MADWEC Techno-Economic Analysis

Cooperative Research and Development Final Report

CRADA Number: CRD-22-23233

NREL Technical Contacts: Tina Ortega and Elena Baca

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5700-91852
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Suggested Citation
Ortega, Tina, and Elena Baca. 2024. *MADWEC Techno-Economic Analysis: Cooperative Research and Development Final Report, CRADA Number CRD-22-23233.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-91852. https://www.nrel.gov/docs/fy25osti/91852.pdf.

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NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

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

Cooperative Research and Development Final Report

Report Date: 08/26/24

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: University of Massachusetts Dartmouth

CRADA Number: CRD-22-23233

CRADA Title: MADWEC Techno-Economic Analysis

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Water Power Technologies Office

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$105,472.00
Year 2, Modification #1	$.00
Year 3, Modification #2	$.00
Year 4, Modification #3	$.00
TOTALS	$105,472.00

Executive Summary of CRADA Work:

The objective of this project was for the facility to conduct a techno-economic assessment of the Maximal Asymmetric Drag Wave Energy Converter (MADWEC), developed by the University of Massachusetts Dartmouth (UMass Dartmouth), used for powering remote monitoring and AUV charging systems compared to other existing power supply options. The assessment estimates capital expenditures (CapEx), operational expenditures (OpEx), and power performance for 18 scenarios with the purpose of identifying key cost drivers, comparing total system cost, and comparing the power performance of the power supply options in terms of required installed capacity and estimated theoretical annual energy performance. The scenarios include two end-uses: (1) AUV charging and (2) offshore remote monitoring); three power sources: (1) MADWEC), (2) photovoltaic (PV) solar buoy, (3) and traditional battery swapping); and three locations; (1) nearshore, (2) far-offshore, and (3) high-latitude). In addition, other project goals included developing high level installation, operation, and maintenance plans for each scenario.

The techno-economic model, created in Microsoft Excel, estimates CapEx, OpEx, and the power performance of each power supply source. The model has a dynamic format that allows custom inputs to accommodate future changes to the systems being assessed. The theoretical annual energy production (TAEP) results for the three power sources are shown below in Table ES-1. The MADWEC generated a maximum TAEP of 2.5kWh at the far offshore location. To power the remote monitoring station, a total of 176 to 415 MADWECs would be required, depending on the location. To power the AUV charging station, a total of 329 to 777 MADWECs would be required, depending on location. The solar buoy, with just a single 160-Watt PV solar panel, produces a TAEP of 121kWh at the far offshore location. The solar buoys are customized to match the solar resource and load; therefore, the number of PV solar panels on each buoy varies depending on the location for each scenario. For the battery scenario, one battery can provide 30.7kWh of energy throughout the year. Assuming a second set of batteries is purchased so that one set can recharge while the other is providing power, a total of 30 batteries is required for the offshore monitoring system, while 56 batteries are required for the AUV charging system. The total number of power generation devices required for each end-use scenario is shown below in Figure ES- 1. The total CapEx of the arrays (sized to meet at least 100% of the end-use case power and energy demands), ranged between $3 million-$21 million, with the MADWEC power source scenarios being on average $10 million more than the other power source scenarios (Figure ES- 2).

Table ES- 1: Theoretical annual energy production, by location and device

Theoretical Annual Energy Production (kWh) Single Device			
	Nearshore (Mass. State Waters)	Far Offshore (Mass. Federal Waters)	High Latitude (Alaska State Waters)
MADWEC (single WEC)	1.0	2.5	1.5
Solar Buoy (single solar panel)	118.6	121.3	71.7
Battery (single battery)	30.7	30.7	30.7

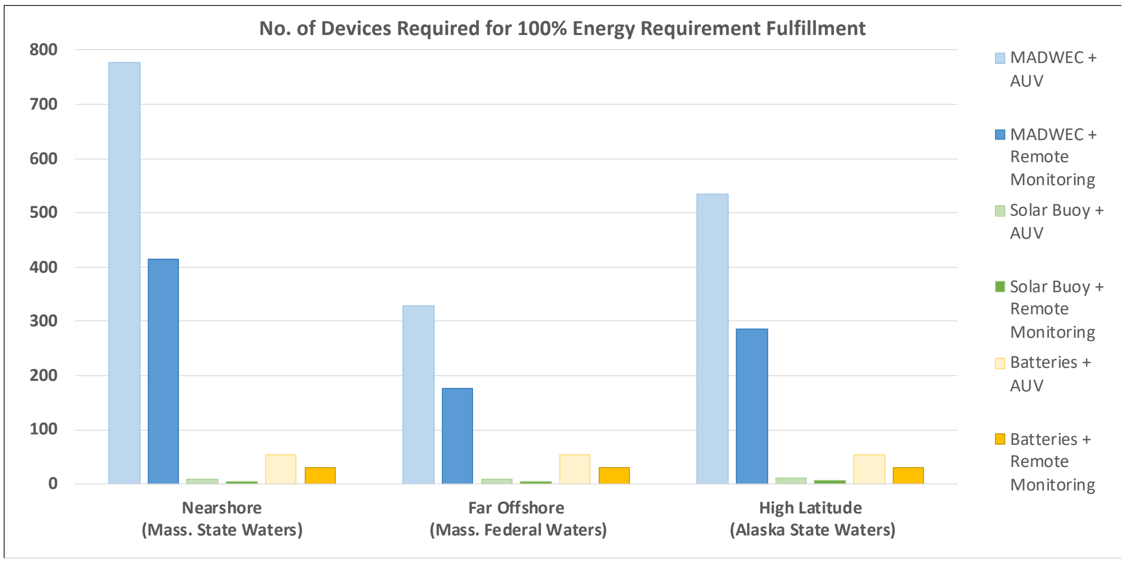

Figure ES- 1: Number of devices required to fulfill the power requirements of the remote monitoring system and AUV system. The number of devices for the solar buoy indicates the total number of solar panels required.

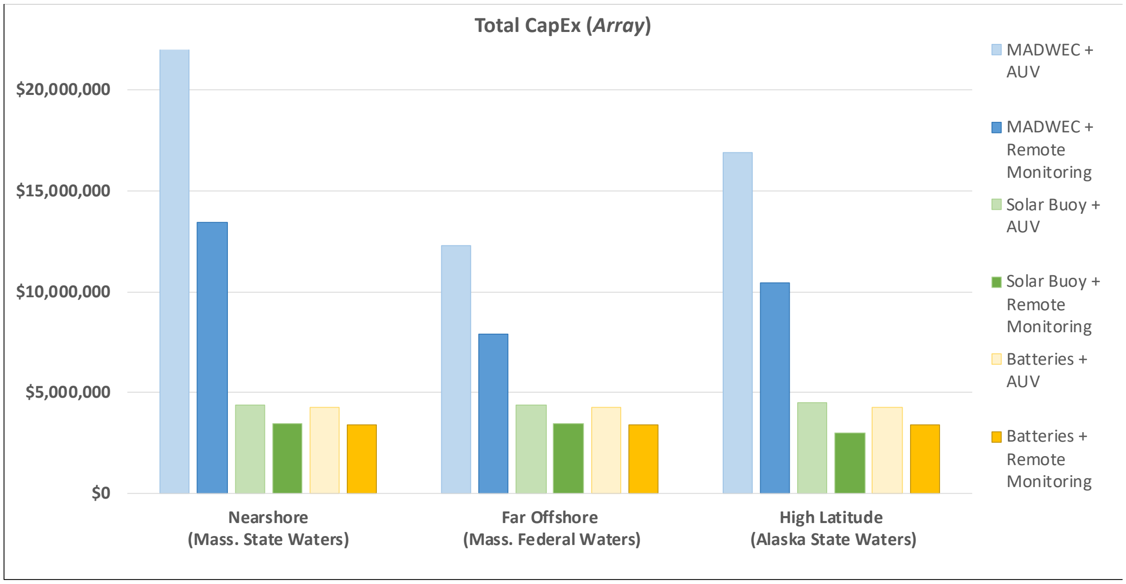

Figure ES- 2: Total CapEx of the arrays (sized to meet 100% of the energy demands of the end-use case).

It should be noted that the MADWEC system, as modeled, is not yet optimized, yielding a very low power output resulting in the excessive costs seen in Figure ES-2. As UMass Dartmouth continues to develop and improve the MADWEC, the model can be edited to provide updated cost and power performance estimates. The TEA model results can be used as cost and performance targets that need to be achieved for the MADWEC to be competitive with other power supply options that are currently commercially available.

CRADA benefit to DOE, Participant, and US Taxpayer:

The CRADA benefitted the participant, UMass Dartmouth, by providing preliminary cost estimates for their wave energy converter design, while also providing a framework cost model that can be continuously utilized even as the design and other project aspects change. The framework cost model has data and information that was gathered during this analysis specific to the MADWEC design, with clear indicators for inputs that can be updated with future costs as the design changes. The cost breakdown of the MADWEC, along with costs of comparative energy generation sources will allow the participant to identify major cost contributors to aid in further research. This work enhances NREL's core competencies by expanding our existing database to include data specific to remote sites such as Alaska. The research allowed NREL to gather cost data and form relationships with companies and developers in comparative industries such as small-scaled solar buoys and AUVs. This work also enhances U.S. competitiveness in the wave energy sector by identifying key design and cost components that can be worked on in future studies to reduce the overall cost of the system, making it more cost competitive against comparative technologies.

<u>Summary of Research Results</u>:

Task 1. Develop initial model framework and identify key inputs: NREL divided the system into multiple processes to develop the initial framework of the cost model. NREL also analyzed the cost data and models of previously defined power supply options and system design scenarios, provided by UMass Dartmouth.

NREL conducted a techno-economic assessment of powering remote monitoring and UUV charging systems with multiple power supply options and scenarios. The assessment estimated capital expenditures (CapEx) operational expenditures (OpEx) for the following scenarios and power supply options.

<u>Remote Monitoring</u>

Scenarios

1. Nearshore (within 100 miles of the coastline)
2. Offshore
3. High Latitude (limited solar)

Power Supply Options

1. PV solar power for remote monitoring
2. Ship Based battery replacement of remote monitoring systems.
3. Power remote monitoring with MADWEC

<u>AUV Charging</u>

Scenarios

1. Nearshore
2. Offshore

Power Supply Options

1. PV solar powered UUV charging
2. Shipboard AUV charging with required deployment and recovery
3. UUV charging with MADWEC

For remote monitoring systems, 3 scenarios were investigated and for each scenario, 3 power supply options were assessed and compared. For AUV charging systems, 2 scenarios were investigated and for each scenario, 3 charging options were assessed and compared. In addition to the cost estimation aspect of the assessment, other objectives were to:

- Develop high level installation, operation & maintenance plans for each scenario and power supply options for the purpose of cost estimation taking into consideration weather resource patterns, distance from shore, retrieval and intervention rates, vessel rates, and labor rates.
- Identify key cost drivers from the TEA model, specifically identifying individual processes within each scenario that make up a higher percentage of the total costs.
- Compare power performance of power supply options in terms of required installed capacity and estimated theoretical annual energy performance.
- Identify and compare non-cost related benefits and drawbacks for each power supply option and scenario including social, environmental, and safety impacts. Test Facility, Equipment, Software, and Technical Expertise

A graphical summary of the 18 scenarios is shown in Figure 1.

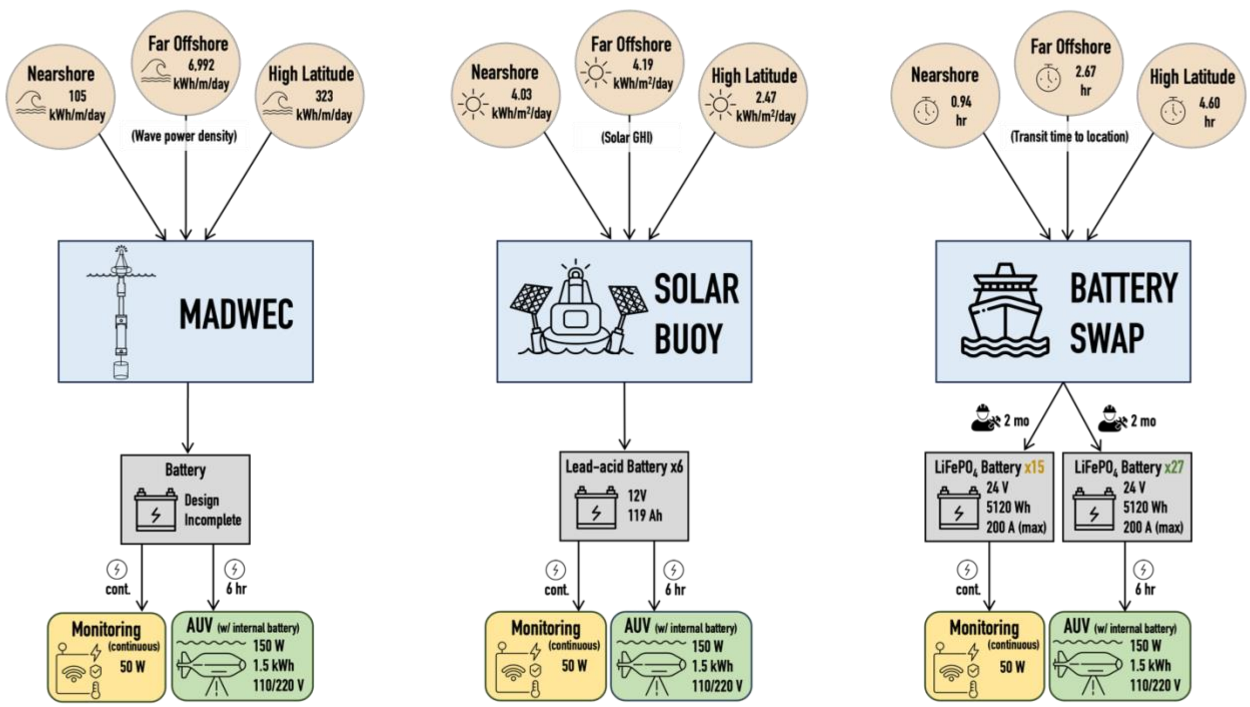

Figure 1: Summary graphic of the 18 scenarios analyzed

Task 2. Input Gathering: NREL gathered input cost data based on the key inputs identified in Task 1. NREL used data provided by UMass Dartmouth to estimate time and costs associated with each process of the model. The total CapEx for each scenario (for a single device) is summarized in Table 1.

Table 1: Total CapEx costs for each scenario, independent of location

	Total CapEx		
Scenario	**Nearshore**	**Offshore**	**High Latitude**
MADWEC + Monitoring System	$3,427,067	$3,411,917	$3,452,931
MADWEC + AUV System	$4,231,966	$4,245,120	$4,252,427
Solar Buoy + Monitoring System	$3,502,550	$3,522,498	$3,529,524
Solar Buoy + AUV System	$4,311,558	$4,331,235	$4,301,984
Battery Swapping + Monitoring System	$3,400,168	$3,413,323	$3,428,969
Battery Swapping + AUV System	$4,209,176	$4,222,331	$4,231,180

The results of the O&M analysis (for a single device) are shown in Table 2.

Table 2: Total O&M costs for each scenario by location

	Total O&M Costs		
Scenario	Nearshore	Offshore	High Latitude
MADWEC	$102,926	$159,543	$136,697
Solar Buoy	$98,817	$155,434	$133,253
Battery Swap + Remote Monitoring	$154,960	$239,885	$213,361

Additional detailed costs for each of the scenarios are included in the TEA Excel model.

Task 3. Development of Model: NREL built and tested the techno-economic model with the relevant key inputs identified by the Parties. NREL put together all gathered data into a single working technoeconomic model containing all processes and scenarios for both the remote monitoring and UUV charging systems.

The TEA model created for this project will aid UMass Dartmouth in their future work to improve the design of MADWEC. As they continue to develop MADWEC, this model can be updated with new cost and power performance data to evaluate the new design. Figure 2 below is a screenshot of the TEA model, built in Microsoft Excel. The model includes a separate tab for calculations for each power generation device (MADWEC, solar buoy, and batteries), and for each calculated parameter (CapEx, Installation, O&M, and power generation), as well as a README and a Results tab.

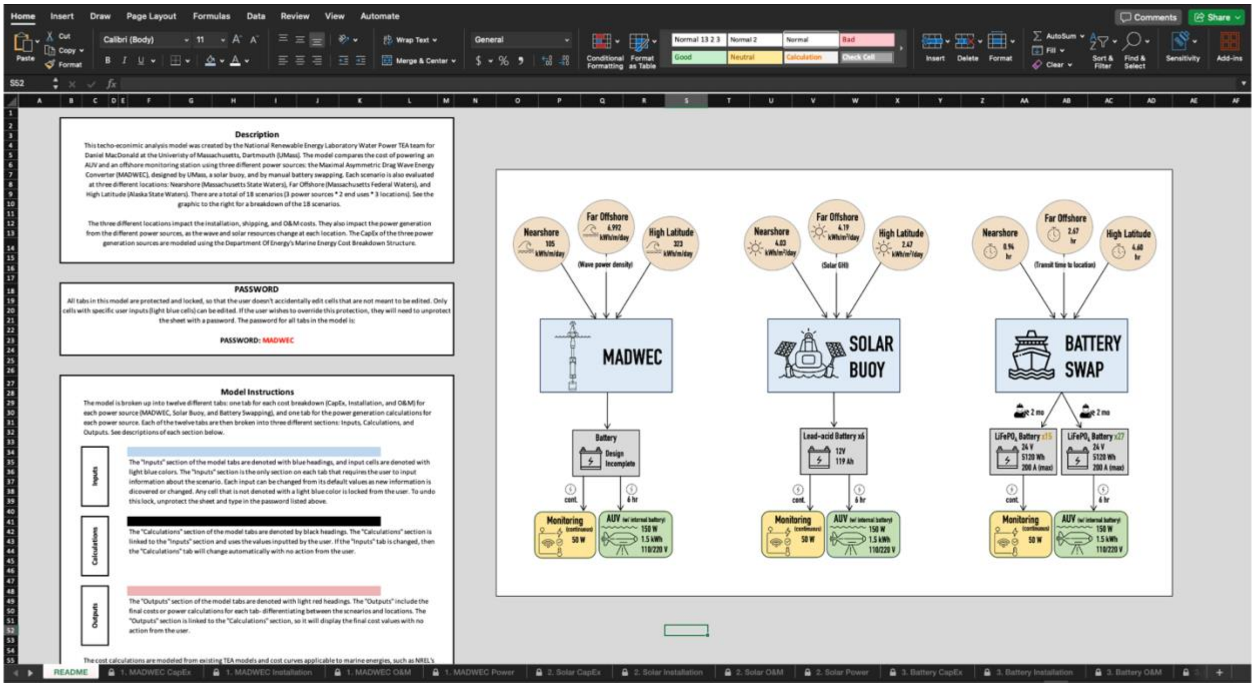

Figure 2: Screenshot of the MADWEC TEA model, built in Microsoft Excel.

Task 4. Analysis and Model Optimization: NREL analyzed and optimized the techno-economic model based on the deployment scenarios modeled. This analysis included comparative analysis and cost estimates.

The results show that a single MADWEC device can produce a total of 1.04 kWh/year at the nearshore location, 2.46 kWh/year at the far offshore location, and 1.52 kWh/year at the far offshore location. To produce enough energy to power the remote monitoring station and the AUV monitoring station, an array consisting of 176-777 MADWEC devices would be required. The solar buoy (with a single solar panel) was able to produce a total of 118 kWh/year at the nearshore location, 121 kWh/year at the far offshore location, and 71 kWh/year at the far offshore location. The solar buoy arrays only required between 4-12 solar panels to fulfill the end-uses power requirements. A single battery used in the battery swap scenario can provide 30 kWh of energy per year assuming it is immediately replaced with the charge runs out. The number of batteries required for the two array scenarios are 54 for the AUV charging scenario and 30 for the remote monitoring scenario. The power performance of the MADWEC will need to be increased to be cost-competitive with the other power generation sources. The CapEx for multi-unit arrays is shown in Table 3.

Table 3: Total Capex for multi-unit arrays

CapEx for 100% energy requirement fulfillment (Array)			
Scenario	**Nearshore (MA State Waters)**	**Offshore (MA Federal Waters)**	**High Latitude (AK State Waters)**
MADWEC + AUV	$22,525,504	$12,438,163	$18,609,926
MADWEC + Remote Monitoring	$13,722,759	$8,460,814	$12,063,694
Solar Buoy + AUV	$4,409,925	$4,421,801	$4,543,226
Solar Buoy + Remote Monitoring	$3,486,460	$3,498,336	$3,035,885
Batteries + AUV	$4,277,022	$4,283,099	$4,284,736
Batteries + Remote Monitoring	$3,433,378	$3,439,455	$3,441,092

Task 5. Reporting: NREL prepared the results of the analysis and share with UMass Dartmouth via a technical report. In addition to the TEA Excel model, NREL also provided UMass Dartmouth with a technical report describing all inputs, process decisions, and results for the model. The report includes details on the methodology for all aspects of the model so that informed decisions can be made in the future by UMass Dartmouth if they wish to change specific aspects or inputs in the model to better represent future MADWEC designs.

Task 6. TEAMER Post Access Requirements: NREL and UMass Dartmouth completed the Post Access requirements (Post Access Report, Post Access Questionnaire, etc.) per the TEAMER award guidelines

Task 7: **CRADA Final Report**: Preparation and submission in accordance with TEAMER guidelines.

This report serves to meet the requirement for the CRADA Final Report with preparation and submission in accordance with the agreements in the TEAMER guidelines.

References:

All references provided were used in the technical report of this TEAMER project.

1. MacDonald, Daniel, Tom, Nathan, Keester, Adam, Baca, Elena, & Raessi, Mehdi. *TEAMER: Maximal Asymmetric Drag Wave Energy Converter*. United States. https://dx.doi.org/10.15473/2007543
2. National Renewable Energy Laboratory and National Technology & Engineering Solutions of Sandia, "WEC-SIM (Wave Energy Converter Simulator)," GitHub, (accessed Feb. 5, 2024). https://wec-sim.github.io/WEC-Sim/master/index.html.
3. Ocean Scientific International Ltd, "3.0M metocean buoy (Albatross)," OSIL, (accessed Feb. 5, 2024). https://osil.com/product/osil-3-0m-metocean-albatross-buoy/
4. Renogy, "24V 200AH Core Series Deep Cycle Lithium Iron Phosphate," Renogy United States, (accessed Feb. 5, 2024). https://www.renogy.com/24v-200ah-core-series-deep-cycle-lithium-iron-phosphate/
5. Pharos Marine Automatic Power, "Beacon Buoy - PMB2400RM," NauticExpo, (accessed Feb. 5, 2024). https://www.nauticexpo.com/prod/pharos-marine-automatic-power/product-200161-577986.html
6. Ocean Observatories Initiative, "Central Surface Mooring (CP01CNSM)," OOI, (accessed Feb. 5, 2024).https://oceanobservatories.org/site/cp01cnsm/
7. Huntington Ingalls Industries, "Remus300M," Huntington Ingalls Industries, (accessed Feb. 5, 2024).https://www.unmannedsystemstechnology.com/wp-content/uploads/2022/06/REMUS-300M-3-31-22_web26.pdf
8. Technical University of Denmark, Global Wind Atlas, (accessed Feb. 5, 2024). https://globalwindatlas.info/en
9. National Renewable Energy Laboratory, "National Solar Radiation Database," NSRDB, (accessed Feb. 5, 2024).https://nsrdb.nrel.gov/data-viewer
10. National Renewable Energy Laboratory, Marine Energy Atlas, (accessed Feb. 5, 2024). https://maps.nrel.gov/marine-energy-atlas/
11. Woods Hole Oceanographic Institution, "R/V Tioga," WHOI, (accessed Feb. 7, 2024).https://www.whoi.edu/what-we-do/explore/ships/ships-tioga/
12. The National Wildlife Refuge System, *TIGLAX*. 1987, http://npshistory.com/brochures/nwr/tiglax.pdf (accessed Feb. 7, 2024).
13. Research Ship Schedules and Information, Tiglax, https://www.researchvessels.org/country/usa/tiglax.html (accessed Feb. 7, 2024).
14. PRIMRE, "Economics," Open Energy Information, (accessed Feb. 7, 2024).https://openei.org/wiki/PRIMRE/Telesto/Economics
15. M. Nabi Allahdadi, Budi Gunawan, Jonathan Lai, Ruoying He, Vincent S. Neary, "Development and validation of a regional-scale high-resolution unstructured model for wave energy resource characterization along the US East Coast", Renewable Energy, Volume 136, 2019, Pages 500-511, ISSN 0960-1481, https://www.sciencedirect.com/science/article/pii/S0960148119300175
16. Gabriel García-Medina, Zhaoqing Yang, Wei-Cheng Wu, Taiping Wang, "Wave resource characterization at regional and nearshore scales for the U.S. Alaska coast based on a 32-year high-resolution hindcast", Renewable Energy, Volume 170, 2021, Pages 595-612, ISSN 0960-1481, https://www.sciencedirect.com/science/article/pii/S0960148121001695

17. Sandia National Laboratories, "Global horizontal irradiance," PV Performance Modeling Collaborative (PVPMC), (accessed Feb. 7, 2024).https://pvpmc.sandia.gov/modeling-guide/1-weather-design-inputs/irradiance-insolation/global-horizontal-irradiance/#:~:text=Global%20Horizontal%20Irradiance%20(GHI)%20is,(180°)%20view%20angle.
18. Markos, F. M., & Sentian, J. (2016, April). Potential of solar energy in Kota Kinabalu, Sabah: An estimate using a photovoltaic system model, *Journal of Physics: Conference Series* (Vol. 710, No. 1, p. 012032). IOP Publishing.
19. United States Environmental Protection Agency, "Green Power Equivalency Calculator," US EPA, (accessed Feb. 7, 2024). https://www.epa.gov/green-power-markets/green-power-equivalency-calculator-calculations-and-references

Subject Inventions Listing:

None

ROI#:

None