Post Access Report

MADWEC Techno-Economic Analysis

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Date: 3/8/24

EXECUTIVE SUMMARY

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 **Error! Reference source not found.**. 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

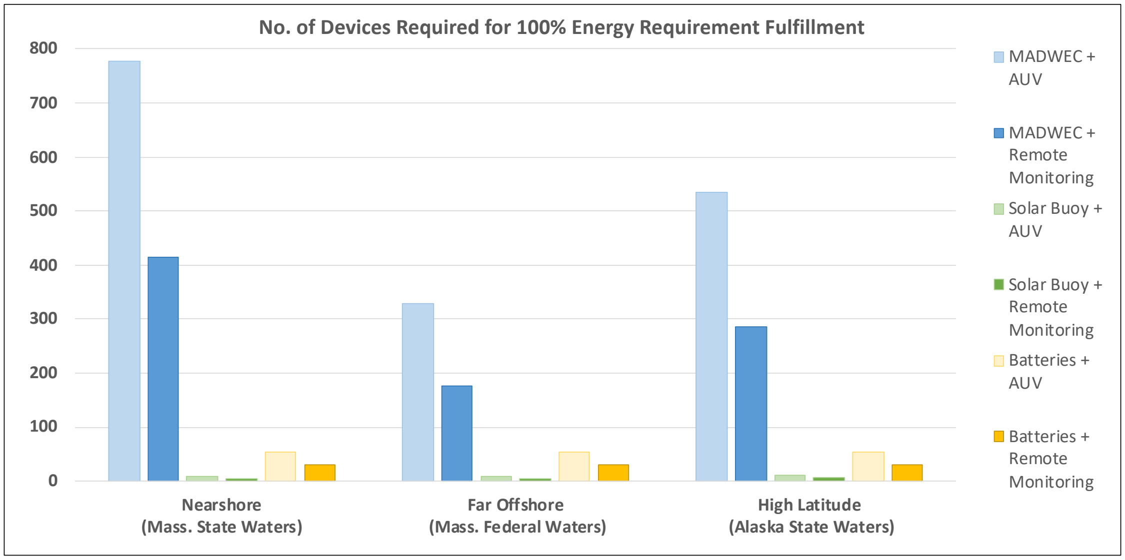

Figure ES- 1: Number of devices required to fulfill the power requirements of the remote monitoring system and AUV system. The number of devices for the solar buoy indicates the total number of solar panels required.

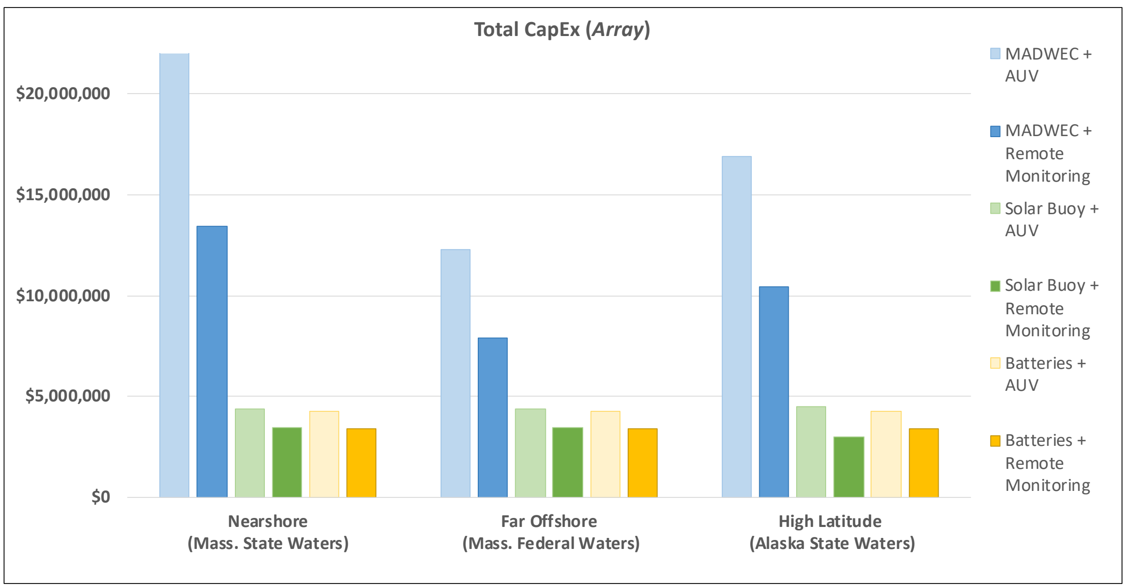

Figure ES- 2: Total CapEx of the arrays (sized to meet 100% of the energy demands of the end-use case).

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.

Introduction to the Project

The University of Massachusetts Dartmouth (UMass Dartmouth) has developed the Maximal Asymmetric Drag Wave Energy Converter (MADWEC), which is designed to provide remote electrical generation for powering the blue economy (PBE) applications. UMass Dartmouth sought the assistance of the National Renewable Energy Laboratory's (NREL) Water Power Research and Development team to conduct techno-economic analysis (TEA) related to the MADWEC device and potential markets. The TEA will investigate powering remote monitoring and unmanned underwater vehicle charging systems with multiple power supply options and scenarios. The analysis will estimate and compare capital expenditures (CapEx) and operational expenditures (OpEx) for each system and scenario. The power supply options being compared are the MADWEC, photovoltaic (PV) solar generation, and battery replacement through the deployment of a vessel. Each power supply option is assessed at near shore (state waters), offshore (federal waters), and high latitude locations with more limited solar irradiance. The analysis estimates capital expenditure (CapEx), operational expenditures (OpEx), and power performance for each power supply type and scenario. The results of the analysis will inform future development of MADWEC and inform the MADWEC development team of the technical requirements of the end-use cases being investigated.

1 Roles and Responsibilities of Project Participants

1.1 Proposed Project Tasks

To complete this TEA, the proposed tasks are as follows:

Task 1. Develop initial model framework and identify key inputs
Task 2. Gather input cost data and process modeling
Task 3. Build and test techno-economic model
Task 4. Analysis and model optimization
Task 5. Reporting
Task 6. Post access report
Task 7. Post access questionnaire

Most responsibilities will fall upon the network facility, NREL, but will be aided by the applicant, UMass Dartmouth, when needed. Specific responsibilities for each project participant and task are described in the following sections.

1.2 Applicant Responsibilities and Tasks Performed

The applicant's main responsibility will be to continuously provide the network facility with any data, feedback, expertise, and resources necessary to create the economic model and subsequent reporting. Specific responsibilities for each task include:

Task 1. UMass Dartmouth to provide NREL with CapEx and OpEx cost data and modeling results from previously defined power supply options and system design scenarios.

Task 2. UMass Dartmouth to assist NREL in collecting cost data through obtaining quotes or estimates and by sharing any previously collected cost data.

Task 3. UMass Dartmouth to provide NREL with ongoing feedback about the model.
Task 4. UMass Dartmouth to provide NREL with ongoing feedback about the model, as well as provide any expertise or resources needed for the model analysis and optimization.
Task 5. UMass Dartmouth to provide NREL with ongoing feedback about the model and report.
Task 6. UMass Dartmouth to develop the post access report.
Task 7. UMass Dartmouth to complete post access questionnaire

1.3 Network Facility Responsibilities and Tasks Performed

This award will engage NREL's Water Power Research and Development team who have the tools and extensive experience in the area of techno-economic modeling of marine energy systems. NREL will obtain cost data to estimate CapEx and OpEx for the proposed power supply options and system design scenarios. Specific responsibilities for each task include:

Task 1. NREL will divide the system into multiple processes to develop the initial framework of the cost model. NREL will also analyze the cost data and models of previously defined power supply options and system design scenarios, provided by UMass Dartmouth.
Task 2. NREL will use data provided by UMass Dartmouth to estimate time and costs associated with each process of the model.
Task 3. NREL will 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.
Task 4. NREL will continually refine the model for the specified scenarios with feedback from UMass Dartmouth.
Task 5. NREL will provide a technical report summarizing the results of the model that compares the various scenarios in terms of project cost (CapEx and OpEx) as well as other potential factors of interest to UMass Dartmouth.
Task 6. UMass Dartmouth will draft and submit the post access report. NREL will assist UMass Dartmouth to draft the report.
Task 7. UMass Dartmouth to complete post access questionnaire.

2 Project Objectives

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

Remote Monitoring

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

AUV Charging

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

NREL's energy and economic analysis of water power technologies leverages decades of experience in system performance modeling, cost estimation, and tool building throughout the renewable energy sector. NREL's marine energy researchers have developed a variety of tools to quantify the economic impact of technology innovations and economic feasibility studies. Our techno-economic modeling and analysis staff is integrated with hydrodynamic modeling, grid integration, resource characterization, and hardware validation/characterization staff as well as other renewable technology researchers to ensure that the most appropriate models and simulation techniques are leveraged for analyses. The NREL team will leverage existing tools as much as possible.

3 Test or Analysis Article Description

The analysis article is a point absorber type wave energy converter (WEC) called the MADWEC shown in Figure 1. The MADWEC's hydrodynamic bodies are comprised of a buoy float and unique tethered ballast system. The tethered ballast system (US Patent 11,156,200 B2) design is intended as a lightweight alternative to heavy and costly steel spars commonly used in traditional point absorber

WECs. The tethered ballast system has a series of nested hollow cylinders. At the bottom of each hollow cylinder, there are louvres that open as the ballast system moves in a downward direction, allowing the device to quickly drop in the water column and position itself properly relative to the free-surface waves. On the ascending half-cycle of the wave period, when the ballast system is forced to move in the upward direction, the louvres close, trapping water in the hollow cylinders and creating significant added mass that keeps the PTO relatively stationary while the buoy continues to ascend. As a result, a relative motion between the buoy and PTO is developed, which is captured by the PTO and converted into electrical energy stored in the battery bank. The modular PTO design allows multiple triplets of generators feeding the modular battery bank that can be used to power a range of applications, from oceanographic sensors and monitoring systems to charging UUVs.

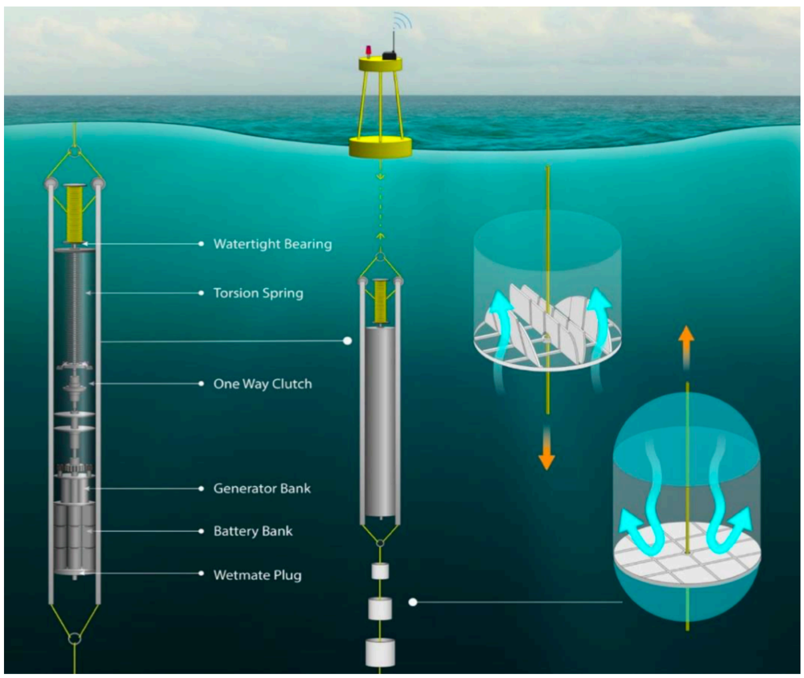

Figure 1: MADWAC high-level overview.

4 Work Plan

4.1 Numerical Model Description

The original work plan proposed NREL to develop a custom cost model using a combination of Microsoft Excel and MATLAB while leveraging prior work and existing tools such as the System Advisor Model (SAM). MATLAB was anticipated to be used for analysis, plotting, and visualizations, while Excel would be used for data collection and analysis. Instead, based on the request of UMass Dartmouth, Microsoft Excel is used exclusively for the TEA model. The TEA model is dynamic, allowing inputs to be edited and enabling the results to update automatically. The TEA model includes the required data inputs for the scenarios assessed and summarizes the results with visualizations and tables.

4.2 Test and Analysis Matrix and Schedule

The analysis team worked according to the schedule shown in Figure 2.

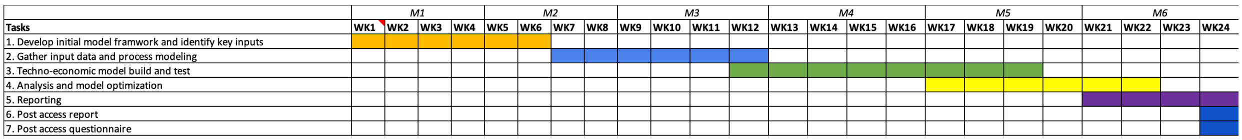

Figure 2: Analysis schedule.

4.3 Safety

There are no safety concerns related to the development of the techno-economic model.

4.4 Contingency Plans

Minor project delays occurred toward the end of the project schedule because the project team (UMass and NREL parties) had unexpected personal time off due to illness and family responsibilities.

4.5 Data Management, Processing, and Analysis

4.5.1 Data Management

The data summarized in Table 1 will be submitted to Marine and Hydrokinetic Data Repository (MHKDR) prior to the conclusion of the project.

Table 1: Data for MHKDR submission.

Data	Format	Description
MADWEC_TEA_Model	.xlsx	Full cost model with any sensitive cost information redacted.

4.5.2 Data Processing

Data processing will be required for making performance and cost estimates. Cost estimates may be made using aggreged cost data. Aggregate cost data collected from various sources will be analyzed to create trends that relate cost to project parameters such a weight, capacity, etc. Cost estimates are inherently uncertain. Data sources and assumptions used during data processing will be clearly defined to provide transparency in calculated results.

5 Project Outcomes

5.1 Methods

5.1.1 Scenario Design

The purpose of the economic model is to compare the system cost and power performance of three power supply systems for two end-use cases at three locations. A total of 18 scenarios are assessed in the analysis. The power supply options include:

1. MADWEC
2. solar buoy
3. manual battery swapping.

The two end-use cases include:

1. offshore monitoring
2. AUV charging.

The three locations evaluated are located in Massachusetts state waters (nearshore), Massachusetts federal waters (offshore), and Alaska state waters (high latitude). A graphical summary of the 18 scenarios is shown in Figure 3.

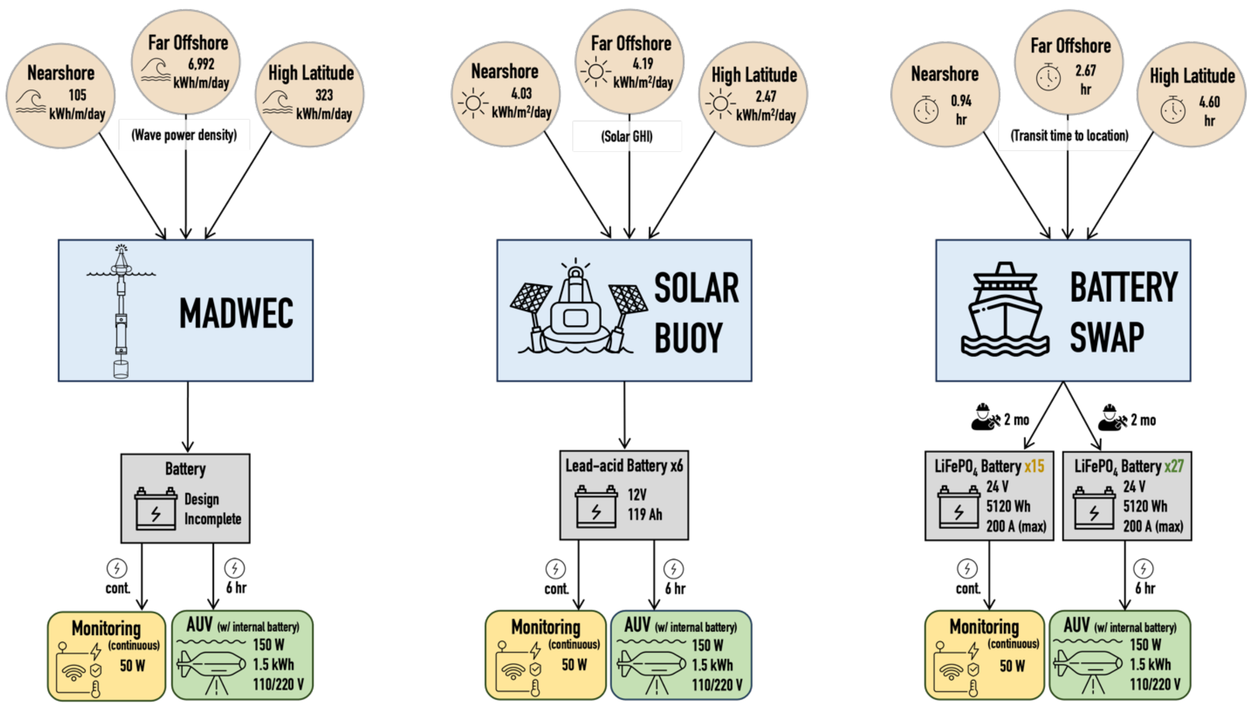

Figure 3: Summary graphic of the 18 scenarios analyzed.

5.1.1.1 Power Supply Options

5.1.1.1.1 MADWEC

UMass Dartmouth provided NREL with a power matrix and component breakdown for the MADWEC system, as well as known cost estimates for components. Some aspects of the MADWEC system have not yet been designed or specified (such as the onboard energy storage) but placeholder values were placed in the model in anticipation of future design changes as agreed upon by the awardee and facility. The placeholder values can be edited as more information becomes available in the future. The MADWEC power matrix used in this analysis was developed in a previous TEAMER project between NREL and UMass Dartmouth [1], using the Wave Energy Converter Simulator (WEC-Sim) [2].

5.1.1.1.2 Solar Buoy

The solar buoy selected for the analysis is the OSIL 3.0m Albatross Metocean Buoy [3]. The Albatross buoy, shown in Figure 4, is advertised for applications such as water quality monitoring, scientific studies, offshore engineering, maritime traffic control, and renewable energy studies. The Albatross buoy is sold fully assembled and ready to deploy, and includes four 160W solar panels, six 12V/119Ah batteries, a waterproof electronics housing, navigation aids, and telemetry options. The buoy does not include mooring and anchors, or the end-use (monitoring sensors or AUV) that the power generation will supply, which were specified and costed separately.

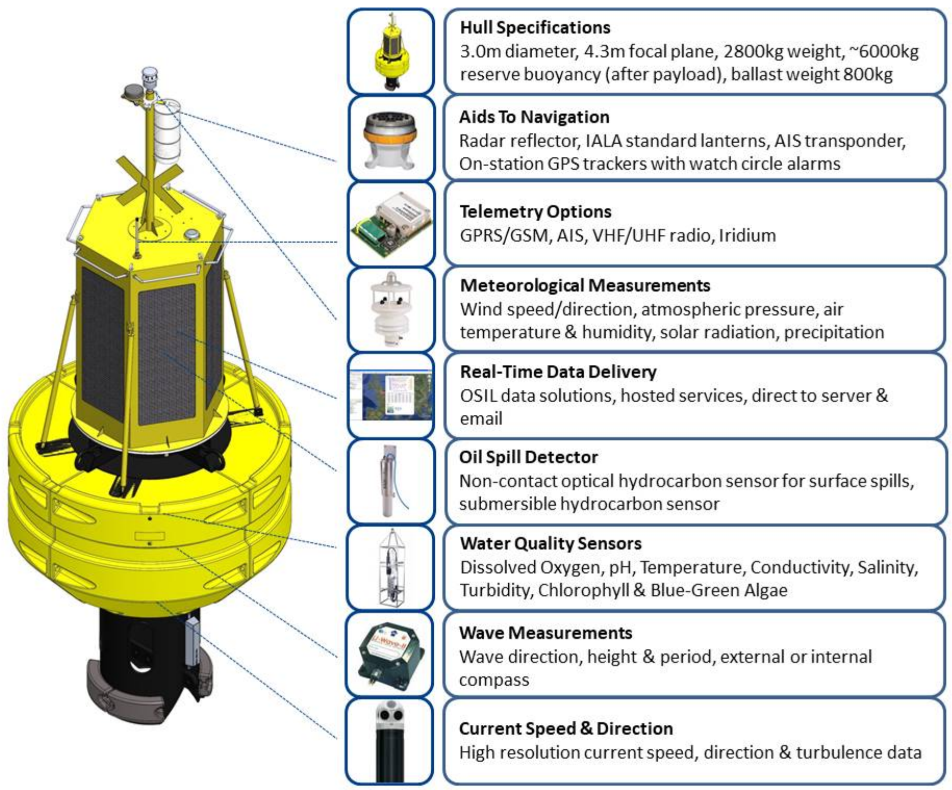

Figure 4: Breakdown of the Albatross solar buoy components. Figure from [3].

The Albatross buoy is custom designed for each application and customer, so NREL obtained multiple cost quotes for different Albatross configurations from OSIL until the final design was agreed upon between NREL and UMass. A list of solar buoy configurations and their costs are shown in

Table 2. Configurations 3 and 4 were selected to use in the analysis based on the ability to meet power demands of the end-use case.

Table 2: Costs of different solar buoy configurations.

Configuration	Solar Panel Wattage (W)	No. of Solar Panels	No. of Batteries	Total Cost
1	75	4	4	$110,820
2	75	4	6	$111,720
3	160	4	6	$113,760

4	160	6	6	$115,620

5.1.1.1.3 Battery Swap

The batteries used for the battery swap scenario were selected based on the power and energy demands of the end-use cases with the assumption that the batteries would be swapped every two months. The monitoring station requires 50W of continuous power and 72kWh of energy storage. Meanwhile, the AUV requires approximately 95W of continuous power for 10 hours of operation with 6 hours of downtime for charging, which equates to about 135 kWh of energy storage. A variety of battery types were investigated including lithium ion, lithium polymer, lithium iron phosphate ($LiFePO_4$), absorbed glass mat, gel, flooded deep cycle, and nickel metal hydride. For each battery type, we determined how many batteries would be required to meet the energy requirements by dividing the energy needs of the two cases by the energy capacities of the different batteries. Then the total cost and weight of the different batteries were compared to find the battery type with the lowest cost and weight. Once a battery type was selected, we verified that the specifications could meet the power and energy requirements of the end-use cases. Afterwards, we used the total weight and volume of the batteries to find a buoy that could be used to house them. Figure 5 shows the batteries evaluated for both cost and weight. Of the batteries evaluated, lithium iron phosphate ($LiFePO_4$) batteries were selected because they have both low cost and weight.

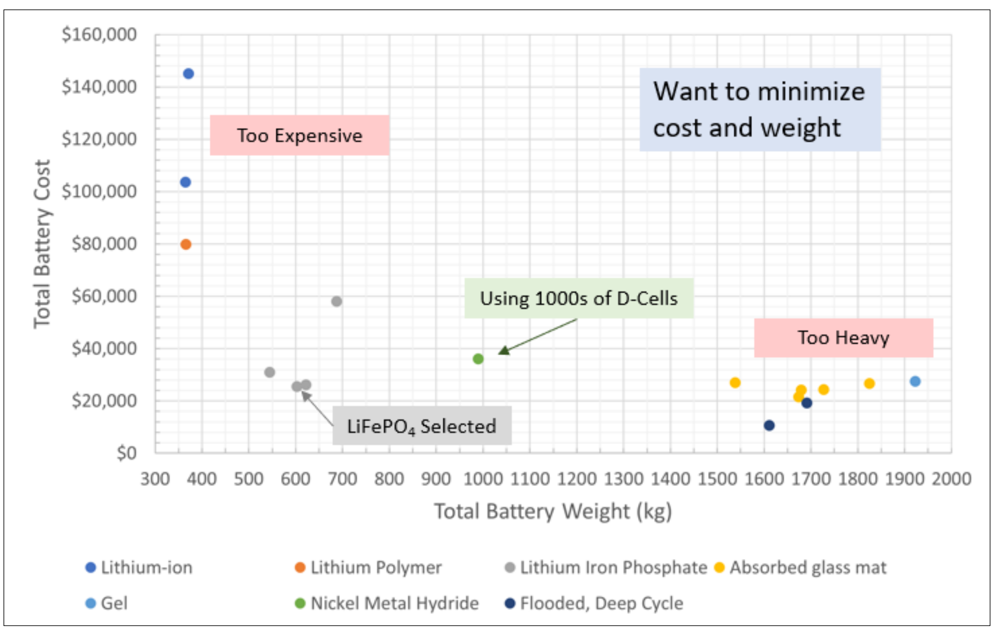

Figure 5: Total battery weight vs cost for the monitoring buoy battery swap scenario. Note that the same trend and ideal battery were found for the AUV case.

For this TEA analysis, the Renogy 24V 200Ah $LiFePO_4$ battery [4] is used, which has an energy capacity of 5.12kWh, maximum current of 200A, maximum of 5,000 cycles, and a maximum discharge of 5.1kW, all of which meet the criteria for both scenarios. For the monitoring station, 15 of the Renogy $LiFePO_4$ batteries would be needed for a total cost of $25,500, total weight of 603kg, and total volume of 0.46m^3 respectively. For the AUV, 27 of the Renogy $LiFePO_4$ batteries would be needed for a total cost of $45,900, total weight of 1,085kg, and total volume of 0.83m^3.

For the battery housing, the PMB2400 Navigation Buoy was selected as it meets the volume and weight requirements for both scenarios [5]. The buoy has 3,000kg of buoyancy and should therefore support the 1,000kg of battery weight. Additionally, it has an internal volume in its base of about 3m^3 which should fit the roughly 0.5 – 0.8m^3 of batteries. The buoy costs $15,400 and has a weight of 1,000kg.

5.1.1.2 End-use Cases

5.1.1.2.1 Offshore Monitoring Station

A potential application for the MADWEC device is powering offshore monitoring systems. For the comparative analysis, a representative oceanographic observation system was developed to estimate the power and energy requirements for this potential use case, and to estimate the total cost of the monitoring system. The representative observation system was inspired by the Ocean Observatories Initiative's (OOI) Central Surface Mooring off the New England coast [**Error! Reference source not found.**].

The representative monitoring platform includes the sensors shown in Table 3. The total power demand for the monitoring platform is estimated to be 41.74W of continuous power, which is the sum of the average power of each sensor. Because the power may fluctuate when data is being collected or stored, a contingency of 20% was added to this power requirement to equal 50W. The total cost of the sensors for this representative system was determined to be $465,120. This total cost is only representative of the sensor costs but does not include any additional hardware or platform buoys that may be required for the operation of the monitoring system.

Table 3: Types of sensors used in our modeled platform including the amount of each type, average typical power consumption, and average cost.

Sensor	Average Power, Single Sensor (W)	Price (2022$)	# of Sensors in Array	Total Average Power (W)
ADCP	0.41	35,349	3	1.23
Anemometer	0.57	12,985	1	0.57
Camera	6.3	43,415	1	6.30
Catalytic/Solid State H_2 Sensor	2.20	1,050	2	4.40
CTD	2.74	13,767	3	8.22
Data Logger & Communications	0.54	3,495	6	3.24
Fluorometer	0.66	14,429	1	0.66
pH Sensor	0.13	22,098	2	0.26
Meteorological Probe	0.12	1,190	2	0.24
Motion Sensor	0.50	1,860	1	0.50
Optical Sensor	2.40	33,435	3	7.20
Optode	0.46	6,536	2	0.92
pCO_2 Sensor	4.00	31,029	2	8.00
	Total	**465,120**	**29**	**41.74**

5.1.1.2.2 Autonomous Underwater Vehicle

Another potential application for the MADWEC is offshore AUV charging. The AUV that was chosen for this analysis is the Remus300, designed and manufactured by Huntington Ingalls Industries (HII) shown in Figure 6. The Remus300 is a commercially available autonomous underwater vehicle (AUV) with a

1.5kWh capacity battery, 10-hour endurance, 6-hour recharge time, and 55km range. This AUV was requested by UMass due to their familiarity with the AUV and its reputable design. It is advertised for applications such as mine detection, search and recovery, rapid environmental assessment, marine archeology, offshore oil and gas, and renewable energy uses.

Figure 6: Figure of the Remus300, 1.5kWh battery capacity configuration. Figure from [7].

NREL obtained a quote for the Remus300 1.5kWh configuration from HII, who manufacturers the AUV. The quote was estimated for $1,038,225 for the AUV, plus another $129,402 for shipboard equipment, $36,000 for O&M training, and $64,332 for an external battery box. A more detailed description of the AUV can be found on the HII website [7].

5.1.1.2.3 Scenario Locations, Ports, and Vessels

Three locations were selected for this analysis, which include a nearshore, offshore, and a high-latitude location. The locations impact the power performance results for the MADWEC and solar buoy, while also impacting costs related to installation, operations, and maintenance for all power supply options. A high-latitude location is used to evaluate the MADWEC power performance compared to a PV solar buoy located in a suboptimal solar resource. Figure 7 shows the nearshore and offshore locations.

The nearshore location is located at coordinates (41.2354° N, 71.0237° W), roughly 17 miles offshore from the Port of New Bedford, Massachusetts. This location is in Massachusetts state waters. It has a bathymetry of 20m [8], an average annual Global Horizontal Index (GHI) of 168.06W/m^2 [9], and an average annual omnidirectional wave power of 4kW/m [10]. The MADWEC requires a bathymetry of at least 100m to be deployed, but as this is only a hypothetical study of cost and power performance, the bathymetry feasibility was ignored for this analysis and cable/mooring lengths were assumed to be at least 100m. Actual locations will need to be further analyzed in the case of real deployment. The vessel assumed to carry out the installation, operations, and maintenance for this location is the research vessel R/V Tioga, owned by the Woods Hole Oceanographic Institution (WHOI). The vessel has a 60ft length, 4,600lb capacity A-frame, 800m winch, and a 400NM range. Its daily rental rates are $15,000 and fuel rates are approximately $400/hr. Its stage location is in Woods Hole, Massachusetts, which is approximately 14NM to the port location [11].

The offshore location is located at coordinates (40.9334° N, 70.7985° W), roughly 48 miles offshore from the port of New Bedford, Massachusetts. This location is in Massachusetts federal waters. It has a bathymetry of 50m [8], an average annual Global Horizontal Index (GHI) of 174.59 W/m^2 [9], and an average annual omnidirectional wave power of 12 kW/m [10]. The MADWEC requires a bathymetry of at least 100m to be deployed, but as this is only a hypothetical study of cost and power performance, the bathymetry feasibility was ignored for this analysis and cable/mooring lengths were assumed to be at least 100m. Actual locations will need to be further analyzed in the case of real deployment. The vessel assumed to carry out the installation, operations, and maintenance for the offshore location is the R/V Tioga, which is owned by the Woods Hole Oceanographic Institution (WHOI). The vessel has a 60ft length, 4,600lb capacity A-frame, 800m winch, and a 400NM range. Its daily rental rate is $15,000/day and fuel rates are approximately $400/hr. The vessel's stage location is at Woods Hole, Massachusetts, which is approximately 14NM to the port location [11]. The nearshore and offshore locations are shown in Figure 7.

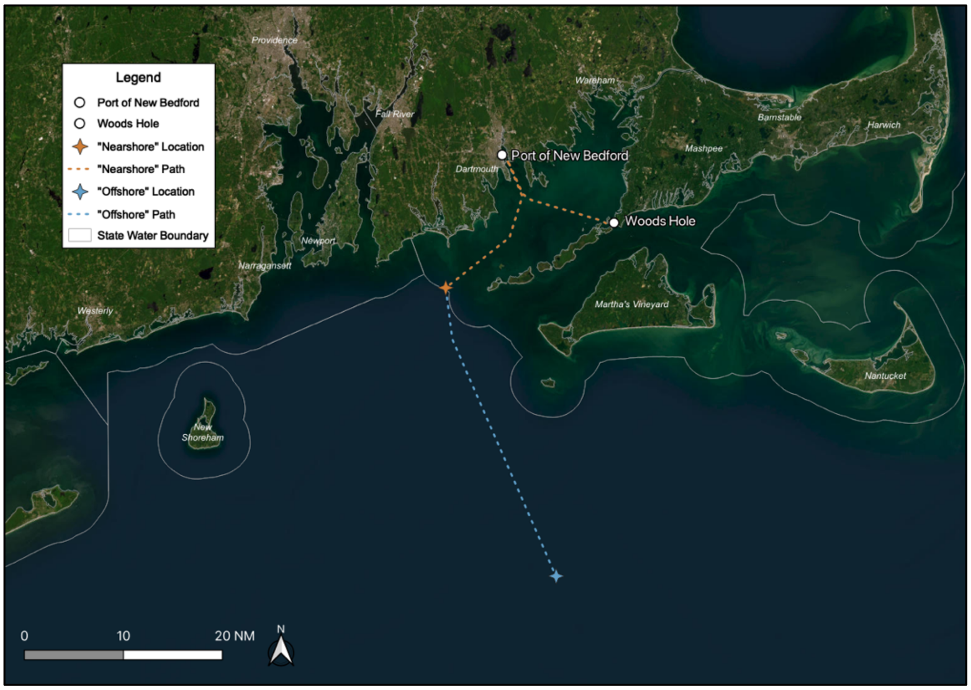

Figure 7: Map of the nearshore and offshore locations, including the typical travel path from the stage and port.

The high-latitude site, shown in Figure 8, is located at coordinates (59.0605° N, 152.0117° W), which is roughly 46 miles offshore from the port in Homer, Alaska. This site is in Alaska state waters, has a depth of 175m [8], an average annual Global Horizontal Index (GHI) of 102.91W/m^2 [9], and an average annual omnidirectional wave power of 13kW/m [10]. The research vessel assumed to carry out the installation, operations, and maintenance for this location is the Tiglax, owned by the U.S. Fish and Wildlife Service (USFWS) [12, 13]. The vessel's daily rental rate is $11,375/day and fuel rates are approximately $400/hr. For the high-latitude scenario, the stage location is in Homer, Alaska, which is also the port closest to the power generation site.

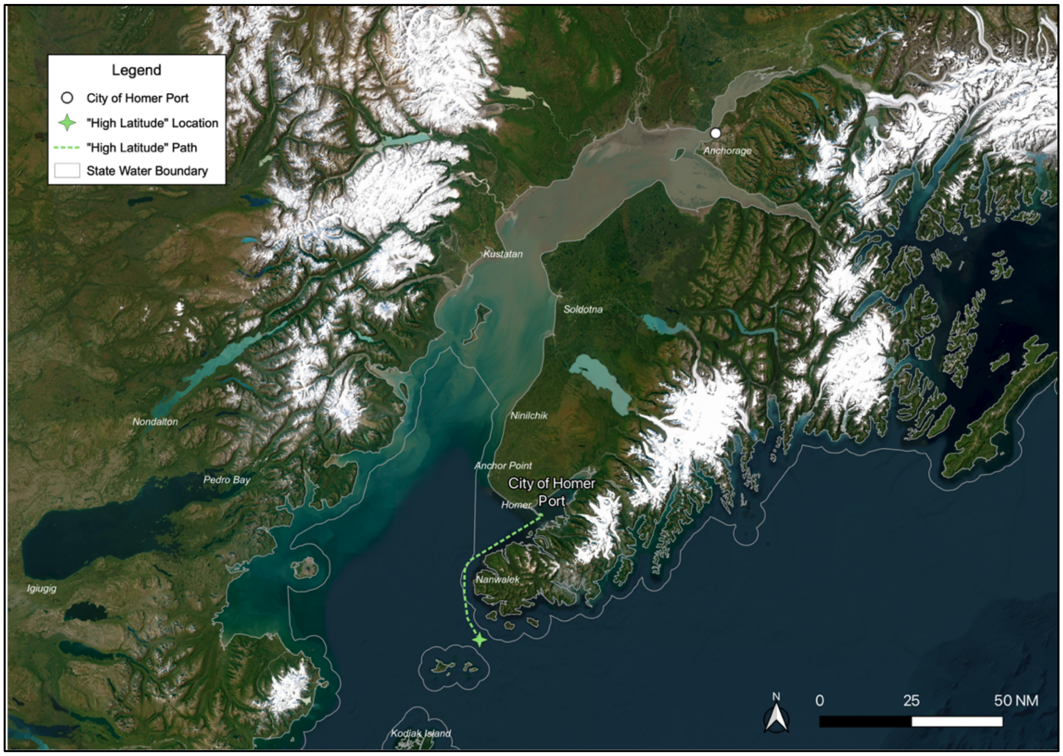

Figure 8: Map of the "High Latitude" location, including the typical travel path from the Stage and Port to the locations.

A summary of the three deployment site locations is provided in Table 4.

Table 4: Summary of the three location scenarios

	Nearshore	Offshore	High latitude
Coordinates	41.2354° N, 71.0237° W	40.9334° N, 70.7985° W	59.0605° N, 152.0117° W
Port Location	New Bedford, MA	New Bedford, MA	Port in Homer, AK
Distance Offshore	17	48	46
Vessel Supplier	WHOI	WHOI	USFWS
Avg. Annual GHI (W/m2)	168	174	102
Avg. Annual Omnidirectional Wave Power (kW/m)	4	12	13

5.1.2 TEA Model Design

The techno-economic model, created in Microsoft Excel, is organized by power source, where each power source has sheets dedicated to a specific analysis (i.e., CapEx, O&M, etc.). In total there are 12 sheets used for the analyses. The model also has a "README" sheet with instructions on how to use the model, and a "Results" sheet with visualizations and graphics of the model results. The model gives analysis results for the current MADWEC design but can be easily revised and updated as the MADWEC design changes.

5.1.2.1 Capital Expenditures

The capital expenditures (CapEx) cost breakdown used for the analysis was adapted from NREL's Marine Energy Cost Breakdown Structure (CBS) [14]. This CBS describes the project costs of a marine energy system which includes three main cost centers: the marine energy converter, the balance of system (BOS), and financials. The CBS shown in Table 5 was used for all three power supply options. For other power sources like the solar buoy and batteries, the CBS is modified to accommodate the technology while making and effort to keep cost assumptions the same where possible to promote apple to apple comparison. While NREL's CBS includes financial costs, they are omitted in this analysis because it is assumed that the systems will be bought outright without financing. Additionally, the cost of components that are identical for all scenarios are omitted in CapEx estimates.

Table 5: The Cost Breakdown used for the CapEx.

CBS Level & Category Description
1 Capital Expenditures (CapEx) - All installed costs incurred prior to commercial operations date (COD).
1.1 Marine Energy Converter (MEC) - Converts kinetic energy from water into three phase alternating current (AC) electrical energy.
1.1.1 Structural Assembly - Primary energy capture (e.g. float paddle, turbine, flap, etc.) and supporting structural components.
1.1.2 Power Take-Off System (PTO) - Power Take-Off System is comprised of a drivetrain (converts the energy captured by the device into mechanical power), a generator (converts mechanical power into electrical power), short term storage, and power electronics.
1.1.3 Mooring, Foundation, and Sub-Structure - All elements of the marine energy converter mooring system and/or foundation
1.2 Balance of System (BOS)
1.2.1 Development - All activities from project inception to financial close, where financial close is the date when project and financing agreements have been signed and all the required conditions have been met.
1.2.2 Engineering and Management - Engineering and management activities from financial close through commercial operation date (COD).
1.2.3 Electrical Infrastructure - All electrical infrastructure to collect power from generators and deliver to the grid.
1.2.4 Plant Commissioning - Cost incurred by owner or prime contractor to test and commission the integrated power plant.
1.2.5 Site Access, Port & Staging - Activities and physical aspects of a staging port. Elements needed to support the delivery, storage, handling, and deployment of marine energy converter (MEC) components.
1.2.6 Assembly & Installation - Assembly and installation activities conducted at the staging port and at the project site. Assume financial costs related to warranties, contractor insurance, Selling, General & Administrative (SG&A), profit margin, etc., are loaded in day rates for vessels, labor, and equipment.
1.2.7 Other Infrastructure - Other capital investments made by the project company prior to commercial operation date (COD).

In most cases, the cost of system components for each power source were determined by gathering cost quotes from manufacturers, otherwise values based on engineering judgment are assumed. Most of the BOS cost estimates are based off existing NREL cost models. These values may not reflect actual BOS costs with a high level of certainty required for planning an actual deployment and should be updated as new information becomes available.

Installation costs are a key cost contributor to the CapEx BOS cost category and represent the cost of installing each power source for each of the end-use case at the three locations. Installation costs are primarily comprised of labor, vessel, and fuel costs but also include other one-time costs such as permitting and leasing fees, port fees, and shipping costs. The required inputs for estimating installation costs include information about the location, vessels, estimated installation time duration, labor rates, shipping costs, and other one-time costs. The location information defines the port locations, the offshore deployment locations, the distances to and from the stages, which influence the time and cost of vessel mobilization. Similarly, the cruising boat speed, fuel costs, and vessel rental rates determine how long the vessel is mobilized and how much it will cost to rent during that period of time.

One-time installation costs include port docking fees, permitting, and leasing fees. Port docking fees for the Port of Homer were estimated to be $258 and the same cost is assumed for the Port of New Bedford. The permitting and leasing fees are dependent on the location of the offshore energy project, and whether the location is in state or federal waters. Table 6 below are general lists of permits that may be applicable to offshore energy projects in the three locations chosen for this analysis. It is likely that some permits were missed or looked over in this analysis, so these lists should not be taken as a guideline or "roadmap" for applying for offshore renewable energy projects. They should only be used as a reference for estimating permitting and leasing costs. It should be noted that while the "high latitude" location is in Alaska federal waters, the cost of permitting in state waters were used in this analysis.

Table 6: Summary of permits that may be required for an offshore energy project at each of the three scenario locations. This list may not be exhaustive and should not be used as a guidance for obtaining permits.

Agency	Permit	MA State Waters	MA Federal Waters	AK State Waters
USACE (New England or Alaska District)	General Permit	$0	$0	$0
	Pre-construction Notice	$0	$0	$0
USFWS	ESA Section 7 Consultation	$0	$0	$0
NOAA	ESA Section 7 Consultation	$0	$0	$0
NOAA	Essential Fish Habitat Consultation	$0	$0	$0
US Coast Guard	Private Aid to Navigation Permit	$0	$0	$0
MA Tribal Historic Preservation Office	Tribal Consultation	$0	$0	n/a
MA State Historic Preservation Office	Project Notification Form	$7.25	$7.25	n/a
Alaska State Historic Preservation Office	Notification Form	n/a	n/a	$0
MA Coastal Zone Management Office	BRP Minor Fill and Excavation Projects Form	$95	$95	n/a
Town Harbor master	Section 10A permit (if applicable in town)	$1/ft^2	n/a	n/a
MA DEP	Chapter 91 Permit test project application	$1,165	$1,165	n/a
AKADF&G	Title 16 Fish Habitat Permit	n/a	n/a	$0

Agency	Permit	MA State Waters	MA Federal Waters	AK State Waters
AKDNR	Temporary Water Use Authorization	n/a	n/a	$450
	Submerged Land Lease	n/a	n/a	$1,200
	Total	**$2,267**	**$1,267**	**$1,650**

Shipping costs are included for various project components to the "high latitude" location only as it was found that shipping costs for the Massachusetts deployment site are negligible. The batteries had free shipping and the MADWEC would be constructed nearby. However, the costs to ship the MADWEC, AUV, batteries, and the buoy housing the batteries for the battery swap scenario to Alaska were substantial. A summary of shipping costs assumed in the model for the "high latitude" location are shown in Table 7.

Table 7: Summary of shipping costs to High Latitude location.

Item	Total Shipping Cost to High Latitude Location
MADWEC	$6,854
Solar Buoy	$5,799
Batteries (Monitoring scenario)	$6,794
Batteries (AUV scenario)	$7,065
Monitoring System	$6,794
AUV	$724

Labor costs are estimated by assuming install duration (time) for each component and multiplied by the number of workers and assumed labor rate. Similarly, vessel costs are estimated by multiplying the vessel rental rate with the install durations. Vessel fuel rates are estimated using the distance traveled from the staging location to the port and offshore location. The total installation cost for each scenario also includes an operational contingency factor of 10% (10% of installation cost) and any one-time costs (shipping and permitting). Table 8 shows an example of how operational costs are estimated in the TEA model.

Table 8: Example of how operational costs are estimated for the nearshore remote monitoring case.

Operational Detail	Hours	Vessel Cost ($)	Labor Cost ($)	Operation Subtotal ($)
Vessel mobilization from stage 1 to port 1	0.78	$1,283	$64	$1,347
Load remote monitoring onto vessel	1.00	$1,650	$218	$1,868
Transit from port 1 to nearshore	0.94	$1,558	$206	$1,764
Install remote monitoring station (onsite)	5.00	$8,250	$1,089	$9,339
Standby for testing and commissioning	1.00	$1,650	$218	$1,868
Transit from nearshore to port 1	0.94	$1,558	$206	$1,764
Vessel demobilization from port 1 to stage 1	0.78	$1,283	$64	$1,347
Operational contingency	-	-	-	$1,930
	Remote Monitoring Installation Total			***$21,227***

5.1.2.2 Operation and Maintenance

Operation and maintenance (O&M) costs are estimated using a similar method as installations costs. OpEx is driven by labor, vessel, and fuel costs. For the O&M analysis a "frequency of maintenance" is assumed which defines the number of interventions required for the deployment duration. Maintenance involves onshore and offshore maintenance activities. Offshore maintenance encompasses minor occurrences that can be addressed offshore at the deployment site. Onshore maintenance requires the device to be removed from the deployment site and brought back to land to be addressed. The analysis does not take into consideration power generation lost during either of these occurrences.

The analysis assumes an overlap in the frequency of maintenance trips required for the power source and for the end-use case or load. For example, If the MADWEC requires 4 minor offshore maintenance repairs, and the AUV requires 5, then it is assumed that each time the AUV is addressed, the MADWEC will be addressed too. So, the maximum of the two values is assumed to be the frequency, not the sum. The actual frequency of occurrences for minor, offshore trips for the MADWEC + AUV scenario will be 5, not 9. This assumption is made to reduce the number of trips made for maintenance to save time and money. However, there is no overlap assumed between offshore maintenances and onshore maintenances; these two frequencies occur independently. Similar inputs used in the installation analysis are required for the O&M analysis, including the distances to and from the stage, port, and offshore locations, as well as labor, vessel, and the time required to address the maintenance issues. These inputs impact the total time and costs required for O&M.

5.1.2.3 Power Performance

The power performance analysis estimates the MADWEC and solar buoy power performance at each of the three resource locations. Details on how the battery's energy capacities were determined are found in Section 6.1.1.1.3.

The average annual energy production for the MADWEC is estimated using the wave energy converter's (WEC) power matrix and the resource joint probability distribution matrix (JPD) for the resource location. The power matrix for the MADWEC used in this analysis was generated in a previous TEAMER project between NREL and UMass Dartmouth, using the Wave Energy Converter Simulator (WEC-Sim) [2]. The power matrix represents the mean instantaneous power generated by the WEC in each sea state. The resource JPDs used in this analysis represents the annual average probabilities of sea state occurrences at each location, which were generated using time-series sea state data from the HINDCAST dataset, published by the National Renewable Energy Laboratory [15, 16]. As further development of the MADWEC occurs and new power performance simulations are run, the power matrix can be edited in the TEA model. However, the wave energy converter's power matrix and the resource's JPD are required to have the same sea state binning.

The theoretical annual average energy production (TAEP) is calculated using Equation 1:

$$TAEP = \left(\sum PM * JPD\right) * \frac{8760hr}{yr} \quad \textbf{(1)}$$

where:

TAEP [Wh/yr] = theoretical annual energy production (does not include availability or cable losses)

PM [W] = power matrix of size (mn)

$$PM = \begin{pmatrix} pm_{11} & \cdots & pm_{1n} \\ \vdots & \ddots & \vdots \\ pm_{m1} & \cdots & pm_{mn} \end{pmatrix}$$

JPD [n/a] = joint probability distribution matrix of size (mn)

$$JPD = \begin{pmatrix} jpd_{11} & \cdots & jpd_{1n} \\ \vdots & \ddots & \vdots \\ jpd_{m1} & \cdots & jpd_{mn} \end{pmatrix}$$

The product of the two matrices gives the theoretical annual average instantaneous power of the WEC at a given resource location. When this instantaneous power is multiplied by the number of hours in the year (8,760 hours), it gives the TAEP at that location.

The average annual energy production of the solar buoy can be calculated using the solar panel's total area, the panel's solar yield (or efficiency), the resource's solar irradiance, and the performance ratio of the system. The solar panel's area was calculated from information given from the solar buoy manufacturer, OSIL [3]. The manufacturer reported that there are 43 individual solar cells in the panels, measuring 0.016m^2 each, for a total of 0.687m^2 per panel. The solar panels are rated at 160 Watts. The solar yield (or efficiency) of the panels, which resulted in 0.233, can be calculated with Equation 2:

$$r = \frac{P}{A} * H_{STC} \quad \textbf{(2)}$$

where:

r [n/a] = solar panel efficiency
P [kW] = rated power
A [m^2] = solar panel area
H_{STC} [kW/m^2] = irradiance at Standard Testing Conditions = 1kW/m^2

The global horizontal irradiance (GHI) dataset is used for the PV solar performance estimates. GHI data is readily available in hourly timeseries across the entire United States through the National Solar Radiation Database (NSRDB) [9]. GHI measures the amount of solar irradiance that reaches a surface horizontal to the surface of the Earth [17]. While GHI may not be the most representative data to use because the solar panels on the buoy will be tilted and constantly moving, this limitation is accounted for in the performance ratio. The average hourly GHI for each month of the year is estimated using NSRDB 2022 Typical Meteorological Year GHI data. The performance ratio describes the relationship between the actual and theoretical energy outputs of the solar system. The factors that typically affect the performance ratio include electrical, thermal, and shading losses. Typical performance ratios fall between 0.5-0.75. For this analysis, a performance ratio of 0.5 was assumed since half of the solar panels on the buoy will be facing in the opposite direction of the sun, and to account for the tilt of the panels when using GHI data. The power production of the solar buoy is estimated with Equation 3 [18, 19]:

$$P = A * r * GHI * PR \tag{3}$$

where:

P [kW] = Power
A [m^2] = total solar panel area
r [n/a] = solar panel efficiency
GHI [kW/m^2] = Global Horizontal Irradiance
PR = performance ratio

Equation 3 is used to estimate the power produced at each hour during a specific month of the year. The estimated daily energy production for each month is estimated by taking the sum of the hourly power generation. Then, the daily energy production is multiplied by the number of days in each month to calculate the monthly energy production. Next, the monthly energy production is summed to estimate the average annual energy production. Figure 9 shows an example of the solar buoy power performance calculation in the TEA model.

Month of Year	Hour of Day: 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Daily Energy Production (kWh)	Days per Month	Monthly Energy Production (kWh)
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.08	0.10	0.11	0.11	0.09	0.06	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.62	31	19.10
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.06	0.09	0.13	0.14	0.13	0.12	0.09	0.06	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.84	28	23.62
3	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.06	0.10	0.15	0.17	0.17	0.16	0.16	0.14	0.09	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	1.28	31	39.66
4	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.09	0.13	0.17	0.21	0.22	0.20	0.18	0.14	0.09	0.06	0.02	0.00	0.00	0.00	0.00	0.00	0.00	1.56	30	46.93
5	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.11	0.15	0.19	0.22	0.22	0.22	0.19	0.16	0.13	0.08	0.04	0.01	0.00	0.00	0.00	0.00	0.00	1.82	31	56.30
6	0.00	0.00	0.00	0.00	0.00	0.04	0.08	0.11	0.16	0.19	0.22	0.24	0.24	0.21	0.18	0.15	0.10	0.05	0.02	0.00	0.00	0.00	0.00	0.00	1.98	30	59.49
7	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.12	0.16	0.20	0.23	0.23	0.24	0.23	0.20	0.15	0.10	0.05	0.02	0.00	0.00	0.00	0.00	0.00	2.02	31	62.66
8	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.10	0.15	0.19	0.22	0.23	0.23	0.22	0.17	0.14	0.08	0.03	0.00	0.00	0.00	0.00	0.00	0.00	1.82	31	56.57
9	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.12	0.16	0.18	0.20	0.19	0.17	0.14	0.10	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	1.43	30	42.75
10	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.09	0.13	0.15	0.16	0.15	0.13	0.10	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.04	31	32.34
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.06	0.09	0.11	0.12	0.11	0.09	0.06	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.68	30	20.39
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.07	0.09	0.08	0.07	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.47	31	14.58
																									Annual Energy Production (kWh)		***474.41***

Figure 9: Image of the solar power performance calculation in the TEA model.

5.1.3 Power Performance Results

5.1.3.1 MADWEC

A single MADWEC device at the nearshore, offshore, and high latitude locations produces annual energy productions of 1.04kWh, 2.46kWh, and 1.52kWh, respectively. A summary of TAEP estimates for each location is shown in Table 9. A single MADWEC device can produce a maximum power output of 2.5W using the current power matrix, but the results show that the device is sensitive to changes in the resource location.

Table 9: Average theoretical annual energy production of a single MADWEC device.

Theoretical Annual Energy Production	
Location	TAEP (kWh)
Nearshore	1.04
Offshore	2.46
High Latitude	1.52

5.1.3.2 Solar Buoy

Using a single 160-Watt solar panel described on the solar buoy, the hourly GHI data from the NSRDB [9], and Equation 3 from Section 6.1.2.3, the annual energy production of the single solar panel was estimated to be 118.6 kWh nearshore, 121.29 kWh offshore, and 71.67 kWh at the high latitude location as shown in Table 10**Error! Reference source not found.**. The far offshore location produces just slightly more solar energy than the nearshore location, but they both produced significantly more than the high latitude location. The reason that the AEP was calculated for a single panel and not a "single device", is because the solar buoys manufactured by OSIL are not a "one-size-fits-all" buoy and are designed with a various number of panels based on the specific needs of the location and end-use. Therefore, there is no "typical" buoy for this analysis, and the buoys for each scenario differ slightly by size and price.

Table 10: Annual energy production of a single solar buoy in a typical meteorological year.

Theoretical Annual Energy Production	
Location	AEP (kWh)
Nearshore	118.6
Far Offshore	121.3
High Latitude	71.7

5.1.3.3 *Battery Swap*

Using just a single battery with a 200Ah energy capacity, the annual energy capacity of the single battery system was estimated to be 30.7 kWh per year as shown in Table 11. This estimate assumes that the battery is immediately replaced when it no longer has any charge. In this analysis, it is assumed that the batteries last two months from a full charge and are replaced six times per year.

Table 11: Annual energy storage for the battery systems.

Energy Storage	
Scenario	Energy Storage (kWh)
Single battery	30.7

5.1.3.4 *Total Power Generation*

The total energy required for the offshore monitoring is 432 kWh per year, and for the AUV charging is 810 kWh per year as shown in Table 12**Error! Reference source not found.**. Based on these estimates, none of the power generation scenarios can produce the power needed to charge the end-use cases throughout the year with just a single device (or single solar panel). Therefore, an array with various numbers of devices for each scenario is necessary to meet the annual energy demands of the end-uses.

Table 12: End-use energy demands per year.

End-Use Energy Demand	
End-use	Energy Storage (kWh)
Offshore Monitoring	432
AUV	810

For the MADWEC to meet 100% of the energy needs of the monitoring system, an array of 415 devices is required for the nearshore location , 176 devices for the offshore location, and 285 devices at the high latitude location would be required. This would put the total AEP for the MADWEC array between 432-433 kWh per year, exactly matching the needs of the offshore monitoring system. Similarly, the number of devices needed for the AUV charging scenario would be 777 devices nearshore, 329 devices far offshore, and 534 devices at the high latitude locations. These arrays would also produce the exact energy needs of the AUV system, between 810-811 kWh per year. The number of devices needed, and the total energy produced by the MADWEC arrays are shown below in Table 13. Arrays of this size are impractical, but the model can be updated as the MADWEC power performance improves with future research and development.

Table 13: Number of devices in the MADWEC arrays, and their total annual energy production estimates.

MADWEC (*array*)		
Scenario	**No. of Devices**	**TAEP (kWh)**
AUV, Nearshore	777	810.63
AUV, Far Offshore	329	810.49
AUV, High Latitude	534	810.69
Remote Monitoring, Nearshore	415	432.96
Remote Monitoring, Far Offshore	176	433.57
Remote Monitoring, High Latitude	285	432.67

For the solar buoy, using a single device with just four 160-Watt panels fulfills the needs of the offshore monitoring energy requirements at both the nearshore and offshore locations, but not for the high latitude location. Table 14 shows the number of solar buoys required for each scenario and the respective annual energy production estimate.

Table 14: Number of devices in the Solar Buoy arrays, and their total annual energy production estimates.

Solar Buoy (*array*)		
Scenario	**No. of Devices**	**AEP (kWh)**
AUV, Nearshore	Two 4-paneled buoys	948.41
AUV, Far Offshore	Two 4-paneled buoys	970.35
AUV, High Latitude	Three 4-paneled buoys	860.04
Remote Monitoring, Nearshore	One 4-paneled buoy	474.41
Remote Monitoring, Far Offshore	One 4-paneled buoy	485.17
Remote Monitoring, High Latitude	One 6-paneled buoy	430.02

For the battery power supply scenario, the energy capacity of a single battery is multiplied by the number of batteries needed to reach 100% of the energy demands of the remote monitoring system and AUV charging system. Table 15 shows the number of batteries required for each scenario and the estimated energy capacity each system provides.

Table 15: Number of batteries in the Battery arrays, and their total theoretical annual energy production estimates.

Battery System (*array*)		
Scenario	**No. of Devices**	**Energy (kWh)**
AUV Charging	54	829
Remote Monitoring	30	461

A total of 15 batteries are needed to provide 461 kWh of energy to the remote monitoring system, and a total of 27 batteries are needed to provide 829 kWh of energy to the AUV charging system. Since it is assumed that the batteries must be swapped for charging, the total number of batteries required is doubled, as one set of batteries is being used and the other is a backup.

5.1.4 Economic Results

The economic results report CapEx and O&M costs for the 18 scenarios. The CapEx include all installed costs incurred prior to commercial operations date (COD). The O&M cost results represent all project costs incurred after COD for the duration of project life.

5.1.4.1 Capital Expenditures

CapEx is comprised of three main cost centers: the device cost of the marine energy converter (or other power source), balance of systems (BOS) costs, and financial costs. For this analysis all financial related costs are assumed to be zero because it is assumed the CapEx will not be financed.

5.1.4.1.1 Device costs

The estimated MADWEC device cost is $37,942. The MADWEC component costs breakdown is shown in Table 16. Most of the component cost estimates are obtained from component manufacturer's online catalogues or quotes, while others are based on estimates produced in previous cost modeling work by NREL. The solar buoy device cost totaled $120,621 shown in Table 17. The total device cost of the battery swapping system for the monitoring station scenario is $23,376, as shown in Table 18.

Table 16: MADWEC system costs.

Device Costs	Cost	Notes
Structural Assembly	$28,525	Estimated using the mass of the system and cost curves for structural steel
Power Take Off-System	$3,141	Estimated using component manufacturer cost catalogs
Mooring, Foundation, & Substructure	$6,276	Estimated from existing NREL models and previous projects
Total	**$37,942**	

Table 17: Solar buoy system costs.

Device Cost	Cost	Notes
OSIL Albatross Metocean Buoy	$113,760	Cost quote derived from OSIL
Data Web Hosting	$585	Cost quote derived from OSIL
Mooring, Foundation, & Substructure	$6,276	Estimated from existing NREL models and previous projects
Total	**$120,621**	

Table 18: Battery system costs.

Device Cost	Cost	Notes
Renogy 24V 200Ah Lithium Iron Phosphate	$1,700	Cost quote derived from Renogy for a single battery
Pharos Marine Automatic Power Platform Buoy	$15,400	Cost quote derived from Pharos Marine Automatic Power
Mooring, Foundation, & Substructure	$6,276	Estimated from existing NREL cost models and previous projects
Total	**$23,376**	

5.1.4.1.2 Balance of system costs

BOS costs are estimated for each scenario and vary greatly due to differences between the scenarios. However, the BOS costs shown in Table 19 were assumed for each power generation system since they are all roughly the same size and would have similar BOS requirements. These costs estimates were all determined based on existing NREL cost models and should be used as placeholders until more information about the project is determined. Better estimates can be made if the cost of labor (engineers, researchers, geologists, etc.) and the time required to perform these tasks are known.

Table 19: Balance of system costs estimates used for all three power generation scenarios.

BOS	Cost	Notes
Development	$1,916,000	Estimate derived from existing NREL cost models and previous projects
Engineering & Management	$958,000	Assuming half the cost (and time) of development
Electrical Infrastructure	$1,628	Riser cable cost estimate derived from existing NREL cost model
Plant Commissioning	$0	n/a
Other Infrastructure	$0	n/a
Total	**$2,882,108**	

5.1.4.1.3 Installation costs

Installation costs includes the costs of installing the system offshore, and includes costs of location-dependent parameters, such as permitting and leasing fees, labor rates, vessel rates, port fees, and shipping costs. Labor rates for engineers, technicians, vessel captains and crewmembers ranged between $41-45 per hour in the Northeast United Sates and ranged between $39-46 per hour in Alaska. These values were multiplied by estimated installation times to calculate total labor costs. The vessel used for the Massachusetts locations had an hourly rental rate of $1,250 and the Alaskan vessel had an hourly rental rate of $948. The total vessel transit cost is estimated using the hourly rental rate, the vessel's average cruising speed, distance traveled, and fuel costs. A fuel costs of $400 per hour is assumed. In addition to the installation costs, the shipping costs were also included in this analysis. The installation analysis results are included in CapEx estimates. Table 20 summarizes the total Installation cost estimated for each scenario.

Table 20: Total installation costs for each scenario by location.

	Total Installation Costs		
Scenario	**Nearshore**	**Far Offshore**	**High Latitude**
MADWEC	$20,670	$26,747	$34,797
Solar Buoy	$18,616	$30,492	$31,296
Battery Swap	$13,479	$19,556	$21,193

5.1.4.1.4 End-use case costs

The system cost for the two end-use cases were estimated using quotes from manufacturers. The total estimated cost of the sensors used for the offshore monitoring system is $465,120 (see Section

6.1.1.2.1). The total estimated cost of the AUV system is $1,267,959 (see Section 6.1.1.2.2). These costs are added to the final CapEx estimates. The total CapEx for each scenario (for a single device) is summarized in Table 21.

Table 21: Total CapEx costs for each scenario, independent of location.

Scenario	Total CapEx 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

5.1.4.2 *Operation and Maintenance Costs*

The results of the O&M analysis (for a single device) are shown in Table 22. Based on the results, the battery swapping scenarios have a higher O&M cost than the other power supply options due to the increased frequency of maintenance. The offshore location has the highest O&M costs for all scenarios.

Table 22: Total O&M costs for each scenario by location.

Scenario	Total O&M Costs 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

5.1.4.3 *Array Costs*

To estimate the cost of an array, learning rates are applied to the first-of-a-kind unit cost to discount the next-of-a-kind (n^{th}) unit cost. For example, the cost of a single MADWEC device was estimated to be $37,942, but by applying a learning rate of 0.08, the n^{th} unit cost for a 415-unit array (for the nearshore remote monitoring system) is $18,375. Learning rate (r-value) of 8% was applied to MADWEC device costs and 6% learning was applied to electrical infrastructure costs for all MADWEC scenarios. The CapEx for multi-unit arrays is shown in Table 23. Learning rates are not applied to the solar buoy or the battery device because of the limited number of devices required in the array.

Table 23: Total Capex for multi-unit arrays.

Scenario	CapEx for 100% energy requirement fulfillment (Array) 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

5.2 Lesson Learned and Test Plan Deviation

In this work there have been few deviations from the original test plan. The location of one of the scenarios deviated slightly, with the offshore location originally being planned for more than 100 miles offshore. After review of the wave resource in the area and considering some of the islands surrounding the Massachusetts coastline, the offshore location ended up only being 48 miles offshore. This location was agreed upon by UMass Dartmouth and NREL. Another aspect that changed was the format of the model. It was originally stated that the model would be developed in MATLAB and Excel, but UMass and NREL determined it would be best to develop the model in Excel due to being a user-friendly tool that is easily revised.

6 Conclusions and Recommendations

The results show that the MADWEC can produce a total of 1.04 kWh at the nearshore location, 2.46 kWh at the far offshore location, and 1.52 kWh 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 at the nearshore location, 121 kWh at the far offshore location, and 71 kWh 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 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.

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