants by researching shared mooring systems that require fewer anchors and cables. This project is described below, titled OSW Consortium 1, Floating Structure Moorings.

Background Objectives

This project explores the feasibility of shared mooring systems to lower the cost of deep-water floating wind farms. Station keeping system component and installation costs are significant and have a direct impact on the levelized cost of energy (LCOE) of floating wind systems. In deeper waters, longer mooring lines are required and anchor installation can be more difficult, increasing station keeping costs and raising the LCOE. For deep-water offshore wind sites to be competitive with other energy sources, the LCOE needs to be lowered. Thus far, only traditional mooring systems using chains and anchors for each turbine individually have been used. As such, the total wind farm station keeping system cost increases in proportion to both water depth and farm size.

The aim of this project is to investigate the feasibility of using shared moorings in a floating wind farm to reduce overall station keeping system material and installation costs, hence lowering the LCOE of wind farms in deep waters. A shared mooring arrangement sees mooring lines in the interior of the farm running directly between adjacent floating platforms, rather than running to anchors. This reduces the number of mooring lines reaching the seabed, thus reducing total mooring material, and reduces the number of anchors used by the farm. It also enables a reduction in per-turbine mooring line and anchor requirements as the number of turbines increases. The objectives of this project are to develop a shared mooring floating wind farm design, improve simulation tools to enable loads analysis of such a farm, and conduct analyses to compare the performance and cost of the shared mooring farm with those of a conventional individually moored farm. The goal is to demonstrate significant cost reduction opportunities and provide the industry with design tools that can be used to pursue these cost reductions commercially.

Task 0: Project Management and Progress Reporting

Responsibility

The Contractor will be responsible for the timely completion of all the Tasks in the Appendix A – Joint Work Statement (JWS) per the Project Schedule included herein. The Contractor will provide all project management activities necessary for the performance of this JWS, which shall include the following activities:

- Coordinate the Work of the Contractor's employees and information from Advisors that are undertaking Tasks described in this JWS;
- Ensure control over the budget and adherence to the Project Schedule; and
- Provide all project reporting as specified in this JWS.

Expert Advisory Committee

The Contractor will work with NYSERDA to assemble an expert advisory committee (hereafter, "Advisory Committee") to provide periodic input and feedback to the Contractor. This Advisory Committee shall be composed of technical experts nominated by the R&D Committee of the National Offshore Wind Research and Development Consortium as well as other technical experts nominated by the Contractor or by NYSERDA. The final composition of the Advisory Committee shall be mutually agreed by the Contractor and NYSERDA. The Contractor will solicit feedback from the Advisory Committee quarterly based on the progress reporting below and prior to each go/no-go decision point.

Progress Reporting

The Contractor shall submit **periodic** progress reports, no less frequently than quarterly, to Project/Program Manager no later than the 8th of the month following each reporting period. The Progress Reports shall include information on the following subjects in the order indicated, with appropriate explanation and discussion:

a. Name of Contractor
b. Title of the project.
c. Agreement number.
d. Reporting period.
e. Project progress including a summary of progress, findings, data, analyses, results and
f. Planned work for the next reporting period.
g. Identification of problems.
h. Planned or proposed solutions to identify problems described in (g) above.
i. Ability to meet Project Schedule, reasons for slippage in schedule.
j. Project Schedule - percentage completed and projected percentage of completion of performance by calendar quarter - may be presented as a bar chart or milestone chart.
k. Budget- analysis of actual costs incurred in relation to the budget.

Project Kick-off Meeting

The Contractor will hold a project kick-off meeting within thirty days from the Agreement execution date. The Contractor will coordinate with Project/Program Manager to arrange the meeting at a mutually convenient time and place. The Contractor is encouraged to invite representatives of subcontractors and equipment vendors. The purpose of this meeting shall be to finalize the strategies for accomplishing the objectives of this work and provide/review relevant materials (*ex. metrics reporting, project close-out process, invoicing, and Contractor close-out checklist).* In a timely manner, the Contractor will submit to Project/Program Manager a brief report summarizing the issues discussed and decisions made, if any, during this meeting.

Deliverable: A brief report regarding the project kickoff meeting.

Project Completion Meeting

The Contractor will conduct a project completion meeting, it shall occur within time period covering 15 days prior to and 15 days following the submission of the draft Final Report. The Contractor will coordinate with Project/Program Manager to arrange the meeting at a mutually convenient time and place.

The Contractor will review the Contractor close-out checklist with Project/Program Manager before and after the project completion meeting. The Contractor will only submit the final invoice after all checklist items have been completed and authorization has been received by Project/Program Manager.

Deliverable: A brief report regarding the project completion meeting.

Annual Metrics Reports

On an annual basis, the Contractor will submit, to Project/Program Manager, a prepared analysis and summary of metrics addressing the anticipated energy, environmental and economic benefits that are realized by the project. All estimates shall reference credible sources and estimating procedures, and all assumptions shall be documented. Reporting shall commence the first calendar year after the Agreement was executed. Reports shall be submitted by January 31st for the previous calendar year's activities (i.e. reporting period). The Contractor will provide metrics in accordance with a web-based form, which will be distributed by Project/Program Manager**.**

Task 0 Deliverables:

(1) Written periodic Progress Reports.

(2) Quarterly reports of feedback from the Expert Advisory Committee.

(3) Brief report summarizing the Kick-off Meeting and Minutes.

(4) Brief report summarizing the Completion Meeting and Minutes.

(5) Annual Metrics Reports**.**

Task 1: Shared Mooring System Conceptual Design

In this task, the Contractor shall develop a preliminary shared mooring system design for a representative U.S. deep-water site. In cooperation with Equinor, the Contractor shall identify a U.S. Pacific Coast lease site, or a set of site conditions representative of such a site, to serve as the site parameters for the design processes. The Contractor shall direct its subcontractor Equinor to provide a description of the basic characteristics of an array based on 10-MW variants of their Hywind platform that it would consider for such a site, in terms of array layout, spacing, and nominal mooring approach (line type, anchor spacing, and line length). The Contractor will create a non-proprietary version of this farm and platform design, using their engineering judgement where necessary for any proprietary or confidential information not provided, to create corresponding OpenFAST and FAST.Farm simulations of the conventionally moored floating wind farm at the site. The Contractor will also obtain or estimate parameters for metocean conditions at the site which can later be used to form dynamic load cases (DLCs). [Milestone 1.1]

The Contractor will begin conceptual design work exploring mooring system options for the floating wind farm that utilize shared (intra-array) mooring lines. The mooring approaches that the Contractor considers shall include multiple line materials (chain, wire rope, and synthetic materials), clump weights, buoyance structures along the lines, multiple anchor types (drag embedment anchors and suction piles), and shared (multiline) anchors. The purpose of considering these technologies is to find the most advantageous way to achieve a shared mooring system for the farm; the focus will be to realize maximum benefit from shared inter-platform lines within the station-keeping system design.

The Contractor's conceptual mooring design work shall be based on the site conditions and array details developed in cooperation with Advisors. However, the Contractor may adjust the array layout—including number of turbines and geometric arrangement—to make it better suited to a shared mooring system. Mooring system design and modeling shall account for power cables since they may be important to system restoring properties and motion constraints. The Contractor will explore conceptual mooring designs considering steady-state wind thrust forces, hydrodynamic drift forces, and wave excitation across the farm. Given these environmental loadings, the Contractor will seek mooring system designs and component sizes that satisfy ABS safety factors against mean and cyclic tension amplitudes for a few selected design-driving load conditions. The Contractor will use in-house computational tools based around the MoorDyn mooring dynamics model to explore design performance. In the interest of efficiently exploring many design options in this conceptual design stage, detailed loads analysis will be left to a later Task.

In the conceptual design stage, the Contractor shall direct its subcontractor Equinor to provide guidance on farm design considerations including power cabling. the Contractor shall direct its subcontractor InterMoor to provide guidance on synthetic line material properties and costs as well as mooring system installation considerations. the Contractor shall direct its subcontractor ABS to provide guidance on design rules, particularly with regards to interpretation for intra-array mooring lines and cabling. The Advisory Committee shall provide guidance on general considerations pertaining to mooring connections between turbines from their respective fields of experience.

The Contractor shall seek shared mooring system design concepts that perform well in terms of minimizing the following: mooring and anchoring system cost (including installation), propensity for extreme loads or snap events, installation and service complexity, and obstruction to marine traffic. Costs shall be estimated algorithmically using its existing cost models (updated as need), while the other considerations shall be assessed qualitatively. At the end of the conceptual design process, the Contractor shall identify a shared mooring system design that is deemed most promising with respect to the above objectives for more detailed analysis. The Contractor shall create a report describing this design, its estimated cost and performance characteristics, and the methodology and considerations by which the design components were selected. Lastly, the Contractor shall adapt the developed individual and shared mooring designs to suit semisubmersible rather than spar platforms. The performance of the semisubmersible arrays shall be compared to ensure that the effectiveness of the developed shared-mooring configuration is not limited to spar platforms. [Milestone 1.2]

Task 1 Milestones

- Milestone 1.1: Site characteristics and baseline individually moored array design identified.
- Milestone 1.2: Leading conceptual shared mooring designs identified, and top candidate selected.

Task 1 Deliverables

- Deliverable 1.1: A report describing site parameters and basic properties of the baseline
- (individually moored) floating wind farm design.
- Deliverable 1.2: A report describing the conceptual design process, the resulting shared mooring designs, the rationale for selecting one design further study, and a discussion the effectiveness of the design for semisubmersible platforms.
- Deliverable 1.3: Report documenting preliminary cost estimates using existing NREL cost models for the shared mooring system design concepts studied.

Task 2: Upgrading Design Tool Capabilities for Shared Mooring Systems

Contractor shall upgrade its FAST.Farm modeling capability to support coupled loads analysis of floating wind farms with shared moorings, including array-wide wake effects. This Task occurs in parallel with, and independent from, Task 1.

FAST.Farm can currently model offshore wind farms with floating foundations, however the incident waves at each wind turbine are modeled independently, with no accounting for the propagation of a single sea state across the farm area. The Contractor shall upgrade the wave loading calculations in FAST.Farm so that wave kinematics at each platform adhere to consistent phasing of wave components propagating across the wind farm (the effect of one platform on waves experienced at another platform is assumed to be negligible). [Milestone 2.1]

OpenFAST, which models the turbine and platform dynamics in FAST.Farm, is currently set up to consider an independent mooring system for each turbine, modeled via the MoorDyn module. The Contractor shall update MoorDyn and restructure the module-to-module coupling of FAST.Farm to facilitate inter-platform mooring lines handled within a single farm-level

MoorDyn instance. As part of this, the Contractor shall devise and implement a means of modeling suspended power cables between platforms within OpenFAST using MoorDyn.

Task 2 Milestones

- Milestone 2.1: FAST.Farm extended to correctly model wave phase propagation across the wind farm.
- Milestone 2.2: OpenFAST MoorDyn module adjusted and FAST.Farm coupling restructured to support intra-array mooring lines and power cables.

Task 2 Deliverables

- Deliverable 2.1: FAST.Farm with wave loading updates published online along with associated documentation.
- Deliverable 2.2: MoorDyn module and FAST.Farm updates for intra-array mooring published online and documentation updated (including note on power cable modeling).

Go/No-Go Evaluation:

GO/NO-GO: In order to progress to Task 3, the Contractor must demonstrate to NYSERDA, in its sole discretion, substantial progress towards meeting the milestones of Tasks 1 and 2. If NYSERDA determines that substantial progress has not been made, the Contractor will provide the reason(s) for not meeting the milestones and an assessment of achieving the milestones. The Contractor will not proceed to Task 3 until it has received written approval from NYSEDA to proceed, which approval may be granted or withheld at the NYSERDA's sole discretion.

Task 3: Mooring Design Refinement and Dynamic Performance Evaluation

Task 3 uses the modeling capability developed in Task 2 to refine and evaluate the shared mooring farm design developed in Task 1.

The Contractor shall construct two (2) farm models in the OpenFAST/FAST.Farm tool upgraded in Task 2. The first model will be of the individually moored farm design identified at the beginning of Task 1 (the "baseline design"). The second model will be of the shared mooring farm design concept selected at the end of Task 1 (the "shared mooring design"). The Contractor shall implement these designs following the details developed in Task 1, filling in any additional details or adjusting as required to be able to simulate both farm designs in FAST.Farm. The Contractor shall include power cables in the models. The Contractor shall also develop DLCs for the site based on metocean conditions gathered in Task 1 and the failure modes anticipated from the farm designs, especially with regards to failures that could affect the shared mooring design. [Milestone 3.1]

The Contractor shall simulate the baseline and shared mooring designs in FAST.Farm under a subset of DLCs that are expected to be design driving and will examine the results in terms of key performance metrics (mooring line fatigue and extreme loads, power cable curvature, etc.). The DLC simulations will involve consistent wave propagation across the farm and include wind turbine wake and array effects. From these results, the Contractor shall adjust the designs to ensure performance constraints are met while also minimizing overdesign within the mooring system. This shall be done in keeping with ABS guidelines. Adjustments of the baseline design are expected to be minor, while those on the shared mooring design may be more involved. If the full coupled dynamic analysis reveals problematic behaviors in the shared mooring design, the Contractor shall revise the design configuration as needed to improve performance. At the end of this design refinement process, the Contractor shall settle on updated details for the baseline design and the shared mooring design and shall provide these details in a report. [Milestone 3.2]

With designs finished, the Contractor shall conduct simulations of governing International Electrochemical Commission (IEC) DLCs that are deemed relevant for evaluating the mooring system performance. This loads analysis shall be done for both the baseline and shared mooring designs. The Contractor shall analyze the results to create a comparison that details the merit of the shared mooring design relative to the baseline design. Turbine load measures—such as tower-base bending moments, blade-root bending moments, and nacelle accelerations—will be directly compared between designs. Mooring load measures—such as fatigue and extreme mooring tensions—will be compared in a way that normalizes for the different mooring behaviors between the designs (e.g. by comparing fatigue life estimates and extreme loads normalized by mooring line minimum breaking strength). Platform global response measures will be compared relative to pertinent factors for the farm design (e.g. change in spacing imposed on intra-array power cables). Farm power production will also be considered, and mooring costs will be re-estimated based on the latest load predictions and design adjustments. The Contractor shall input these values into existing cost models to produce LCOE estimates for both wind farm designs. Using these comparisons, the Contractor shall develop observations and conclusions around the advantages and disadvantages of the shared mooring approach for the farm. [Milestone 3.3]

Task 3 Milestones

- Milestone 3.1: FAST.Farm models of the baseline and shared-mooring farm designs created, and DLCs defined.
- Milestone 3.2: Baseline and shared mooring farm designs revised/tuned with dynamic results.
  Milestone 3.3: Baseline and shared mooring farm designs simulated across relevant DLCs, and results processed, compared, and interpreted.

Task 3 Deliverables

- Deliverable 3.1: Complete FAST.Farm input file sets for the baseline and shared mooring designs, along with a spreadsheet defining the DLCs.
- Deliverable 3.2: A report describing the revised farm designs, along with any observations made and conclusions drawn during the design refinement process.
- Deliverable 3.3: A report conveying the results of the loads analysis, providing a comparison of the performance and cost (including LCOE analysis) of the two designs, and discussing the benefits and drawback of the shared mooring design relative to the baseline design.

Task 4: Final Report

Upon completion of the Work, the Contractor will prepare a non-proprietary/non-confidential Final Report covering all aspects of the work performed under this Agreement; the Final Report shall include the following:

- Discussions of the observations, findings and recommendations from all tasks, with avenues for further work and improvements, as appropriate;
- Discussions of the project results and lessons learned regarding configuration,capabilities, and benefits of the project;
- Environmental, and economic benefits, and implementation scenarios associated with the shared-mooring designs;
- Recommendations for further design development towards a commercially viable pilot; and
- Recommendations for shared-mooring design validation studies, for example wave basin testing of a shared-mooring array.

Draft Version and Final Version of Final Report: A draft version of the Final Report shall be submitted to Project/Program Manager no later than the date specified in the Project Schedule. Project/Program Manager will comment on the draft version within 30 working days after receipt of such draft. Within 30 working days after receipt of Project/Program Manager's comments, the Contractor shall prepare a final version of the Final Report reflecting therein careful consideration of Project/Program Manager's comments to the satisfaction of Project/Program Manager and submit the final version of the Final Report.

Task 4 Deliverables:

(1) A draft version of the Final Report.

(2) A final version of the Final Report.

This report serves to meet the requirement for the CRADA Final Report with preparation and submission in accordance with the agreement's Article X**.**

Subject Inventions Listing: None

ROI #: None

The work completed under this CRADA is documented below:

New York State Energy Research and Development Authority (NYSERDA). 2021. “Shared Mooring Systems for Deep-Water Floating Wind Farms: Final Report,” NYSERDA Report, Contract 142869. Prepared by Matthew Hall, Stein Housner, Ericka Lozon, and Senu Sirnivas – National Renewable Energy Laboratory, Golden, Colorado. nyserda.ny.gov/publications.

Also available as of September 2025 at: https://nationaloffshorewind.org/projects/shared-mooring-systems-for-deep-water-floating-wind-farms/