RCAM's Path: Players, Policies, and Processes Guide

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UM SEAS and RCAM Technologies Master of Science Capstone Partnership

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RECOMMENDED PATH

Pursuing various pilot projects such as through NELHA at HOST Park, HI is not only the immediate path of least resistance but also a necessary first step to prove commercial viability for M-PHES. We recommend continuing to interface closely with our NELHA contact, Alex Leonard, and await the results of the March 6 funding proposal (see “Players” section for additional guidance). However, there are still many seeds of opportunity RCAM can plant in the commercial market even before concluding a successful pilot project.

Action 1: Engage Immediately with Offshore Wind Lessees

Concurrently with a pilot underway, RCAM should connect with Conventional Lease winners (decided by BOEM), especially those who won during the December 2022 California auction. Given the constrained timeframe and fact that RCAM cannot be a Conventional Lease holder (see “Processes” section), RCAM should engage now with the biggest companies in the industry.

In the case of California, involved parties are three months into the pre-site assessment plan (SAP) planning and meeting process. Because this is still well before the actual site assessment period and the Construction and Operation Plans (COP) submittal period, there is still time to try to persuade one of the five lessees to include RCAM’s storage device in their long-term plans. Even if such a relationship couldn’t include a full-scale demonstration of the device due to the resource limitations, risks, and logistics of today, perhaps a developer would include a contingent RCAM pilot demonstration within their COP and lease area instead. The contingency of the pilot’s success could forge a lasting relationship at future sites leased by the developer, or perhaps BOEM would allow for additional construction during the operations timeframe (~20+ years) solely to install new commercial storage spheres.

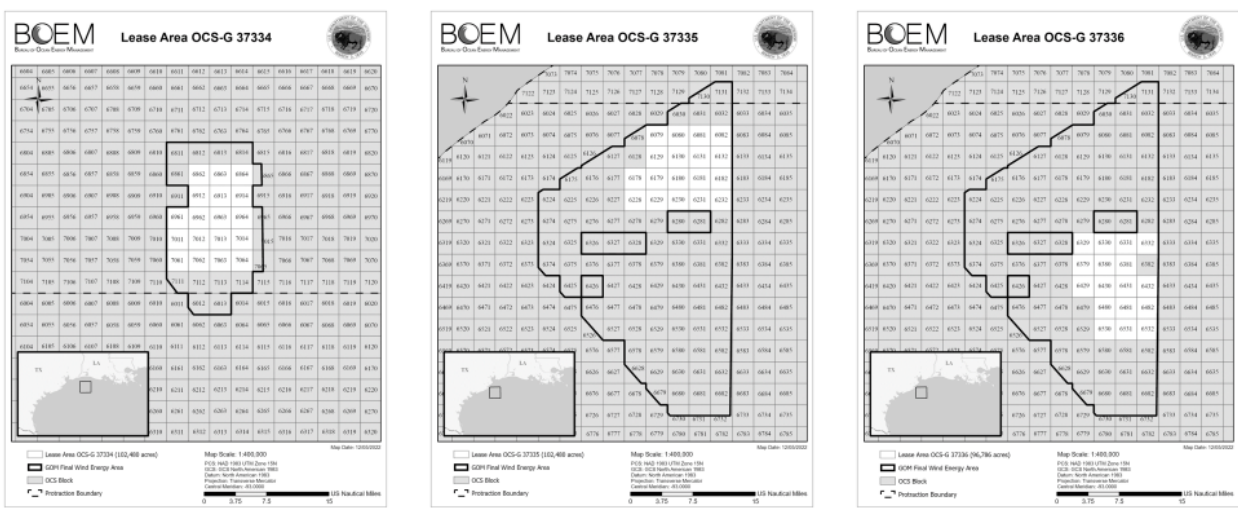
The further along in BOEM’s project timeline we progress (Figure 7), the lower the likelihood for RCAM to be included. This becomes especially true once the COP is submitted and subsequently approved. It would be very undesirable from a lessee’s perspective to modify their COP after the fact and reopen the approval process with BOEM due to the construction delays and additional due diligence this would trigger. Therefore, RCAM needs to be formally written into any initial COP. Indeed, BOEM representatives suggested that RCAM attach itself to a wind development lease and be embedded in that project’s COP as a more efficient use of the lease.

The five California lessees are RWE Offshore Wind Holdings LLC, California North Floating LLC, Equinor Wind US LLC, Central California Offshore Wind LLC, and Invenergy California Offshore LLC. The “Offshore Wind Developers” portion of the “Players” section includes a synopsis of all lessees and their parent companies. Casting a wide outreach net for brand exposure and exploration of potential developer interest is the best course of action. Where RCAM does not have an existing point of contact or relationships, cold contact is still worthwhile, such as an online contact form from a developer's website.[1]

This type of industry engagement could also have regulatory benefits. The lack of precedent for M-PHES technology and absence of any comparable product in the market means RCAM is operating in uncharted waters ahead of the very regulatory frameworks meant to regulate it. Therefore, RCAM must be vocal advocates in spurring regulatory frameworks to evolve and expand their scope alongside evolving technology. This starts by being more visible at every stage of the offshore wind leasing process, especially during public comment periods. Likewise, RCAM should continue to attend industry conferences and meet with localities and accelerators.

Announced in February 2023[2] and as of this writing, BOEM is in the public commentary phase of its first-ever offshore wind lease sale in the Gulf of Mexico: two WEAs comprising three leasable areas totaling 1,221.12 km^2, which are shown below in Figure 1.

Figure 1
Gulf of Mexico Wind Energy Areas[3]



Though depths within the WEAs support the development of fixed bottom turbines and are not deep enough for optimal storage operation, depths just outside of the WEAs appear suited for

[1] This is an example of an online contact form: RWE's Renewables Team, https://www.rwe.com/en/contact-services/contact-form/?c=caae473e5b784c86b02c9b1d3de783c8.
[2] "Interior Department Proposes First-Ever Offshore Wind Sale in Gulf of Mexico." *U.S. Department of the Interior*, 22 Feb. 2023. www.doi.gov/pressreleases/interior-department-proposes-first-ever-offshore-wind-sale-gulf-mexico
[3] "Gulf of Mexico Activities." *Bureau of Ocean Energy Management*, www.boem.gov/renewable-energy/state-activities/gulf-mexico-activities

RCAM's device. As a full geospatial and regulatory analysis of the Gulf market was not a part of the project scope, this is only a hypothesis and further investigation in this region is needed. Below are one topographic and two bathymetric maps of the WEAs (Figures 2-4).

Figure 2

Gulf of Mexico Bathymetry in Relation to WEAs, Version 1 (Author: Eamon Espey)

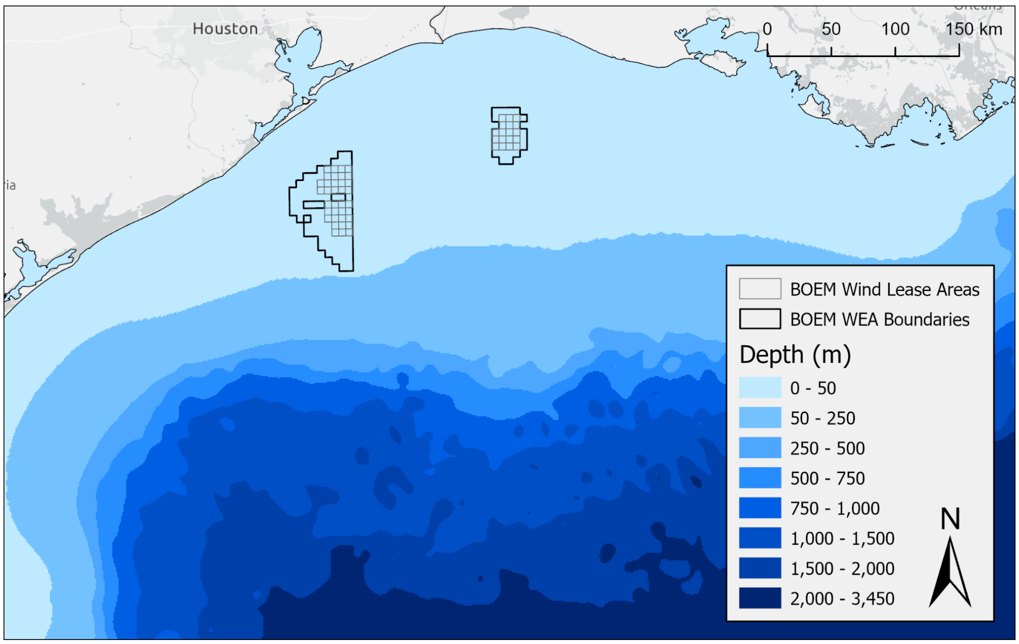


Figure 3

Gulf of Mexico Bathymetry in Relation to WEAs, Version 2 (Author: Eamon Espey)

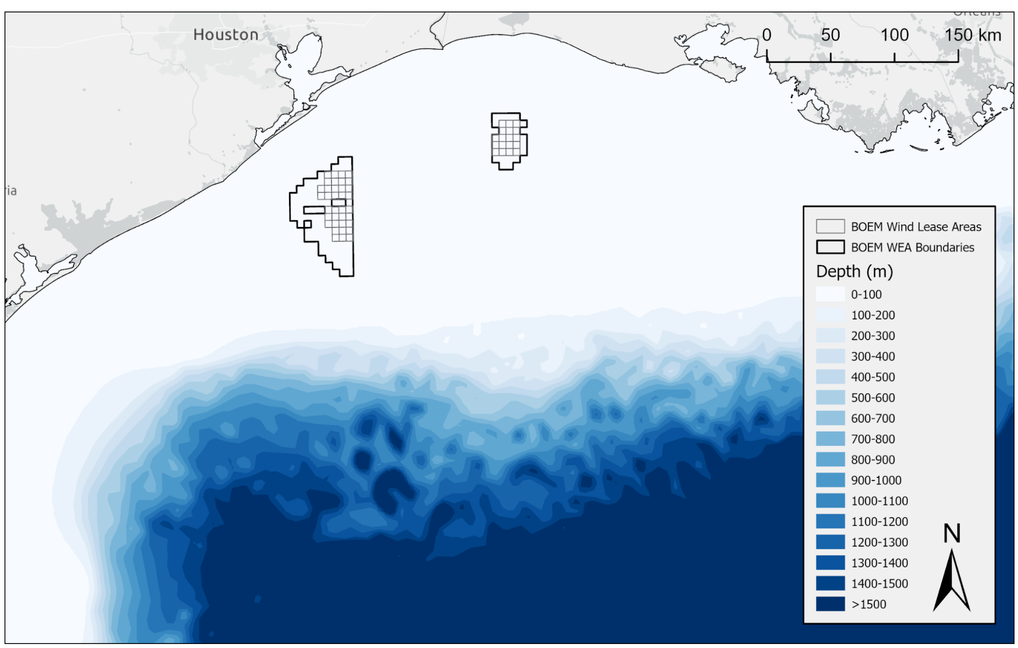
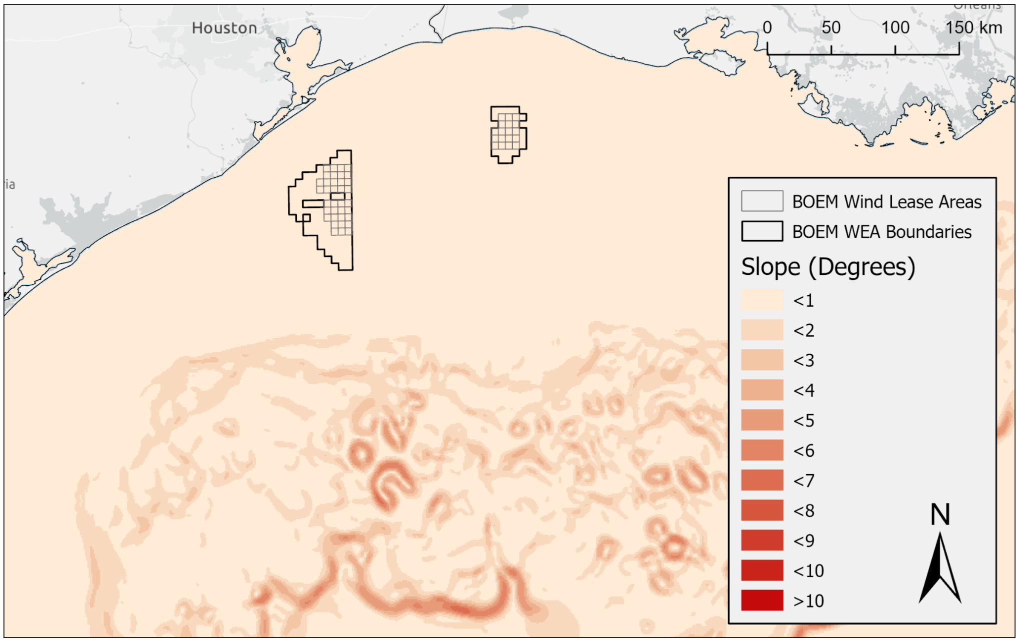


Figure 4

Gulf of Mexico Topography in Relation to WEAs, (Author: Eamon Espey)



An anticipated downside in this market is the extra distance away from the turbines and the cable length that would be required—though these exact parameters, comparable to what California would require, have not been calculated. We estimate that the closest suitable commercial storage depth (700m) is located roughly 40 miles from the southernmost leasable areas within the OCS-G 37336 block to the west, which we understand may be a prohibitive factor. On the contrary, this downside could be offset by being able to connect to fixed bottom turbines rather than floating turbines and their surface challenges in California. Furthermore, shallower depths much closer to both WEAs could also be leveraged for viable pilot demonstrations.

If RCAM is unable to capitalize on the Humboldt and Morro Bay leases, the new Gulf of Mexico market and timeline are in alignment for additional opportunity. Now is the time to consider developers who may bid and chart an outreach plan of action. The best place to start would be with the five winning California lessees and two additional bidders who participated in the December 2022 auction: Avangrid Renewables LLC and Castle Wind LLC.[4]

[4] "PACW-1 Round by Round Results_Final.xlsx." *Bureau of Ocean Energy Management*, 6-7 Dec. 2022. https://www.boem.gov/sites/default/files/documents/renewable-energy/state-activities/PACW-1-Round-by-Round-Results.pdf.

Action 2: Submit Project Description to FERC

In order to operate a hydrokinetic project on the OCS, the operator must have a license from FERC, which is separate from a BOEM-issued lease (see "Processes" section for differentiation). A key question to which we do not yet have the answer is whether the storage device would be considered hydrokinetic and subsequently subject to licensing by FERC. A FERC representative unofficially advised us that RCAM's technology could very well be considered hydrokinetic. However, to explore such a question of jurisdiction officially, RCAM would need to file a detailed description of the project proposal with FERC. A project is considered hydrokinetic if it "generate[s] electricity from the motion of waves or the unimpounded flow of tides, ocean currents, or inland waterways."[5] This is a gray area given the unique functionality of RCAM's storage device, its connection to actual energy generating devices (i.e., grid-connected wind turbines), and the lack of regulatory precedent for this type of new technology.

We recommend proactively submitting a project proposal description to FERC. In addition to getting closer to a legitimate answer to this key question, early contact with the agency (before commercial deployment is a reality) could catalyze positive attention and regulatory options for RCAM in the near future. The link to register to submit a project proposal online is contained within this citation.[6]

PLAYERS

While the following is not an exhaustive list of involved actors, it is a list of the most pertinent and immediate players with which RCAM should engage.

Bureau of Ocean Energy Management

The Bureau of Ocean Energy Management (BOEM) within the DOI is responsible for overseeing all renewable energy development and management in federal waters.

- 2009: DOI announces regulations for OCS Renewable Energy Program as authorized by the EPAct. "These regulations provide a framework for issuing leases, easements and rights-of-way for OCS activities that support production and transmission of energy from sources other than oil and natural gas."[7]

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[5] "White Paper on Licensing Hydrokinetic Pilot Projects." *Federal Energy Regulatory Commission*, 14 Apr. 2008. https://www.ferc.gov/sites/default/files/2020-04/white_paper.pdf.
[6] "Filing Instructions." *Federal Energy Regulatory Commission*, https://www.ferc.gov/filing-instructions.
[7] "Renewable Energy." *Bureau of Ocean Energy Management*, https://www.boem.gov/renewable-energy.

Federal Energy Regulatory Commission

The Federal Energy Regulatory Commission (FERC) regulates the interstate transmission of electric power, oil pipelines, natural gas, and hydroelectric projects. It defines hydrokinetic projects as involving the generation of "electricity from waves or directly from the flow of water in ocean currents, tides, or inland waterways without the need for a dam."[8]

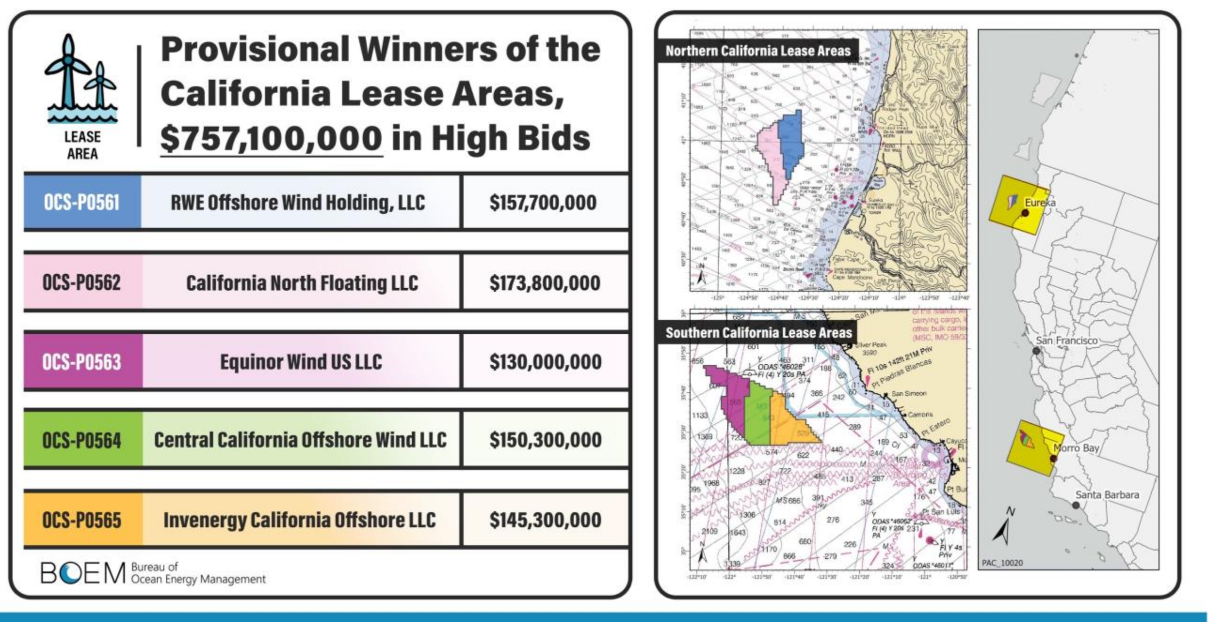
- 2009: A Memorandum of Understanding was signed by DOI (including BOEM) and FERC to clarify their jurisdiction on the OCS, streamline the regulatory process, and encourage development in an environmentally sensitive manner.

Offshore Wind Developers

Figure 5 below details the five winning lessees in the historic Pacific Wind Lease Sale held on December 6 and 7, 2022. The five paragraphs beneath Figure 5 are quoted from this citation.[9]

Figure 5

California Offshore Wind Activities[10]



[8] Bowler, Stephen. "FERC Regulatory Perspective." *BOEM Offshore Renewable Energy Workshop*, 29-30, Jul. 2014. https://www.boem.gov/sites/default/files/about-boem/BOEM-Regions/Pacific-Region/Renewable-Energy/1-Hudock Bowler---FERC-2014-BOEM-Workshop.pdf.

[9] "Who are these companies?" Bud's Offshore Energy (BOE), 14 Dec. 2022. https://budsoffshoreenergy.com/tag/california-north-floating.

[10] "California Activities." *Bureau of Ocean Energy Management,* www.boem.gov/renewable-energy/state-activities/california

"California North Floating, LLC, is a subsidiary of Copenhagen Infrastructure Partners (CIP), and RWE Offshore Wind Holdings, LLC, a German multinational energy company. (So it looks like RWE purchased one lease and is a partner in another.) Since entering the US offshore market in 2016, CIP has built a leading offshore wind position through its affiliate Vineyard Offshore. This includes Vineyard Wind 1, the country's first commercial scale offshore wind project which is currently under construction, as well as two lease areas under development totaling approximately 5.0 GW off the coast of Massachusetts and New York.

Central California Offshore Wind is managed by an East Coast offshore wind energy company, Ocean Winds North America LLC, which formed a joint venture with the Canada Pension Plan Investment Board to win the lease. Ocean Winds has more than 10 years of experience in floating offshore wind, most notably through the development and operation of Windfloat Atlantic (offshore Portugal), the world's first fully commercially operational floating offshore wind farm

Equinor, a Norwegian company, is a major international oil and gas producer, an important wind energy investor, and a leader in the development of floating wind turbine technology. Equinor operates the Hywind Tampen floating offshore wind farm which will supply power to Norwegian offshore oil and gas fields.

Invenergy and its affiliated companies develop, own, and operate large-scale renewable and other clean energy generation and storage facilities in the Americas, Europe and Asia. Invenergy's home office is located in Chicago, and it has regional development offices in the United States, Canada, Mexico, Spain, Japan, Poland, and Scotland.

RWE Renewables has experience covering the offshore and onshore wind energy value chain from development to construction and operation. These activities are the responsibility of two functional units, "Unit Renewables Europe & Australia" and "Unit Offshore Wind", as well as the subsidiary RWE Renewables Americas. RWE Renewables also invests in large-scale solar projects and supports power producers, plant operators and other stakeholders in the development, construction and operation of photovoltaic and solar energy plants as well as in the construction of battery storage systems. The focus is on large-scale industrial projects" (end of quoted material).

Avangrid Renewables LLC is a member of the Spain-based Iberdrola Group. They placed an "Exit" bid in the thirty-first and final round of the California lease auction and did not win a holding.[11] Castle Wind LLC is backed by TotalEnergies Renewables USA and Trident Winds.

[11] "PACW-1 Round by Round Results_Final.xlsx."

Castle Wind LLC placed an "Exit" bid in the sixth round of the California lease auction and did not win a holding.[12]

Natural Energy Laboratory of Hawaii Authority

The Natural Energy of Hawaii Authority's (NELHA) mission is to diversify Hawaii's economy through environmentally-sound marine research, education, and commercial partnerships. Much of this activity takes place at NELHA's established Hawaii Ocean Science and Technology (HOST Park) facility. Fortunately, RCAM was able to establish a promising relationship with NELHA liaison Alex Leonard in 2022. In addition to continuing that relationship and applying for mutual funding opportunities with NELHA, below are the standard steps for a commercial entity to begin business and testing at HOST Park.

Itemized Steps for Conducting Pilot at HOST Park[13]

Preliminary Step: Write a letter to the Hawaii Office of Coastal Management & Conservation Lands (OCCL) as it is a crucial linchpin entity. Describe RCAM's project in detail, and ask for their blessing for RCAM's project. Be prepared to explain answers thoroughly to pertinent questions. This could steer the agencies away from a full EIS if they are initially satisfied.

> **Step 1:** Schedule a consultation session with a NELHA Leasing Specialist. The SEAS-RCAM call with Alex Leonard in October 2022 may have informally qualified as this. *"Discussing the project concept with a NELHA staff member will help applicants to determine whether the proposed project is appropriate for HOST PARK, and whether the resources HOST PARK has to offer appear to meet its needs. If appropriate, consultation with other NELHA staff may also be recommended at this time."*
>
> **Step 2:** RCAM submits Initial Project Summary form (page 24). NELHA will determine suitability and direct to either a commercial/non-profit or research project. *"The basic research project is concerned with topics that contribute to the knowledge base of science and technology but have no immediate commercial application."* Assuming RCAM is suitable and deemed a research project, proceed to Step 2.
>
> **Step 3:** RCAM submits Basic Research Proposal (example on page 29). NELHA Staff and Research Advisory Committee (RAC) will review and its Board of Directors will make the final decision. *"Applicants are encouraged to personally attend NELHA Board meetings at which their proposals are discussed to support their project ideas and should*

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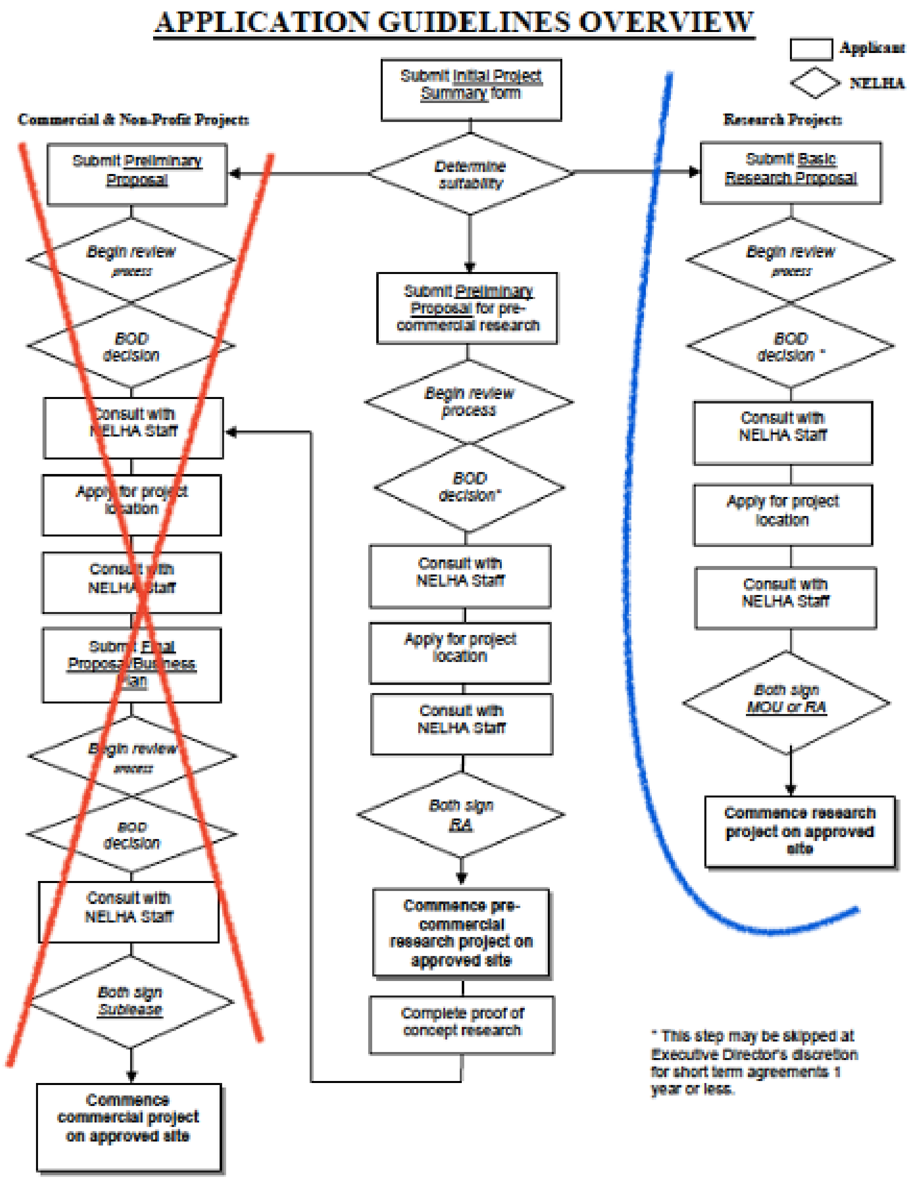
[12] "PACW-1 Round by Round Results_Final.xlsx."

[13] "Project Initiation Packet (PIP)." *Natural Energy of Hawaii Authority,* https://nelha.hawaii.gov/wp-content/uploads/2013/05/PIP-Aug-2013.pdf. pp. 23-29. Accessed 12 Mar. 2023.

be prepared to answer any questions that Board members may have. Attendance is not required but may prevent delays should the Board raise new questions regarding an applicant's proposal." If the project is supported, proceed to Step 4.

Figure 6

In blue, flowchart of research project initiation steps at HOST Park[14] — red is commercial/non-profit only



Step 4: Consult with NELHA Staff post-Board decision, apply for a specific project location, and consult with NELHA Staff again. Both RCAM and NELHA will sign a Memorandum of Understanding (MOU) or a Reimbursable Agreement (RA).

[14] "Project Initiation Packet (PIP)." p. 23

Step 5: RCAM may commence its research project on the approved site. *"Applicants must complete the entire application process and sign a land use agreement in order to finalize commitment of an appropriate area for their use."* *Note, if deemed a commercial/non-profit project instead, the steps will differ.

Step 6: Official documentation for tenancy will be prepared (permits, issuance, and lease agreement). *"NELHA staff will prepare a map with the dimensions and total area of the planned project site. The Leasing Specialist will complete a Facilities Use Fees (FUF) form to determine monthly billing of fixed fees and estimated variable charges and a Rental Agreement (RA) between NELHA and the applicant for review. The map, FUF, and NELHA-approved Basic Research Proposal will be included as Exhibits attached to the RA."*

POLICIES

The following policies are relevant—explicitly or tangentially—to the offshore wind industry and/or to RCAM's proposed pilot and commercial development plans.

Submerged Lands Act Boundary

"The Submerged Lands Act Boundary (also known as the State Seaward Boundary or Fed-State Boundary) defines the seaward limit of a state's submerged lands and the landward boundary of federally managed outer Continental Shelf lands."[15]

- "Title III preserves the control of the seabed and resources therein of the outer Continental Shelf beyond state boundaries and to the federal government and authorizes leasing by the Secretary of the Interior in accordance with certain specified terms and conditions"[16] (i.e., leasing by BOEM).
- Three nautical miles offshore is the boundary line of jurisdiction for most coastal states and the start of the OCS. For Texas and Florida's Gulf of Mexico coastlines, the rule is three marine leagues or nine nautical miles.[17]

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[15] "Summary of Law - Submerged Lands Act.pdf." *National Oceanic and Atmospheric Administration*, https://coast.noaa.gov/data/Documents/OceanLawSearch/Summary%20of%20Law%20-%20Submerged%20Lands%20Act.pdf.
[16] "Summary of Law - Submerged Lands Act.pdf."
[17] "Summary of Law - Submerged Lands Act.pdf."

National Environmental Policy Act

"The National Environmental Policy Act (NEPA)…establishes the broad national framework for protecting our environment. NEPA's basic policy is to assure that all branches of government give proper consideration to the environment prior to undertaking any major federal action that significantly affects the environment. NEPA requirements are invoked when airports, buildings, military complexes, highways, parkland purchases, and other federal activities are proposed. Environmental Assessments (EAs) and Environmental Impact Statements (EISs), which are assessments of the likelihood of impacts from alternative courses of action, are required from all Federal agencies and are the most visible NEPA requirements."[18]

Hawaii Environmental Policy Act

"The Hawaii Environmental Policy Act (HEPA) (Hawaii Revised Statutes Chapter 343), was enacted in the early 1970s. Broadly speaking, it requires individuals and agencies to provide environmental assessments and/or environmental impact statements when an action may affect the environment. The Environmental Review Program (ERP) facilitates Hawaiʻi's environmental review process (commonly known as HEPA)."[19]

HEPA Criteria for Environmental Significance

"In most cases, an agency determines that an action may have a significant impact on the environment if it meets any of the following criteria (from Section 11-200-12, HAR):

A. Involves an irrevocable commitment to loss or destruction of any natural or cultural resource
B. Curtails the range of beneficial uses of the environment
C. Conflicts with the state's long-term environmental policies or goals and guidelines as expressed in [Chapter] 344, HRS, and any revisions thereof and amendments thereto, court decisions, or executive orders
D. Substantially affects the economic or social welfare of the community or State
E. Substantially affects public health
F. Involves substantial secondary impacts, such as population changes or effects on public facilities
G. Involves a substantial degradation of environmental quality
H. Is individually limited but cumulatively has considerable effect upon the environment or involves a commitment for larger actions
I. Substantially affects a rare, threatened, or endangered species, or its habitat
J. Detrimentally affects air or water quality or ambient noise levels
K. Affects or is likely to suffer damage by being located in an environmentally sensitive area such as a flood plain, tsunamizone, beach, erosion-prone area, geologically hazardous land, estuary, fresh water or coastal waters

[18] "Summary of the National Environmental Policy Act." United States Environmental Protection Agency, www.epa.gov/laws-regulations/summary-national-environmental-policy-act.
[19] "Environmental Court." *Hawai'i State Judiciary*, www.courts.state.hi.us/special_projects/environmental_court.

L. Substantially affects scenic vistas and view planes identified in county or state plans or studies
M. Requires substantial energy consumption

It is important to note that in considering significance of potential environmental effects, the agency (either proposing or approving) must consider the sum of the effects on the quality of the environment and that the same agency must evaluate the overall and cumulative effects of a proposed action: the expected direct and indirect consequences, and the cumulative, as well as short-term and long-term effects of the proposed action."[20]

Merchant Marine Act of 1920

More commonly known as "The Jones Act" after author Senator Wesley Jones, it "requires goods shipped between U.S. ports to be transported on ships that are built, owned, and operated by United States citizens or permanent residents."[21]

Depending on the originating point, this could impact RCAM as it is transporting its spheres and other equipment out to sea for installation. Increased offshore wind development will also impact the availability of approved vessels and require advanced planning. However, RCAM's localized 3D-printing scheme at ports nearest deployment could mitigate these potential issues all together.

Clean Water Act

Finalized by the EPA in 2014, Section 316(b) of the Clean Water Act "regulates the mortality rates for fish and aquatic life that encounter cooling water intake structures at existing power plants, industrial sites, and manufacturing facilities." More specifically, it "requires that the location, design, construction, and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impacts: impingement and entrainment." The threshold for being subject to this regulation is to "withdraw at least 2 million gallons of cooling water per day (mgd) and use at least 25% of that water for cooling purposes."[22]

Given this language was written into law before questions of offshore wind energy storage arose, it is unclear if this regulation would extend or evolve to regulate the water intake of RCAM's device. Thus, it is a policy of which to be mindful.

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[20] "Guide to the Implementation and Practice of the Hawaii Environmental Policy Act." *State of Hawaii*, 2012. https://files.hawaii.gov/dbedt/erp/OEQC_Guidance/2012-GUIDE-to-the-Implementation-and-Practice-of-the-HEPA.pdf.
[21] Kenton, Will. "What Is the Jones Act? Definition, History, and Costs." *Investopedia*, 5 Jan. 2023. www.investopedia.com/terms/j/jonesact.asp
[22] "Your Guide to Section 316(b) of the Clean Water Act." *Hydrolox*, 2017. http://www.hydrolox.com/uploadedFiles/Content/Literature_Library/5000288_English.pdf.

Ports and Waterways Safety Act

The Ports and Waterways Safety Act of 1972 (PWSA) authorizes the U.S. Coast Guard to "establish, operate and maintain vessel traffic services in ports and waterways subject to congestion."[23] Vessels must also carry specialized electronic devices for participation in the Coast Guard's Vessel Traffic Service project. The Port and Tanker Safety Act (PTSA) of 1978 amended the PWSA. For example, "the USCG implemented a 500-yard safety zone around the wind turbine locations at Block Island Wind Farm during that project's construction activities."[24]

This law is most relevant to RCAM's floating barge pilot near Santa Catalina island. While further investigation into the exact protocol is needed, RCAM should be prepared to interface with the U.S. Coast Guard for such a pilot.

Endangered Species Act

Passed in 1973, the ESA is a far-reaching and monumental law "to conserve endangered and threatened species and their habitat," including "approximately 1,930 species…which are found in part or entirely in the United States and its waters."[25] NOAA, NMFS, and USFWS jointly implement the ESA in marine and freshwater environments. "Section 7 of the ESA mandates that BOEM and all other Federal Agencies consult with the Secretary of Commerce (via NMFS) and/or Interior (via USFWS) to insure that any 'agency action' is not likely to jeopardize the continued existence of any endangered or threatened species or result in the destruction or adverse modification of an endangered or threatened species' critical habitat."[26]

Coastal Zone Management Act

This act "requires that Federal actions that are reasonably likely to affect any land or water use or natural resource of the coastal zone be consistent with enforceable policies of a State's federally-approved coastal management program."[27] There are standard criteria to test the possible effect and every coastal state will have different enforceable policies. For example, effects from renewable energy activity on the OCS off the coast of California (Morro Bay and Humboldt Bay) could invoke the Coastal Zone Management Act.

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[23] "Ports and Waterways Safety System (PAWSS)." *United States Coast Guard Navigation Center*, www.navcen.uscg.gov/ports-and-waterways-safety-system.

[24] "FAQ: Offshore Wind Siting in the Gulf of Mexico." *Bureau of Ocean Energy Management,* https://www.boem.gov/sites/default/files/documents/about-boem/GOM-Fisheries-OSW-FAQ_0.pdf.

[25] "Endangered Species Act (ESA)." *Bureau of Ocean Energy Management,* www.boem.gov/environment/environmental-assessment/endangered-species-act-esa.

[26] "Endangered Species Act (ESA)."

[27] "Coastal Zone Management Act." *Bureau of Ocean Energy Management,* www.boem.gov/environment/environmental-assessment/coastal-zone-management-act.

National Historic Preservation Act

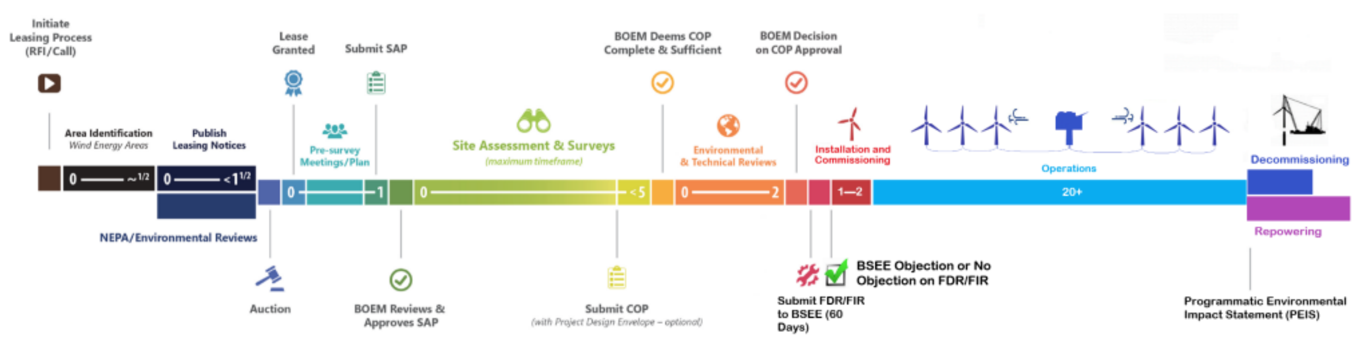
This act requires federal agencies and actors to "take into account the effect of…[their proposed] undertaking on any district, site, building, structure, or object that is included in or eligible for inclusion in the National Register."[28] Historic properties on the OCS "include historic shipwrecks, sunken aircraft, lighthouses, and prehistoric archaeological sites that have become inundated due to the 120-meter rise in global sea level since the height of the last ice age (ca. 19,000 years ago). As the OCS is not federally-owned land, and as the Federal government has not claimed direct ownership of historic properties on the OCS, BOEM only has the authority under Section 106 of the NHPA to ensure that…funded and permitted actions do not adversely affect significant historic properties."[29] RCAM must be mindful of the installation and location of its storage devices to avoid disturbing historical properties.

PROCESSES

Timeline & Survey Guidelines For Renewable Energy Development

Figure 7

BOEM/BSEE Offshore Wind Development Stages and Timeline[30]



"Before BOEM will approve the siting of a facility, structure, or cable proposed for a renewable energy project on the Outer Continental Shelf (OCS), an applicant must submit with its Site Assessment Plan (SAP), Construction and Operations Plan (COP), or General Activities Plan

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[28] "National Historic Preservation Act." *Bureau of Ocean Energy Management,* www.boem.gov/environment/environmental-assessment/national-historic-preservation-act.

[29] "National Historic Preservation Act."

[30] "BSEE/BOEM Renewable Energy Split Rule Information and Q&A" *Bureau of Safety and Environmental Enforcement*, 2 Feb. 2023. https://www.bsee.gov/sites/bsee.gov/files/bsee-boem-split-rule-workshop-bsee-boem-020223.pdf

(GAP), and as applicable, the results of its site characterization surveys and supporting data to BOEM. BOEM will use the data from these surveys to evaluate the impact of construction, installation, and operation of meteorological towers, buoys, cables, wind turbines, and supporting structures on physical, biological, and socioeconomic resources, as well as the seafloor and sub-seafloor conditions. The information will be used by BOEM, other Federal agencies, and potentially affected states in the preparation of NEPA documents, for consultations and other regulatory requirements."[31]

All of the information that is required to be submitted to BOEM is the responsibility of the renewable developer and is linked within this citation.[32] However, as RCAM hopes to have a mutual partnership with a leaseholding developer, RCAM should be privy to the types of environmental information BOEM will require of it. The developer will look to RCAM to be the most knowledgeable party about its device and potential impacts when drafting text for its required BOEM documentation.

BOEM Lease and FERC License Requirements

BOEM has several lease types and special use grants for commercial and pilot projects.

Commercial Stage Projects

- Conventional Lease
- Right-of-use and easement (RUE) grant
- Right-of-way (ROW) grant

A **Conventional Lease** is the typical scenario of offshore wind auctions. This awarded lease provides the lessee with the sole "right to use the lease area to develop its plans, which must be approved by BOEM before the lessee can move on to the next stage of the process."[33] The pre-development approval steps a lessee must complete are first a Site Assessment Plan (SAP) followed by a Construction and Operations Plan (COP) once the SAP is approved or modified. Furthermore, it is well understood that most lessees will require the assistance of a large variety of contractors to help with the design, fabrication, and installation of their projects. This includes considering the long-term value added potential from energy storage partners. Therefore, RCAM can be written into a lease holder's COP even though it does not hold the lease. Without this type

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[31] "Survey Guidelines For Renewable Energy Development." *Bureau of Ocean Energy Management,* www.boem.gov/renewable-energy/survey-guidelines-renewable-energy-development.
[32] "Survey Guidelines For Renewable Energy Development."
[33] "Fact Sheet: Wind Energy Commercial Leasing Process." *Bureau of Ocean Energy Management,* https://www.boem.gov/sites/default/files/documents/about-boem/Wind-Energy-Comm-Leasing-Process-FS-01242017Text-052121Branding.pdf.

of documented relationship, developer buy-in, or change in permitting entry points for alternative technologies, RCAM cannot engage easily in the U.S. commercial offshore wind market.

Currently, there is no precedent for siting technology in deeper water outside of the boundary of a WEA, nor for said technology to connect to activity within the lease area; although, it is an ideal scenario for the operating depths RCAM needs. However, a BOEM representative advised of additional market entry options in this realm.

- **Option 1:** A lessee can submit the outside area as part of their project easement through a right-of-way (ROW) grant, which is a proposal for facilities outside the lease area that is normally associated with the export cable corridor. Given the large footprint of the device, though, BOEM might determine that a project easement is not the appropriate instrument for conveying the right to such a large area that was not included in the area identified for the original lease.

- **Option 2:** A lessee could submit an application for a right-of-use-and-easement (RUE) grant, which is a BOEM-issued easement that authorizes use of a designated portion of the OCS to support activities on a lease or other use authorization for renewable energy activities. This would require BOEM to solicit the additional area for competitive interest, which is not ideal.

Because both grants are separate instruments that would be issued for project facilities within an already-issued lease area, BOEM would need to carefully consider the timing for a grant to align with a corresponding COP evaluation process. Considered by BOEM as "alternate use of existing OCS facilities,"[34] these two scenarios would still require the awarded lessee to be an active project partner and sponsor on RCAM's behalf. Below are full ROW and RUE definitions:

- **"Right-of-use and easement (RUE) grant** means an easement issued by BOEM under this part that authorizes use of a designated portion of the OCS to support activities on a lease or other use authorization for renewable energy activities. The term also means the area covered by the authorization."[35]

- **"Right-of-way (ROW) grant** means an authorization issued by BOEM under this part to use a portion of the OCS for the construction and use of a cable or pipeline for the

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[34] Frank, Wright and Lan, Christy. "BSEE/BOEM Renewable Energy Split Rule Information and Q&A." *Bureau of Safety and Environmental Enforcement*, 2 Feb. 2023.
https://www.bsee.gov/sites/bsee.gov/files/bsee-boem-split-rule-workshop-bsee-boem-020223.pdf
[35] "Code of Federal Regulations." *United States Government Publishing Office,*
www.govinfo.gov/content/pkg/CFR-2017-title30-vol2/xml/CFR-2017-title30-vol2-part585.xml.

purpose of gathering, transmitting, distributing, or otherwise transporting electricity or other energy product generated or produced from renewable energy, but does not constitute a project easement under this part. The term also means the area covered by the authorization."[36]

Pilot Stage Projects

- Limited lease
- Research lease

It is most desireable for RCAM to locate any pilot project exclusively in state waters to avoid dealing with BOEM as an extra regulatory layer. In the case of operating a pilot in federal waters, there are two appropriate lease types: limited and research.

Limited leases are determined on a case-by-case basis with BOEM, have a lifetime of up to five years, and a power limit of 5MW. Because the lease term is only five years, it is almost guaranteed that the project will run out of time and an environmental review still needs to be conducted ahead of this time. Furthermore, a BOEM representative advised that this lease type is not worth the wait and that they are looking to change it.

Research leases are determined on a case-by-case basis with BOEM, are granted directly to federal or state agencies for research purposes, and cannot have competitive interest. This means RCAM cannot be the lessee, but if a government agency is interested in the technology, then RCAM could attach themselves to the lease and work collaboratively with said agency. The best example of this type of lease was when it was first offered to Oregon State University (OSU) for the PacWave South project for marine hydrokinetic energy testing in federal waters off the coast of Newport, Oregon.[37] The benefits of this lease type are that there are no rents, operating fees, or acquisition fees—financial assurance is only required for decommissioning. The downsides are being one step removed from the process by not being the lessee, a mandated federal environmental review, and being subject to competition for the lease.

Connection to HOST Park and Santa Catalina Island

Conducting a grid-connected pilot at HOST Park would most likely require a FERC license. During our October 2022 call, Alex Leonard of NELHA said he hadn't worked with FERC

[36] "Code of Federal Regulations."
[37] "BOEM Offers First Renewable Energy Research Lease in Federal Offshore Waters Along the U.S. West Coast." *BOEM Newsroom*, 19 Jan. 2021. www.boem.gov/newsroom/boem-offers-first-renewable-energy-research-lease-federal-offshore-waters-along-us-west

before, but given they have a dedicated grid inconnection point, perhaps the licensing and assurance with FERC is already covered. Further conversations are needed.

Conducting a floating barge pilot near the Port of Los Angeles/Santa Catalina Island would not require a FERC license. FERC should classify it as simply device testing: not grid connected, short-term, and experimental in nature.[38] Neither pilot project would need to involve BOEM or securing a lease so long as they take place within state waters (i.e., within the three nautical mile rule of the Submerged Lands Act Boundary).

ACRONYMS AND ABBREVIATIONS

Some of these terms are referenced in the text and some are not. Regardless, RCAM is likely to encounter all of these terms at some point while engaging with regulatory agencies, stakeholders, and others in the renewable energy development space.

ALP	Alternative Licensing Process
BSEE	Bureau of Safety and Environmental Enforcement (DOI)
BOEM	Bureau of Ocean Energy Management (DOI)
CBP	U.S. Customs and Border Protection
CWA	Clean Water Act
CZMA	Coastal Zone Management Act
EA	environmental assessment
EIS	environmental impact statement
EMF	electromagnetic field
EPAct	Energy Policy Act of 2005
ESA	Endangered Species Act
FCC	Federal Communications Commission
FERC	Federal Energy Regulatory Commission

[38] Bowler, Stephen. "FERC Regulatory Perspective."

FONSI	Finding of No Significant Impact
FPA	Federal Power Act
FWS	U.S. Fish and Wildlife Service
HOST Park	Hawaii Ocean Science and Technology Park
ICPC	International Cable Protection Committee
ILP	Integrated Licensing Process
MEC	Marine Energy Council
MHK	Marine hydrokinetics (wave, tidal, ocean and in-river current energy capture tech.)
MMPA	Marine Mammal Protection Act
MSP	Marine Spatial Planning
MTB	mooring and telemetry buoy
MWPMA	Marine Waters Planning and Management Act
NELHA	Natural Energy Laboratory of Hawaii Authority
NEPA	National Environmental Policy Act of 1969
nm	nautical mile (1 mile = ~0.8689 nautical miles)
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOI	Notice of Intent
NOP	National Ocean Policy
NWP	Nationwide Permit
Ocean SAMP	Ocean Special Area Management Plan
OCS	Outer Continental Shelf
OCSLA	Outer Continental Shelf Lands Act
PAD	preliminary application document

PMEC-SETS	Pacific Marine Energy Center South Energy Test Site (DOE)
PP	preliminary permit
PPLP	Pilot Project License Process
TLP	Traditional Licensing Process
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USCG	U.S. Coast Guard
VTSS	vessel traffic service/separation schemes
WEA(s)	wind energy area(s)
WEC	wave energy converter
WETS	Wave Energy Test Site in Hawaii

Resource Potential Analysis of Pilot and Commercial Storage Sites

By Eamon Espey and Ci Song

UM SEAS and RCAM Technologies Master of Science Capstone Partnership

SCHOOL FOR ENVIRONMENT & SUSTAINABILITY
UNIVERSITY OF MICHIGAN

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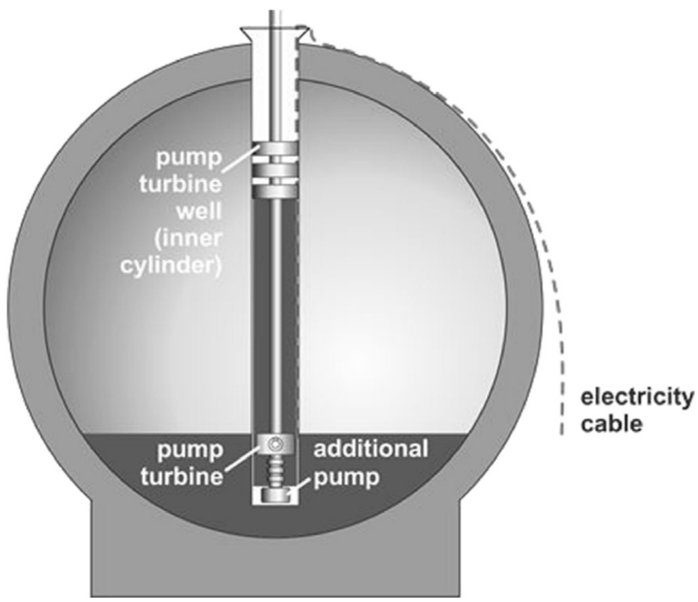
Introduction

RCAM Technologies' Marine-Pumped HydroElectric Storage (M-PHES) units each consist of one pump and turbine coupled with four[1] hollow concrete spheres installed on the seafloor. These units are large batteries that are able to store energy by utilizing hydrostatic pressure deep in the ocean. To charge the batteries, excess electricity from offshore wind turbines or from the grid is used to pump water out of the M-PHES spheres, creating space inside the spheres for water to be pumped in at a later time. When water is allowed to flow into the M-PHES spheres, the pressure difference between the inside and the outside of the sphere turns a turbine and converts mechanical energy into electrical energy; more specifically, this process converts the potential energy from hydrostatic pressure into electrical energy. A schematic cross sectional view of a M-PHES sphere is presented in Figure 1.

Figure 1
A schematic cross sectional view of one M-PHES sphere[2].



The suitability of a location for installing M-PHES spheres depends on several site characteristics. Puchta al.[2] identified various parameters that should be taken into account for site planning, including:

- water depth
- slope

[1] The design described above is only one iteration of M-PHES units. While this configuration may be the most successful in commercial deployment, the company is also testing other pilot configurations.
[2] Puchta, M. ; Bard, J. ; Dick, C. ; Hau, D. ; Krautkremer, B. ; Thalemann, F. ; Hahn, H. (2017). Development and testing of a novel offshore pumped storage concept for storing energy at sea − Stensea. Journal of energy storage. Elsevier Ltd.

- geomorphology
- distance to the electric grid
- distance to installation and maintenance bases
- existence of marine protected areas
- need for electric storage capacity in the vicinity.

Based on RCAM's requirements, our analysis of resource potential and site suitability concentrate on water depth, slope, and distance to the grid connection point. Additionally, we consider the packing factor, the percentage of an area covered by M-PHES spheres, which is dependent on the precision of the installation process. The suitable range of water depth is determined by the power of the pumps and the installation feasibility. Currently, RCAM intends to deploy the M-PHES unit in water depths ranging from 500 to 1500 meters with a slope of less than 10 degrees. Finally, we accounted for the distance from the spheres to the grid interconnection point on land in order to minimize cable cost and environmental impact.

Methods

The total amount of energy that can be stored in a single M-PHES sphere depends on the density of water, the efficiency of the pump and turbine, the depth of the sphere, the acceleration of gravity, and the internal volume of the sphere. We calculate the resource potential of a single M-PHES sphere by following the method proposed by Hahn et al.[3]. The resource potential, or charge capacity (C_{max}) of one sphere, is determined by the equation (1):

$$C_{max} = \rho_{water} \cdot \eta_{turb} \cdot d \cdot g \cdot V_{inner} \tag{1}$$

Hahn et al.[3] assumes a water density (ρ_{water}) of 1,025 kg/m^3 and a turbine efficiency (η_{turb}) of 0.73. Unless otherwise noted, these are the values used in our analyses. Water depth (d) is measured in meters, and the gravitational acceleration (g) is 9.81 m/s^2. Finally, the internal volume of the M-PHES sphere (V_{inner}) is measured in m^3. Equation (1) is used to calculate the resource potential for pilot cases near Hawaii Island and Santa Catalina Island with a single M-PHES sphere.

To calculate the spatial density of resource potential given a matrix of spheres, we consider the packing factor (f_p), which is the percentage of an area that is covered by M-PHES spheres (i.e. how tightly packed the matrix of spheres is). By applying the parameters specific to RCAM's M-PHES, we calculate the spatial density of resource potential with equation (2):

[3] Hahn, Henning ; Hau, Daniel ; Dick, Christian ; Puchta, Matthias. (2017). Techno-economic assessment of a subsea energy storage technology for power balancing services. Energy (Oxford). Oxford: Elsevier Ltd.

$$C_{max} = \rho_{water} \cdot \eta_{turb} \cdot g \cdot d \cdot \frac{4}{3} A_{sphere,\, total} \cdot r$$
$$= \rho_{water} \cdot \eta_{turb} \cdot g \cdot d \cdot \frac{4}{3} A_{total} \cdot f_p \cdot r$$
$$C_{density,\, max} = \rho_{water} \cdot \eta_{turb} \cdot g \cdot d \cdot \frac{4}{3} \cdot f_p \cdot r \qquad (2)$$

We compiled bathymetric data and, using ArcGIS Pro and R, converted them into water depth and seafloor slope layers, which we then used to identify the best candidate sites and map the resource potential. We applieds various criteria discussed before, including water depth, seafloor slope, and distance to the grid connection point, to identify suitable sites for M-PHES installation. Finally, we created maps of the suggested sites and their respective resource potentials.

For our analysis at the Hawaii Ocean Science & Technology Park (HOST Park), in cooperation with the Natural Energy Laboratory of Hawaii Authority, we used the Bathymetric data from the National Oceanic and Atmospheric Administration (NOAA). The resolution of the data is 1 arc-second, which is 30 m, and the vertical accuracy is 50 cm. The Hawaii Island boundary data is downloaded from the Hawaii Statewide GIS Program website.

For our analysis sites in California (Humboldt, Morro Bay, and Santa Catalina), GIS depth contours were downloaded from NOAA's Office for Coastal Management and interpolated to obtain bathymetry in raster format. Slope rasters are calculated from the interpolated bathymetry rasters. For Humboldt and Morro Bay, analysis is constrained to the wind energy area (WEA) boundaries provided by the Bureau of Ocean Energy and Management (BOEM).

Results

Hawaii

Table 1 contains relevant technical parameters of RCAM's M-PHES pilot project in HOST Park.

Table 1
Relevant technical parameters of RCAM M-PHES unit for the pilot in Hawaii.

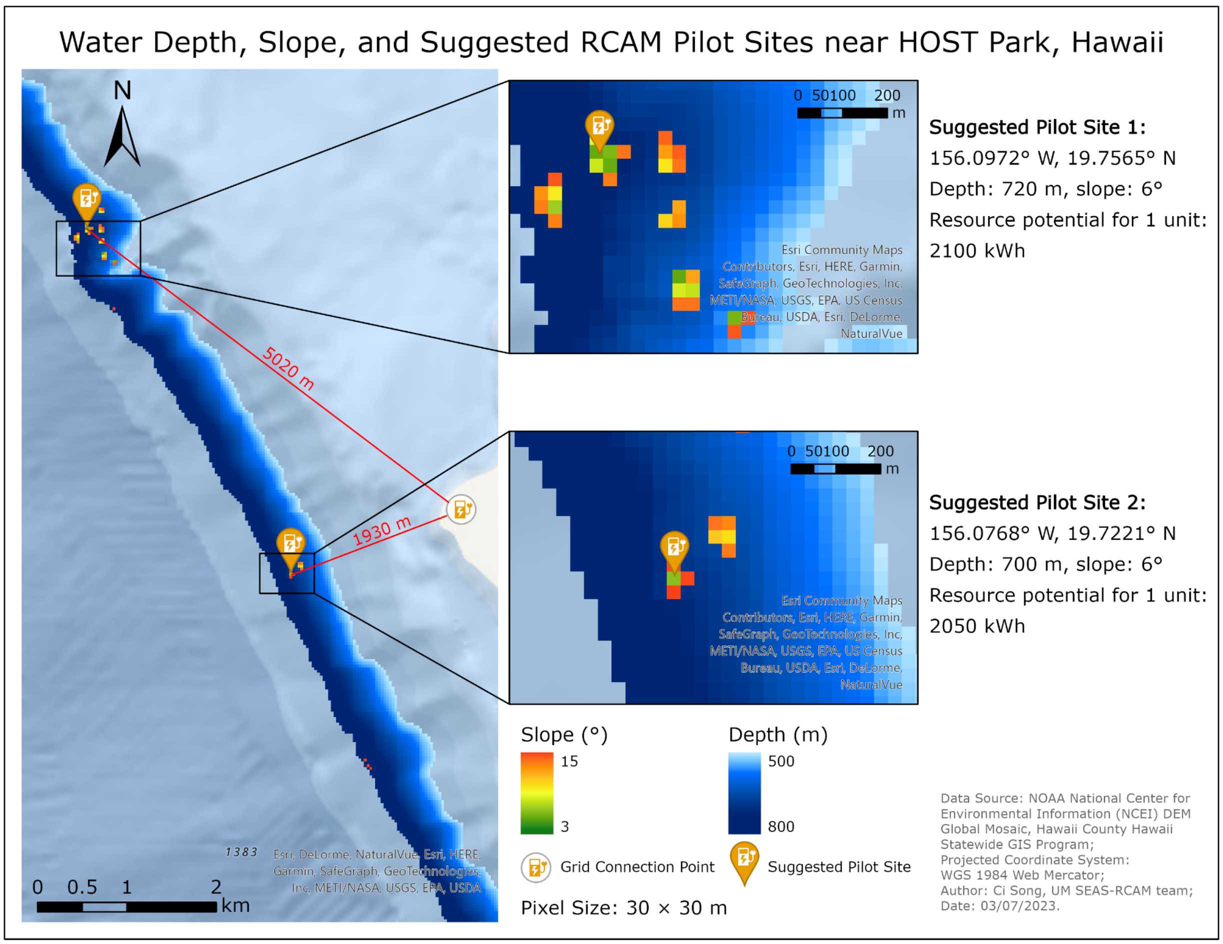
Parameters	unit	value
Construction depth	m	500 - 1500
Inner diameter	m	10
Efficiency	%	50

RCAM plans to install a single unit for the pilot project in Hawaii, consisting of four spheres arranged in a square. We calculated the resource potential for one unit (four spheres) using the method described in the Methods section. The result is shown as below:

$$C_{max} = 4 \cdot \rho_{water} \cdot \eta_{turb} \cdot d \cdot g \cdot V_{inner}$$
$$= 4 \cdot \frac{1025\, kg/m \times 0.5 \times 9.81\, m/s^{-2}}{3.6 \times 10^{6}\, J/kWh} \cdot d \cdot \frac{4}{3}\pi \times (5m)^{3}$$
$$= 2.9248\, d\, (kWh)$$

Figure 2

Water Depth, Slope, and Suggested RCAM Pilot Sites near HOST Park, Hawaii.



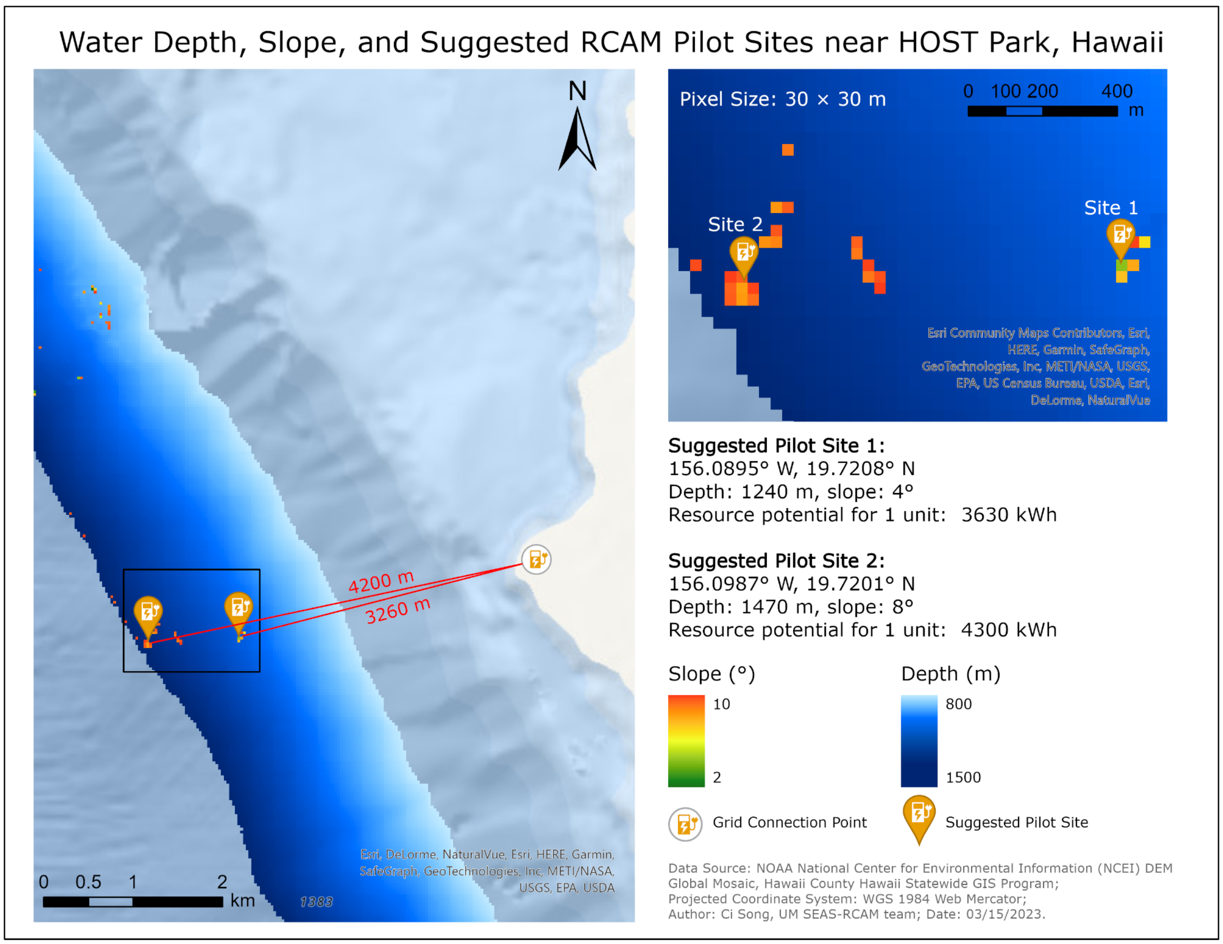
Note: For M-PHES working in a water depth from 500 - 800 m

We have identified two potential pilot sites for the installation of an M-PHES unit with a water depth between 500-800 m (Figure 2). These locations are situated within state waters and the soil type at both locations is estimated to be sand. The coordinates for Suggested Site 2 are 156.0972° W and 19.7565° N, with a water depth of 720 m and a slope of 6°. The estimated resource potential for one unit at this site is 2050 kWh. The resolution of the map is 30 x 30 m. For a single unit composed of four spheres arranged in a square, an area of approximately 50 x 50 m, or even 100 x 100, is required, taking into account the gaps between the spheres and redundancy.

Therefore, due to the data resolution limitations, further fieldwork is required to confirm if Suggested Site 2 can indeed accommodate one M-PHES unit. In the event that it cannot, we propose considering Suggested Site 1, which offers a larger area. It is located at 156.0768° W and 19.7221° N, at 700 m deep, and has a slope of 6°. The estimated resource potential for one unit at this site is 2100 kWh.

Figure 3

Water Depth, Slope, and Suggested RCAM Pilot Sites near HOST Park, Hawaii.



Note: For M-PHES working in a water depth from 800 - 1500 m

Figure 3 displays two recommended demonstration sites for M-PHES with pumps that operate in water depths ranging from 800 to 1500 m. These locations are situated within state waters and the soil type at both locations is estimated to be sand. Suggested Pilot Site 1 (156.0895° W, 19.7208° N) has a depth of 1240 m and a slope of 4°.The predicted resource potential for one unit at this site is approximately 3630 kWh. The distance from Site 1 to the grid connection point is 3260 m. However, only three pixels around this site have a slope under 10°. As a result, field work is required to determine if the site is large enough to accommodate one M-PHES unit, due to limitations in resolution. If not, Suggested Pilot Site 2 (156.0987° W, 19.7201° N) has a larger area of around 100 x 100 m. Its water depth is 1470 m, slope is 8°, resource potential is 4300 kWh. It is located 4200 m from the grid connection point.

California

Santa Catalina Island (floating pilot)

Santa Catalina is a pilot project like HOST, but rather than anchoring the storage unit to the seafloor, RCAM is considering a short-term test wherein a storage unit is connected to a barge and dropped to a certain depth in the ocean. The analysis for this pilot project uses the parameters in Table 2 with equation (1) and results are reported as the amount of energy each sphere could store if dropped all the way to the seafloor.

Table 2
Relevant technical parameters of RCAM M-PHES unit for near Santa Catalina Island.

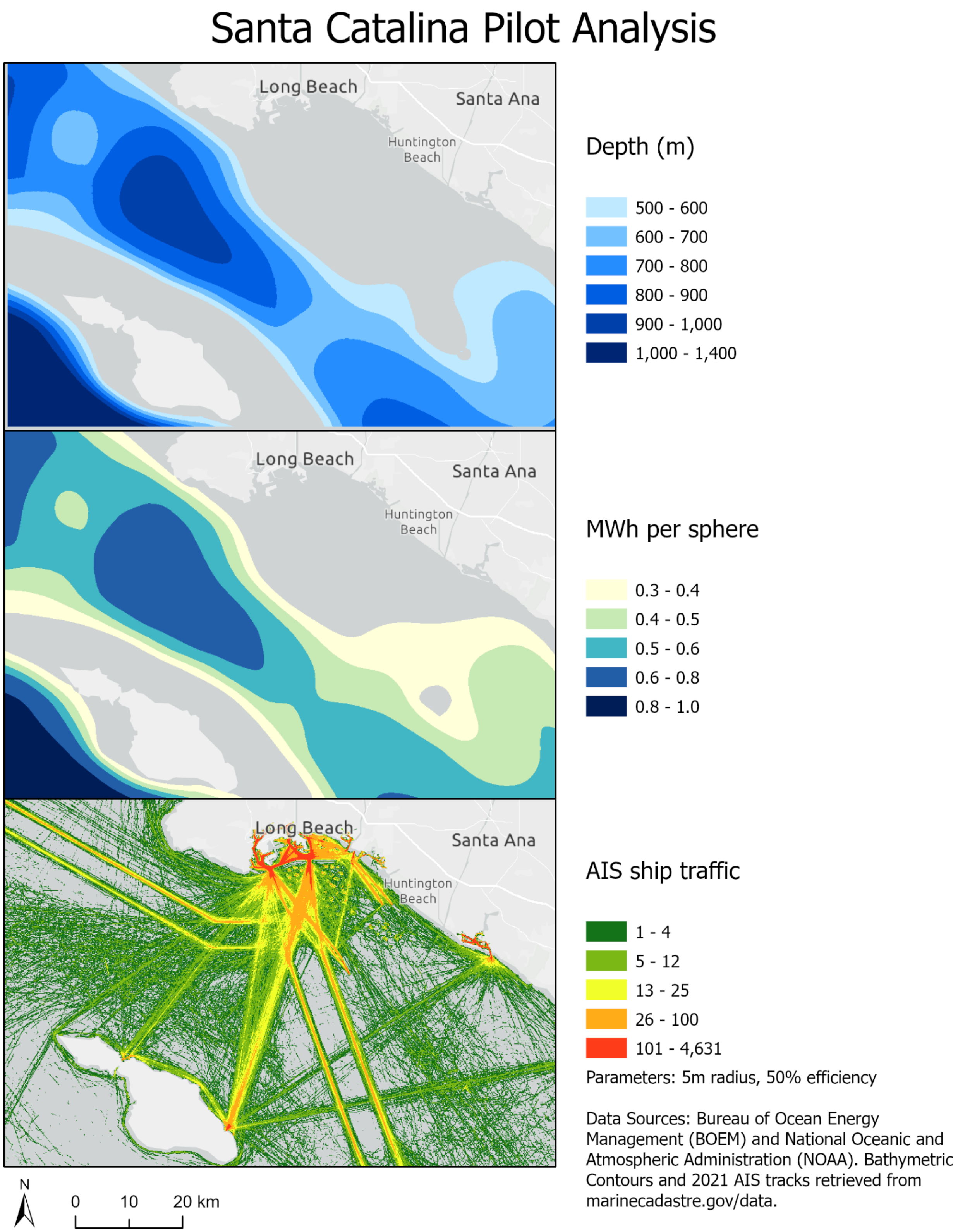
Parameters	unit	value
Construction depth	m	500 - 1000
Inner radius	m	5
Efficiency	%	50

The slope of the seafloor is significant in site planning only if the sphere is being anchored; the floating pilot project near Santa Catalina Island will not be anchored, so slope is not considered in this analysis. Rather, ship traffic is considered as the risk variable. Figure 4 shows the depth and resource potential for the region between Long Beach, CA and Santa Catalina Island as well as ship traffic for the year of 2021. The ship traffic data is from an Automatic Identification System (AIS) and was collected by the U.S. Coast Guard.

A large region located 15 - 35 km north of Santa Catalina Island has a depth in the range of 800 - 1000 m, which could store up to 750 KWh per sphere. There are, however, two lines with a relatively high frequency of ship traffic, so coordination with the U.S. Coast Guard is of utmost importance for safety. While Figure 4 shows the aggregate ship traffic for the entire year of 2021, the real-time ship traffic is not constant throughout the year, so further research is necessary to determine an optimal time to test the pilot project. Another important consideration for planning a time for testing is the weather conditions; high wind speeds and large waves could be prohibitive for testing a floating pilot project on a barge, so weather conditions need to be closely monitored in the days and weeks prior to testing to ensure feasibility and safety. Finally, RCAM will have to interface closely with the U.S. Coast Guard, which has ultimate authority to regulate vessel traffic and any floating apparatuses under The Ports and Waterways Safety Act of 1972.

Figure 4

Water Depth, ship traffic, and energy storage density between Long Beach, CA and Santa Catalina Island.



Humboldt (commercial market)

Our analysis of Humboldt is for a commercial market, so we use equation (2) above (which includes a packing factor, f_p) to calculate the spatial density of energy storage for a matrix of M-PHES spheres. While there is some uncertainty with the commercial scale storage spheres as to what the internal radius or the efficiency will be, the greatest source of uncertainty in energy storage density is in the packing factor; the value of this parameter largely depends on the installation precision, which decreases the deeper the spheres are installed. Because of this uncertainty, we chose conservative values, described in Table 3. To explore the sensitivity of these parameters, please refer to Appendix A.

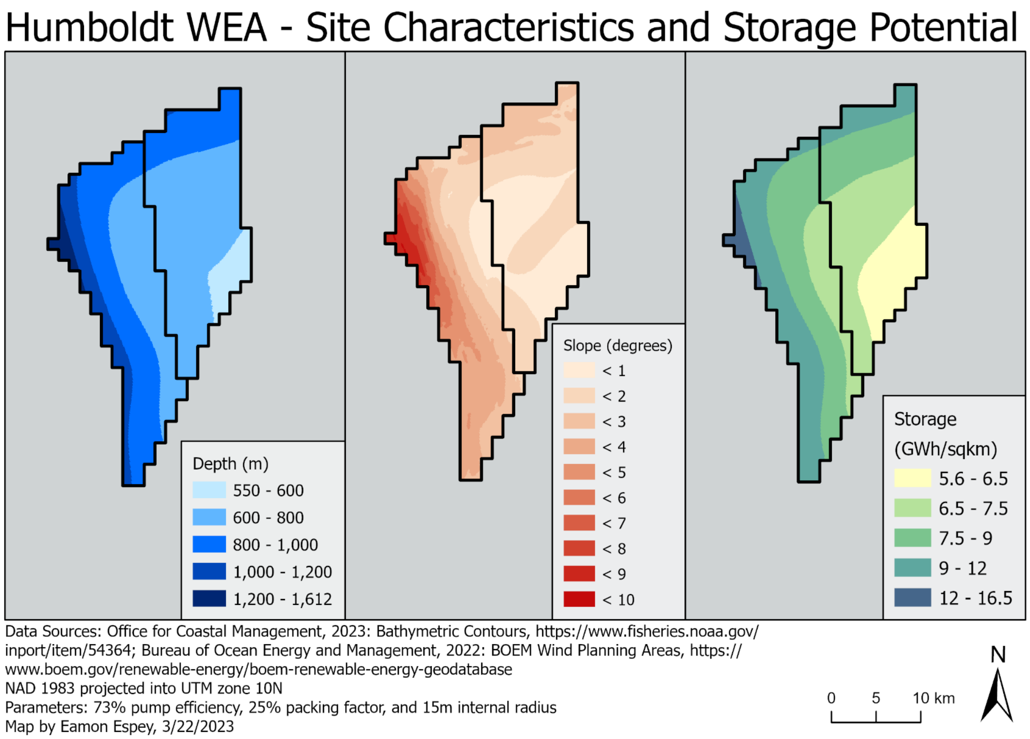
Table 3
Relevant technical parameters of RCAM M-PHES units for Humboldt WEA.

Parameters	unit	value
Construction depth	m	550 - 1612
Internal radius	m	15
Efficiency	%	73
Packing factor	%	25

The Humboldt WEA ranges from roughly 35 to 55 km from the shore and our analysis reveals significant opportunity for M-PHES within the WEA, shown in Figure 5. Most of the Humboldt lease area is under 4 degrees slope with a depth between 550 and 1200m, providing energy storage density of around 5-12 GWh/km^2. The deepest (and steepest) region of the Humboldt WEA is around 1600m deep and could store over 16 GWh/km^2, but the extreme slope (up to 10°) makes this area less suitable for M-PHES.

Figure 5

Water Depth, Slope, and energy storage density in the Humboldt WEA.



Over 90% (494 km^2) of the 540 km^2 of the Humboldt WEA have a slope lower than 5° and could store a total of nearly 4 TWh. The shallowest region (550 m to 600 m deep) closest to the shore is almost entirely under 1° slope and could store 158 GWh in an area of 26.4 km^2. Tables 4, 5, and 6 show the total area, average depth, and storage potential, respectively, for all combinations of depth and slope categories in the Humboldt WEA.

Table 4

Total area in each combination of slope and depth categories in the Humboldt WEA

Area (km^2)	<1°	<2°	<3°	<4°	<5°	<6°	<7°	<8°	<9°	<10°	total
550 to 600m	26.4	0.01	0	0	0	0	0	0	0	0	26.4
600 to 800m	95.5	133	34.8	4.72	0	0	0	0	0	0	268
800 to 1000m	0.04	29.6	62.8	71.1	16.3	9.86	1.87	0	0	0	192

1000 to 1200m	0	0.04	0.75	11.7	6.88	6.25	8.6	8.12	2.24	0	44.6
1200 to 1615m	0	0	0	0	0	0	0.02	0.82	7.51	0.49	8.84
total	122	163	98.3	87.5	23.6	16.1	10.5	8.94	9.75	0.49	540

Table 5

Average depth in each combination of slope and depth categories in the Humboldt WEA

Average Depth (m)	<1°	<2°	<3°	<4°	<5°	<6°	<7°	<8°	<9°	<10°
550 to 600m	586.0	594.7	0	0	0	0	0	0	0	0
600 to 800m	683.7	705.5	752.3	780.0	0	0	0	0	0	0
800 to 1000m	800.7	845.3	884.4	898.8	920.3	952.5	978.7	0	0	0
1000 to 1200m	0	1002	1011	1029	1056	1054	1079	1113	1160	0
1200 to 1615m	0	0	0	0	0	0	1211	1226	1316	1387

Table 6

Total storage potential in each combination of slope and depth categories in the Humboldt WEA

Storage (GWh)	<1°	<2°	<3°	<4°	<5°	<6°	<7°	<8°	<9°	<10°	total
550 to 600m	157	0.06	0	0	0	0	0	0	0	0	158
600 to 800m	666	957	267	37.5	0	0	0	0	0	0	1928
800 to 1000m	0.33	255	566	651	157	95.7	18.7	0	0	0	1744
1000 to 1200m	0	0.41	7.73	123	74.1	67.2	94.6	92.1	26.5	0	486
1200 to 1615m	0	0	0	0	0	0	0.25	10.3	101	6.93	118
total	824	1213	841	812	231	163	114	102	127	6.93	4433

Morro Bay (commercial market)

The analysis of Morro Bay is similar to that of Humboldt as they are both commercial markets in California; the parameter assumptions listed in Table 7 for the internal radius, the efficiency, and the packing factor are all the same between the Humboldt and Morro Bay analyses, but the ranges in depths are different across the two sites.

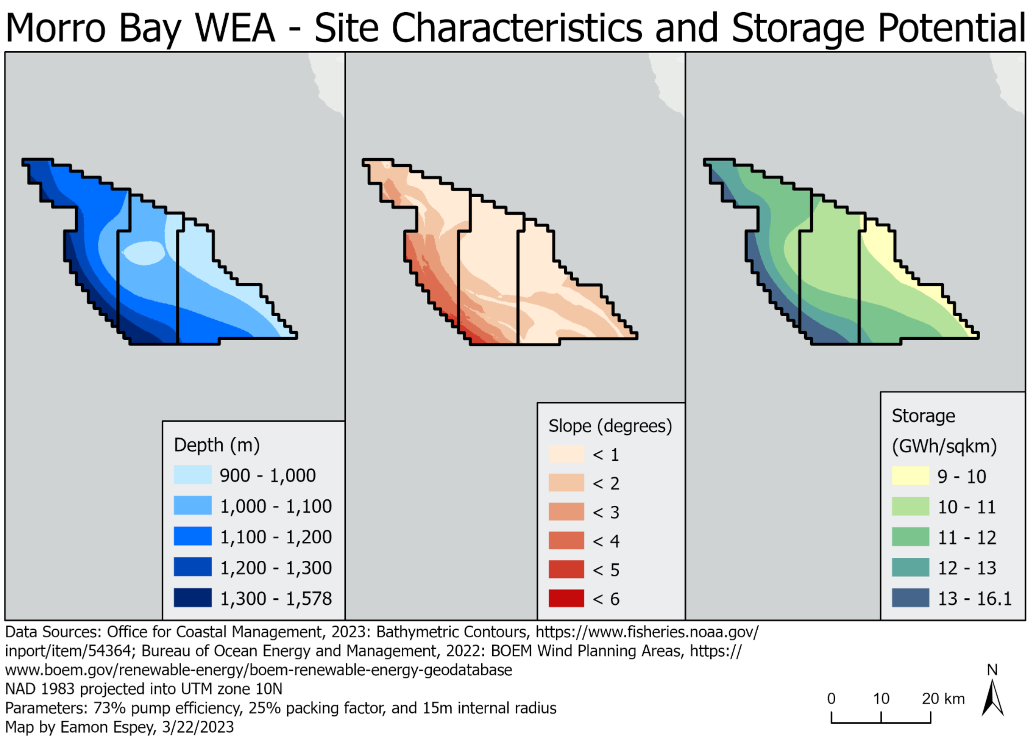
Table 7
Relevant technical parameters of RCAM M-PHES units for Morro Bay wind energy lease area.

Parameters	unit	value
Construction depth	m	900 - 1578
Internal radius	m	15
Efficiency	%	73
Packing factor	%	25

Although the Morro Bay WEA (Figure 6) is deeper on average than the Humboldt wind lease area, it is also generally less steep; both these factors lend Morro Bay to being a very promising site for M-PHES. The Morro Bay WEA ranges from around 30 km to 60 km from the shore; almost half of the WEA is under 1° slope and just over 1% of the wind lease area has a slope steeper than 4°. Additionally, most of the WEA would provide energy storage density in the range of 10 - 13 GWh/km^2.

Figure 6

Water Depth, Slope, and energy storage density in the Morro Bay WEA.



The Morro Bay WEA contains 468 km^2 with a slope under 1°; this could store nearly 5 TWh of energy, which accounts for approximately 45% of the total storage potential in this WEA (slightly more than 11 TWh total). Similar to Tables 4 - 6 for the Humboldt WEA, Tables 8 - 10 show the total area, average depth, and storage potential, respectively, for all combinations of depth and slope categories in the Morro Bay WEA.

Table 8

Total area in each combination of slope and depth categories in the Morro Bay WEA

Area (km^2)	<1°	<2°	<3°	<4°	<5°	<6°	total
900 to 1000m	153.5	39.06	0	0	0	0	192.6
1000 to 1100m	196.5	136.1	0	0	0	0	332.6
1100 to 1200m	112.1	101.8	38.02	0	0	0	251.9
1200 to 1300m	6.21	42.44	48.61	18.24	0	0	115.5

1300 to 1578m	0	2.61	5.71	60.91	13.82	0.12	83.17
total	468.2	322.0	92.34	79.15	13.82	0.12	975.7

Table 9

Average depth in each combination of slope and depth categories in the Morro Bay WEA

Average Depth (m)	<1°	<2°	<3°	<4°	<5°	<6°
900 to 1000m	979.3	965.6	0	0	0	0
1000 to 1100m	1036	1056	0	0	0	0
1100 to 1200m	1131	1151	1158	0	0	0
1200 to 1300m	1206	1233	1251	1260	0	0
1300 to 1578m	0	1309	1316	1376	1444	1501

Table 10

Total storage potential in each combination of slope and depth categories in the Morro Bay WEA

Storage (GWh)	<1°	<2°	<3°	<4°	<5°	<6°	total
900 to 1000m	1532	384.5	0	0	0	0	1917
1000 to 1100m	2075	1466	0	0	0	0	3541
1100 to 1200m	1292	1195	448.9	0	0	0	2936
1200 to 1300m	76.35	533.6	620.2	234.3	0	0	1464
1300 to 1578m	0	34.83	76.62	854.3	203.4	1.837	1171
total	4975	3614	1146	1089	203.4	1.837	11028

Conclusions and Recommendations

In conclusion, Table 11 lists the suggestion sites for RCAM's pilot project in HOST Park, HI.

Table 11

Suggested Sites for RCAM's pilot project in HOST Park, HI.

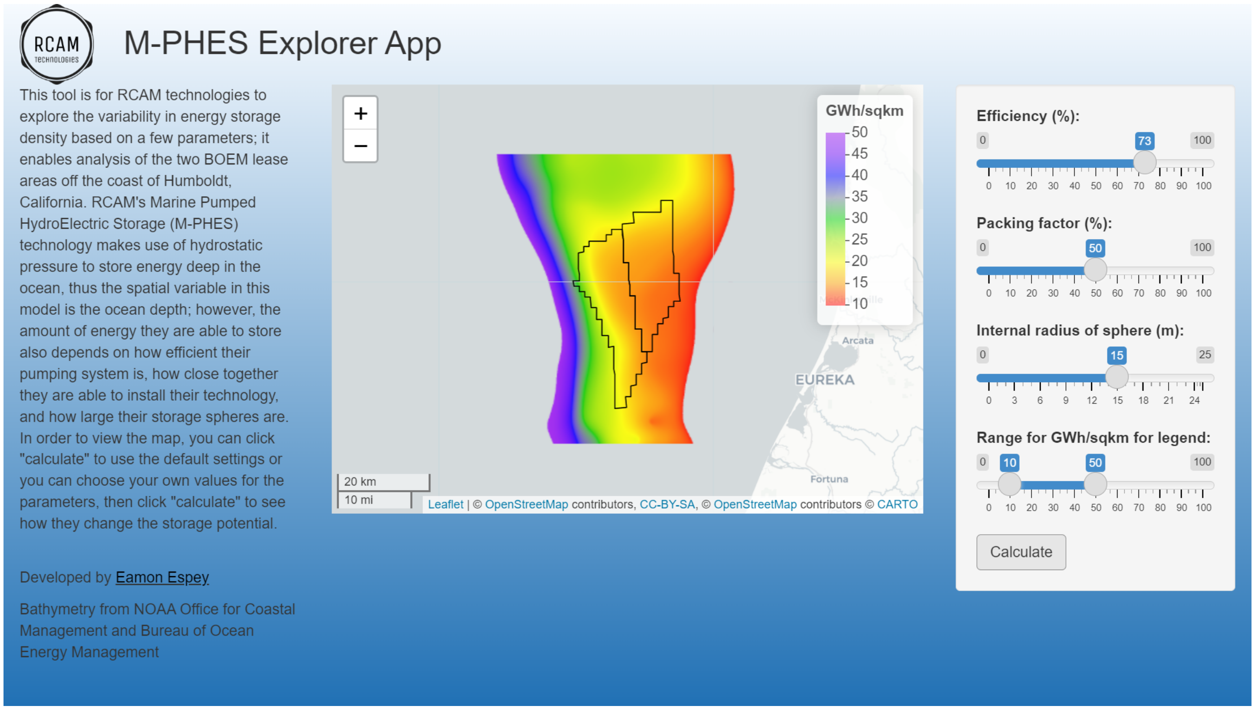
Working water depth (m)	Suggested site	Location	Depth (m)	Slope (°)	Distance to grid connection point (m)	Resource potential (kWh)
500 - 800	1	156.0972° W, 19.7565° N	720	6	5020	2100
	2	156.0768° W, 19.7221° N	700	6	1930	2050
500 - 1500	1	156.0895° W, 19.7208° N	1240	4	3260	3630
	2	156.0987° W, 19.7201° N	1470	8	4200	4300

In Santa Catalina, the major limitations for RCAM to consider are the weather and ship traffic. Wave height and wind speed are the most significant weather related factors and we recommend looking into short term forecasting products like NOAA's WAVEWATCH III model for planning purposes. In terms of planning around ship traffic, the U.S. Coast Guard will be the most helpful partner.

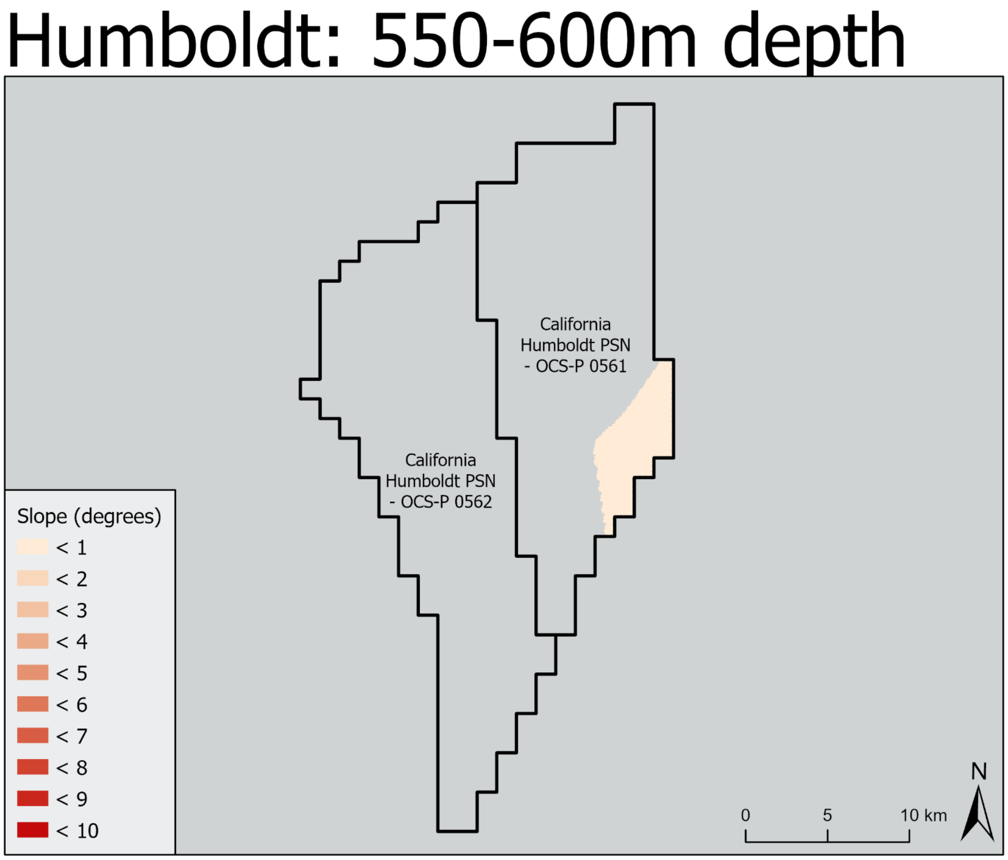
The commercial markets in the Humboldt and the Morro Bay WEAs present significant potential for market success for RCAM and their M-PHES system. All the sublease areas in these WEAs have ample combinations of depth, slope, and resource potential, so any lessees who are willing to partner with RCAM are worth pursuing. The depth is more variable and the terrain is generally more sloped in the Humboldt WEA than in the Morro Bay WEA, but the slope is generally not too extreme in either WEA. As time is of the essence with pursuing these commercial markets, we advise prompt actions to pursue relationships with lessees before it is too late in the permitting process.

Appendix A: M-PHES Parameter Sensitivity App

- https://eespey.shinyapps.io/M-PHES_Planning_Tool/

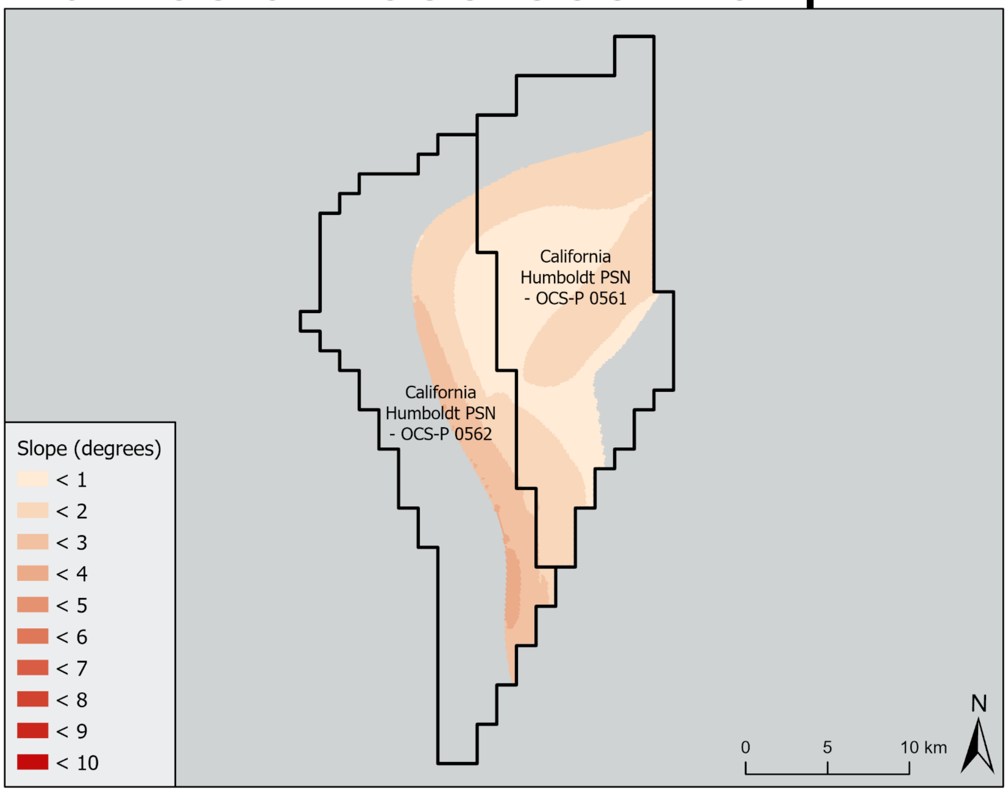


Appendix B: Additional maps for Humboldt WEA



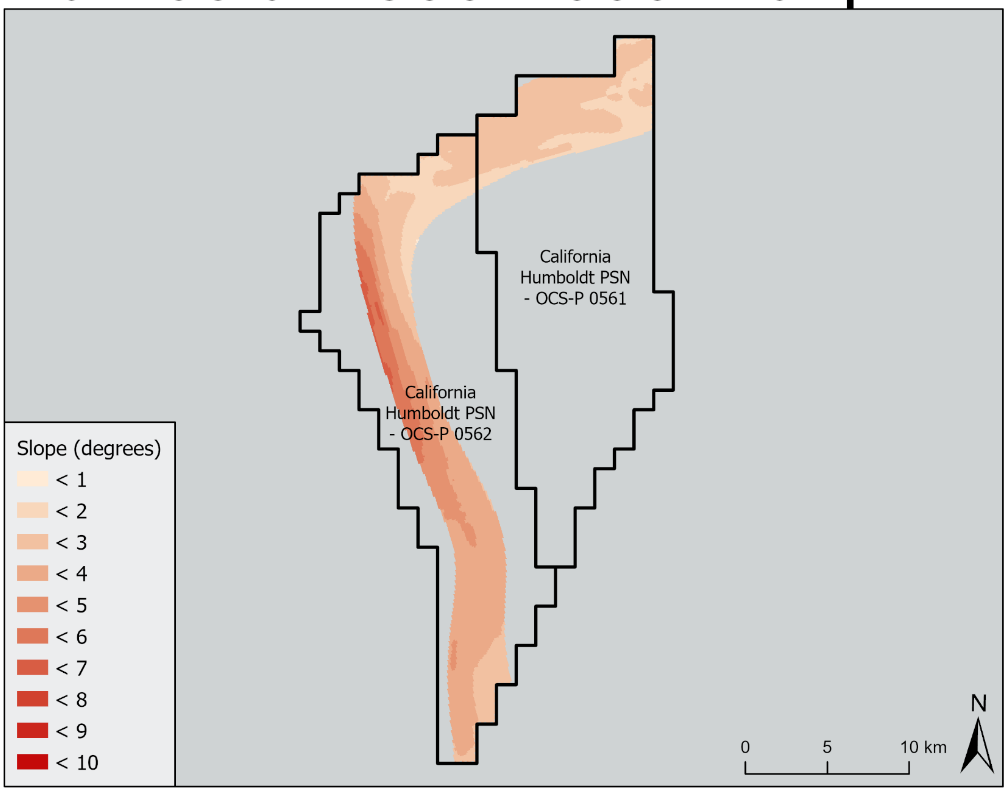
Data Sources: Office for Coastal Management, 2023: Bathymetric Contours, https://www.fisheries.noaa.gov/inport/item/54364; Bureau of Ocean Energy and Management, 2022: BOEM Wind Planning Areas, https://www.boem.gov/renewable-energy/boem-renewable-energy-geodatabase
NAD 1983 projected into UTM zone 10N
Parameters: 73% pump efficiency, 25% packing factor, and 15m internal radius
Map by Eamon Espey, 2/18/2023

Humboldt: 600-800m depth



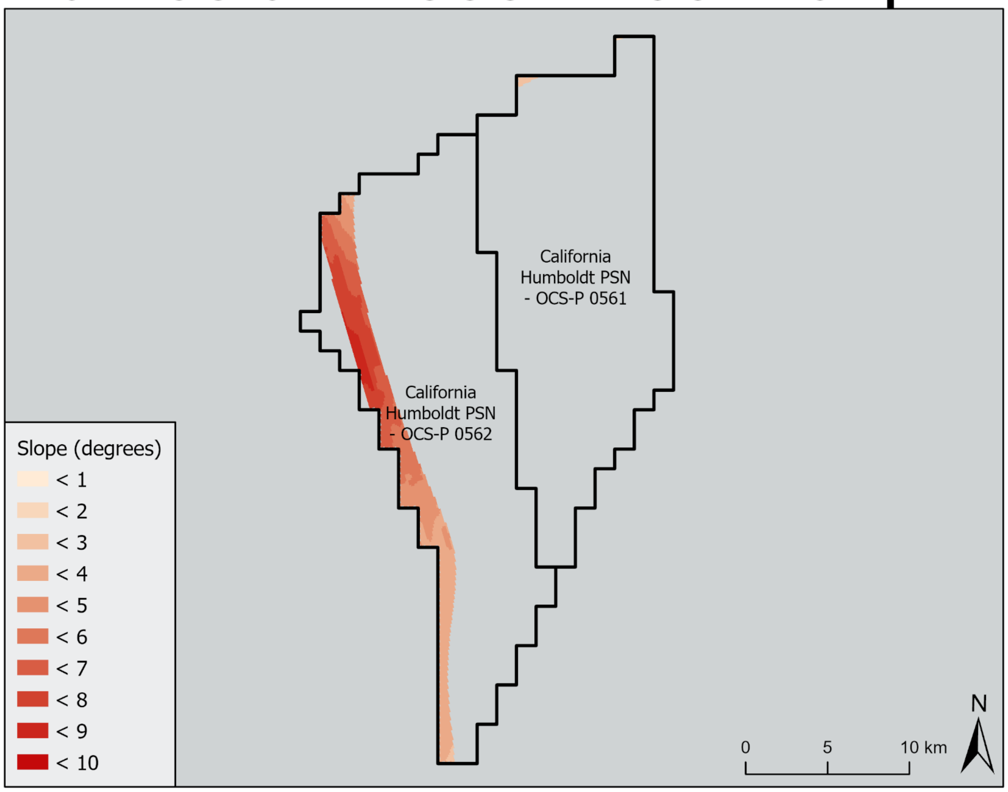
Data Sources: Office for Coastal Management, 2023: Bathymetric Contours, https://www.fisheries.noaa.gov/inport/item/54364; Bureau of Ocean Energy and Management, 2022: BOEM Wind Planning Areas, https://www.boem.gov/renewable-energy/boem-renewable-energy-geodatabase
NAD 1983 projected into UTM zone 10N
Parameters: 73% pump efficiency, 25% packing factor, and 15m internal radius
Map by Eamon Espey, 2/18/2023

Humboldt: 800-1000m depth



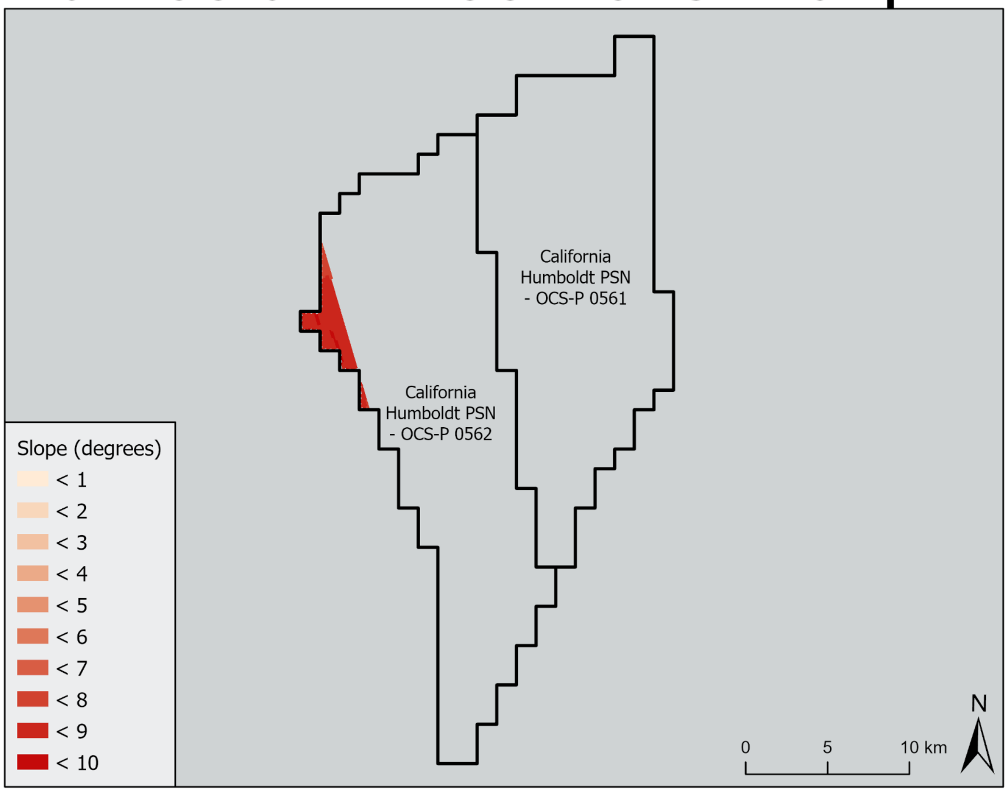
Data Sources: Office for Coastal Management, 2023: Bathymetric Contours, https://www.fisheries.noaa.gov/inport/item/54364; Bureau of Ocean Energy and Management, 2022: BOEM Wind Planning Areas, https://www.boem.gov/renewable-energy/boem-renewable-energy-geodatabase
NAD 1983 projected into UTM zone 10N
Parameters: 73% pump efficiency, 25% packing factor, and 15m internal radius
Map by Eamon Espey, 2/18/2023

Humboldt: 1000-1200m depth



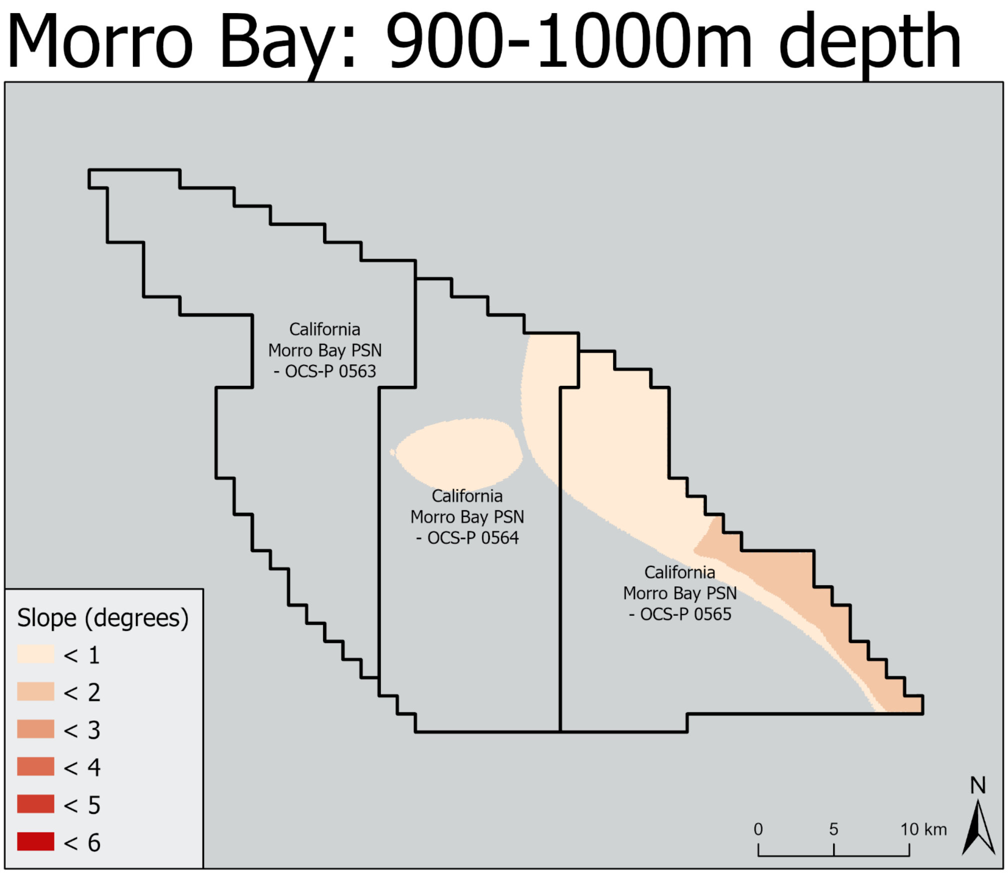
Data Sources: Office for Coastal Management, 2023: Bathymetric Contours, https://www.fisheries.noaa.gov/inport/item/54364; Bureau of Ocean Energy and Management, 2022: BOEM Wind Planning Areas, https://www.boem.gov/renewable-energy/boem-renewable-energy-geodatabase
NAD 1983 projected into UTM zone 10N
Parameters: 73% pump efficiency, 25% packing factor, and 15m internal radius
Map by Eamon Espey, 2/18/2023

Humboldt: 1200-1615m depth



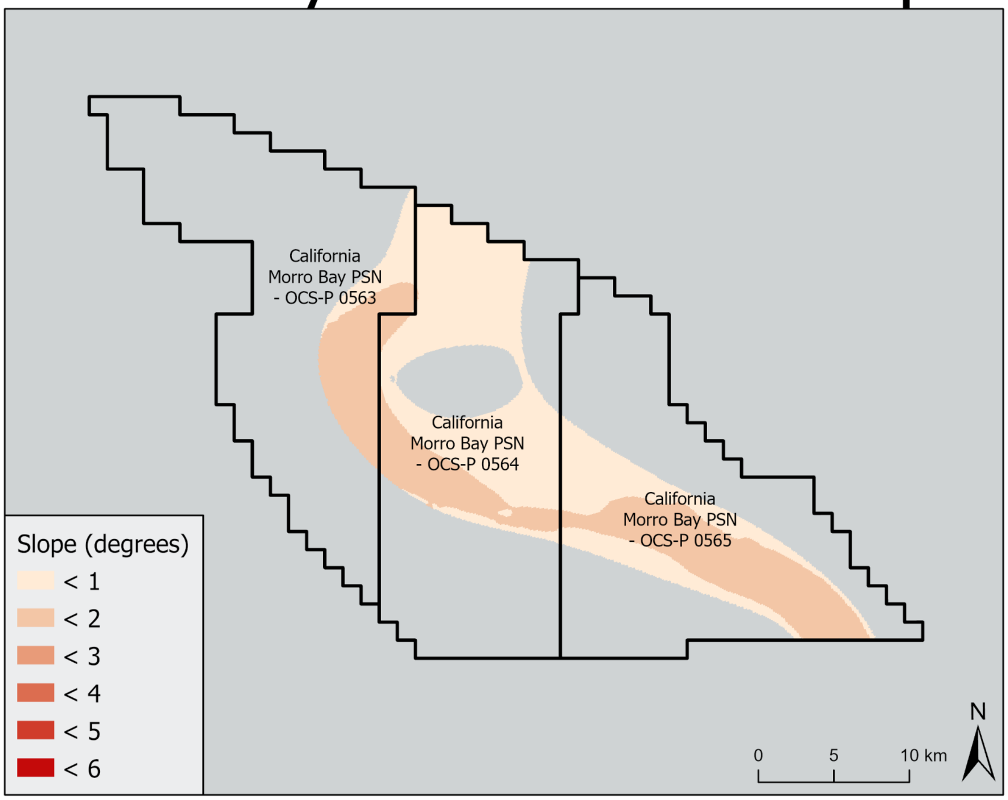
Data Sources: Office for Coastal Management, 2023: Bathymetric Contours, https://www.fisheries.noaa.gov/inport/item/54364; Bureau of Ocean Energy and Management, 2022: BOEM Wind Planning Areas, https://www.boem.gov/renewable-energy/boem-renewable-energy-geodatabase
NAD 1983 projected into UTM zone 10N
Parameters: 73% pump efficiency, 25% packing factor, and 15m internal radius
Map by Eamon Espey, 2/18/2023

Appendix C: Additional maps for Morro Bay WEA



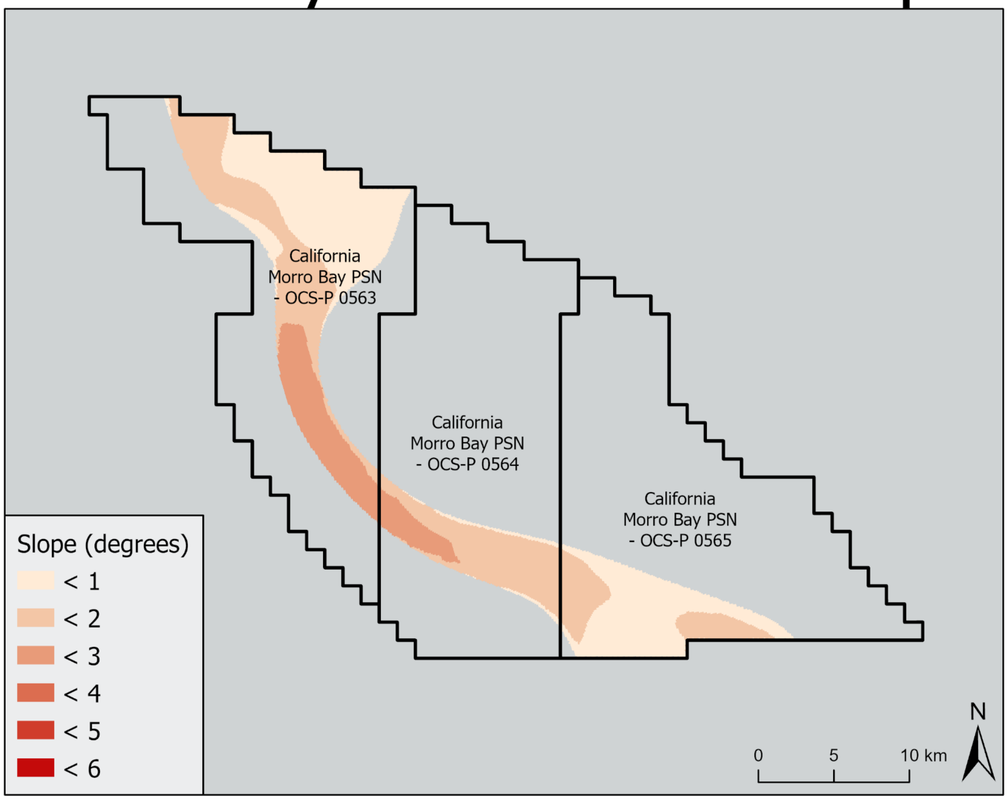
Data Sources: Office for Coastal Management, 2023: Bathymetric Contours, https://www.fisheries.noaa.gov/inport/item/54364; Bureau of Ocean Energy and Management, 2022: BOEM Wind Planning Areas, https://www.boem.gov/renewable-energy/boem-renewable-energy-geodatabase
NAD 1983 projected into UTM zone 10N
Parameters: 73% pump efficiency, 25% packing factor, and 15m internal radius
Map by Eamon Espey, 3/21/2023

Morro Bay: 1000-1100m depth



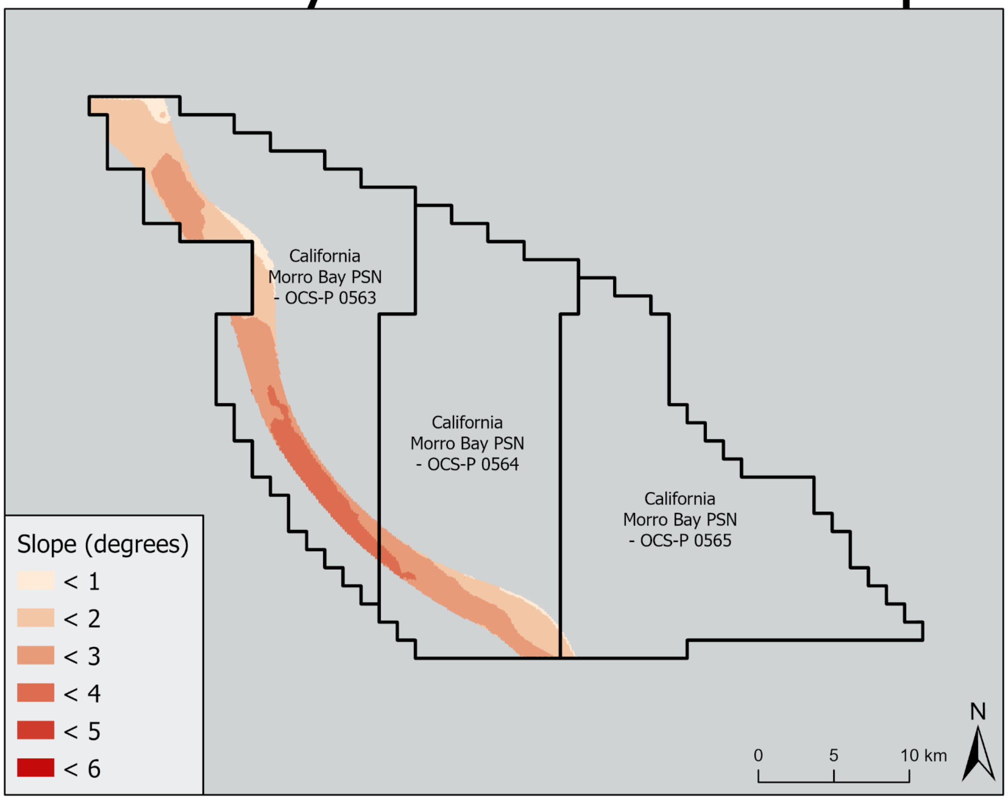
Data Sources: Office for Coastal Management, 2023: Bathymetric Contours, https://www.fisheries.noaa.gov/inport/item/54364; Bureau of Ocean Energy and Management, 2022: BOEM Wind Planning Areas, https://www.boem.gov/renewable-energy/boem-renewable-energy-geodatabase
NAD 1983 projected into UTM zone 10N
Parameters: 73% pump efficiency, 25% packing factor, and 15m internal radius
Map by Eamon Espey, 3/21/2023

Morro Bay: 1100-1200m depth



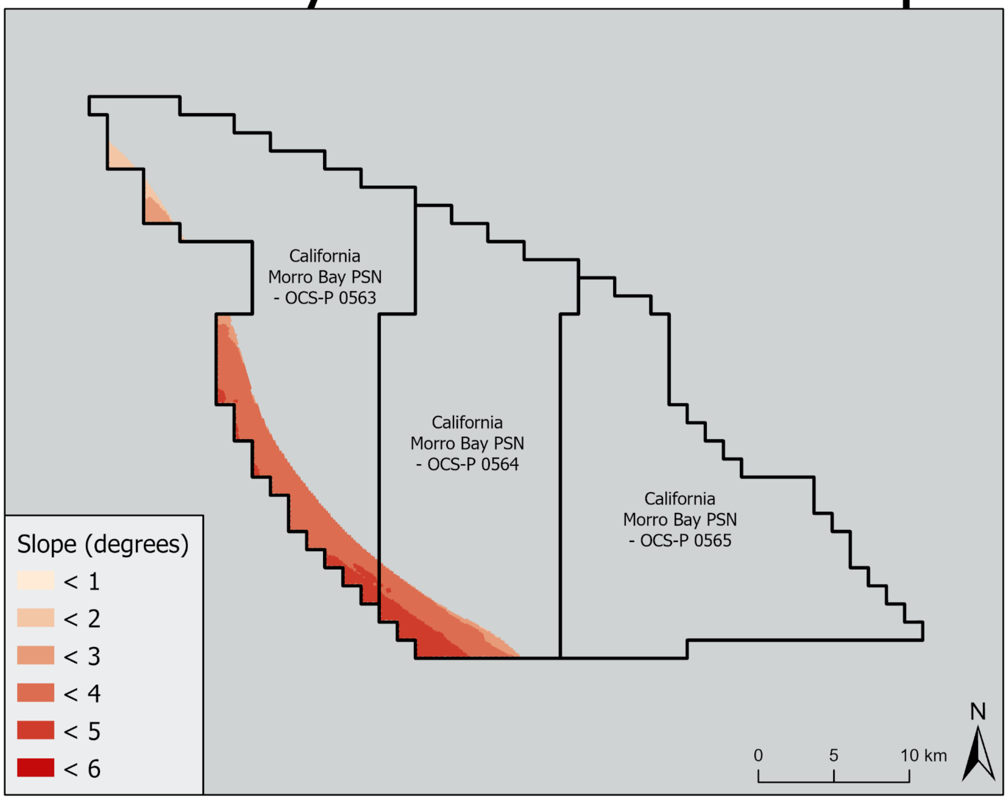
Data Sources: Office for Coastal Management, 2023: Bathymetric Contours, https://www.fisheries.noaa.gov/inport/item/54364; Bureau of Ocean Energy and Management, 2022: BOEM Wind Planning Areas, https://www.boem.gov/renewable-energy/boem-renewable-energy-geodatabase
NAD 1983 projected into UTM zone 10N
Parameters: 73% pump efficiency, 25% packing factor, and 15m internal radius
Map by Eamon Espey, 3/21/2023

Morro Bay: 1200-1300m depth



Data Sources: Office for Coastal Management, 2023: Bathymetric Contours, https://www.fisheries.noaa.gov/inport/item/54364; Bureau of Ocean Energy and Management, 2022: BOEM Wind Planning Areas, https://www.boem.gov/renewable-energy/boem-renewable-energy-geodatabase
NAD 1983 projected into UTM zone 10N
Parameters: 73% pump efficiency, 25% packing factor, and 15m internal radius
Map by Eamon Espey, 3/21/2023

Morro Bay: 1300-1578m depth



Data Sources: Office for Coastal Management, 2023: Bathymetric Contours, https://www.fisheries.noaa.gov/inport/item/54364; Bureau of Ocean Energy and Management, 2022: BOEM Wind Planning Areas, https://www.boem.gov/renewable-energy/boem-renewable-energy-geodatabase
NAD 1983 projected into UTM zone 10N
Parameters: 73% pump efficiency, 25% packing factor, and 15m internal radius
Map by Eamon Espey, 3/21/2023

Impact Assessment of RCAM's M-PHES Technology on Marine Life, Water Quality, and Geology

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UM SEAS and RCAM Technologies Master of Science Capstone Partnership

SCHOOL FOR ENVIRONMENT & SUSTAINABILITY
UNIVERSITY OF MICHIGAN

Introduction: Lessons from Offshore Wind

Of the 651 gigawatts of installed wind energy capacity worldwide, offshore wind farms represent a mere 4.5%.[1] Thanks to technological advances, growing private enterprise, and global political change, offshore wind is poised to take a much larger share of the wind energy and broader renewable energy markets in a matter of years, especially in the United States. Nearly all of the information currently available on the environmental impacts of offshore wind is derived from studies conducted in European waters and at European wind farms. Since the early 2000s, U.S. regulatory agencies have also increased their attention to and capacity to regulate issues of offshore wind environmental compliance, which has become even more relevant in 2023 as multiple commercial lease auctions have taken place or will soon.[2] Therefore, the following environmental assessment draws extensively on academic literature and key lessons learned from offshore wind development and environmental assessments to date. Where possible, we extrapolate relevant wind turbine findings and hypothesize the perceived impact of RCAM Technologies' marine pumped-hydroelectric storage spheres on the U.S. marine environments where they will be commercially deployed in tandem with offshore wind.

Artificial Reefs

The Rhode Island Sea Grant writes that wind turbines can attract fish by providing shelter and food.[3] Wind turbines and other man-made structures of hard substrates that serve this function in marine environments are known as artificial reefs.[4] Organisms like mussels that grow on turbines increase the nutrients of the surrounding area. Researchers at the Rhode Island Sea Grant also found that these areas can play a role in the life cycle of certain fish. They are able to grow in the area before leaving to breed and the cycle can continue with new young fish. These areas can act as de facto marine protected areas if fishing in wind farm areas is disallowed; therefore, this preserves the habitat on the seafloor. However, scientists are unsure if the turbines simply attract fish from other locations or are actually increasing the quantity of fish in these certain areas.

Wind turbines could create an entirely new ecosystem of benthos organisms and possibly displace non-mobile benthos organisms like clams and oysters, which can be a positive.[5] Attraction of new species to the turbine area will change the ecosystem dynamics, and existing research shows a verifiable increase in biodiversity. After looking at waters surrounding the United Kingdom, Dr. Emma Sheehan, an associate professor of marine ecology at University of Plymouth, stated "in areas that were heavily degraded seabed, we've seen that the mussel shell fallout onto the seabed habitat seems to be increasing biodiversity. It's restoring benthic habitats. It's also increasing the benthic commercially valuable species such as lobster and crab on the

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[1] Degraer, S., D.A. Carey, J.W.P. Coolen, Z.L. Hutchison, F. Kerckhof, B. Rumes, and J. Vanaverbeke. 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning: A synthesis. *Oceanography* 33(4):48–57, https://doi.org/10.5670/oceanog.2020.405.

[2] "National Environmental Policy Act and Offshore Renewable Energy." Bureau of Ocean and Energy Management. https://www.boem.gov/renewable-energy/national-environmental-policy-act-and-offshore-renewable-energy. Accessed 12 Feb. 2023.

[3] Rhode Island Sea Grant. "Offshore Renewable Energy Improves Habitat, Increases Fish." Rhode Island Sea Grant, 29 July 2020, https://seagrant.gso.uri.edu/offshore-renewable-energy-improves-habitat-increases-fish/.

[4] Degraer, S., D.A. Carey, J.W.P. Coolen, Z.L. Hutchison, F. Kerckhof, B. Rumes, and J. Vanaverbeke. 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning: A synthesis. *Oceanography* 33(4):48–57, https://doi.org/10.5670/oceanog.2020.405.

[5] Degraer, S., D.A. Carey, J.W.P. Coolen, Z.L. Hutchison, F. Kerckhof, B. Rumes, and J. Vanaverbeke. 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning: A synthesis. *Oceanography* 33(4):48–57, https://doi.org/10.5670/oceanog.2020.405.

seabed."

"Although various types of corals can be found from the water's surface to depths of 6,000 m, reef-building corals are generally found at depths of less than 46 m, where sunlight penetrates."[6] Likewise, few if any species who would call artificial reefs home reside hundreds of meters deep.[7] Given the optimal operating depths of RCAM's storage spheres and the fact that they would not be attached to fixed bottom turbines, the beneficial artificial reef effect would not apply.

Fishing Industry

Many fishermen in the US are opposed to offshore wind farms due to restricted access to fishing areas as well as increased competition due to smaller fishing space. Experts stress that the government must involve fishermen from the beginning of the process in order to decrease conflict.[8] This approach of early fishermen involvement led to success in the case of the Block Island Wind Farm (BIWF). Furthermore, the development of Block Island Wind Farm produced an overall positive effect on recreational fishers in the area. This is because the BIWF creates an artificial reef effect around the turbine foundations, helping attract fish to the area and also providing an easy landmark for fishermen to find.[9] This increase in productivity can also attract larger predators, which is a plus for fishermen as well who want to catch larger species. Contrary to this benefit, there were some concerns expressed about overcrowding of fishermen at the turbine sites. Commercial fisheries in Europe have opposed offshore wind. They raise concerns over ship and equipment damage as well as having to change navigation routes. Since RCAM's technology will not create an artificial reef effect, other options when considering the benefits or downsides for fishermen should be considered.

The European Maritime Spatial Planning platform proposes a number of solutions to help mitigate the effects on commercial fishing.[10] They suggest working with fishermen and residents during the planning stages to ensure their concerns are addressed to the extent possible, as well as drawing upon their regional knowledge to map out and avoid areas that are of high socio-economic importance. Furthermore, allowing migration corridors for boats to either pass through or access specific fishing grounds could also alleviate concerns. Early consultation from planning to construction to implementation is key in order to avoid conflict. Because the optimal depths at which RCAM's commercial technology will operate (700-1500 meters) overlaps with commercial fishing depths,[11] we similarly recommend RCAM engage relevant community stakeholders early and often in the construction process in order to avoid the issues mentioned above. Additionally, depending on how exactly RCAM partners with offshore wind developers and lease holders, we recommend leveraging the leasee's existing community advocacy networks

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6 Degraer, S., D.A. Carey, J.W.P. Coolen, Z.L. Hutchison, F. Kerckhof, B. Rumes, and J. Vanaverbeke. 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning: A synthesis. Oceanography 33(4):48–57, https://doi.org/10.5670/oceanog.2020.405.

7 Degraer, S., D.A. Carey, J.W.P. Coolen, Z.L. Hutchison, F. Kerckhof, B. Rumes, and J. Vanaverbeke. 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning: A synthesis. *Oceanography* 33(4):48–57, https://doi.org/10.5670/oceanog.2020.405.

8 Badding, Margaret. "Offshore Wind and the Fishing Industry: The Path to Co-Existence." Kleinman Center for Energy Policy, 21 June 2021, https://kleinmanenergy.upenn.edu/news-insights/offshore-wind-and-the-fishing-industry-the-path-to-co-existence/.

9 Smythe, Tiffany, et al. "Optimistic with Reservations: The Impacts of the United States' First Offshore Wind Farm on the Recreational Fishing Experience." Marine Policy, vol. 127, 2021, p. 104440., https://doi.org/10.1016/j.marpol.2021.104440.

10 "Offshore Wind and Fisheries." The European Maritime Spatial Planning Platform, 15 Nov. 2021, https://maritime-spatial-planning.ec.europa.eu/sector-information/offshore-wind-and-fisheries.

11 Bland, Alastair. "Race to the Bottom: Impact of Deep-Sea Fishing Severely Underestimated." *Oceans*, News Deeply, 16 Apr. 2018, https://deeply.thenewhumanitarian.org/oceans/articles/2018/04/16/race-to-the-bottom-impact-of-deep-sea-fishing-severely-underestimated.

to avoid duplicating efforts and to operate as a unified front when negotiating with stakeholders.

Noise Impact and Mitigation

The long term effects on marine life from exposure to noise and magnetic fields from wind turbines are unknown.[12] However, temporary turbidity and noise from construction can disturb vegetation and fish species.[13] To address these concerns, many organizations have been working on ways to mitigate and monitor any issues that may affect marine life due to offshore wind farms. Passive acoustic monitoring (PAM) is one strategy that can continuously record marine environments using acoustic sensors.[14] According to the World Wildlife Foundation Conservation Technology series from 2017, "acoustic sensors are small, increasingly affordable and non-invasive, and can be deployed in the field for extended times to monitor wildlife and their acoustic surroundings." PAM is commercially available but the bulk of the cost comes from paying to analyze the data after it is collected.[15] The sensors can be deployed either as buoys or on the ocean floor. NOAA's website states that their framework for PAM "will help wind developers reduce the impact of offshore wind energy projects on marine animals. The national framework applies before, during, and after project construction." These sensors can be installed at depths ranging from 500-6,700 meters which is well within the range of RCAM's technology. As such, this could be a useful tool for RCAM as an environmental precaution.

Marine Spatial Planning (MSP) is another strategy renewable energy actors can use to lessen wildlife disturbances. UNESCO defines marine spatial planning as "a public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives that have been specified through a political process." Processes like MSP allow developers, along with residents of the area, to ensure that all needs are heard and that decisions are made in a balanced way. This ensures protection of the environment while also taking into account social and economic factors such as recreation and fishing. A case study by the World Ocean Council found success using MSP when looking to implement a Special Area Management Plan (SAMP) in Rhode Island that involved government agencies, scientists, and community stakeholders.[16] This establishment of transparency and trust early on allowed the process to be streamlined. A major takeaway from this case study is that the large number of agencies involved led to a lack of clarity of responsibilities, thus the case study recommends increased communication and outlining of roles for future projects utilizing the MSP strategy.

The California coast is home to a number of different whale species including: Gray, sperm, humpback, minke, orca, blue, and fin whales. Humpback whales, included in the endangered species list, reside off the California coast from late April to early December and use coastal waters as their feeding and breeding ground. Similarly, the gray whale migration pattern from Alaska to Baja California cuts down the California coast. Blue whales are also on the endangered

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[12] Rhode Island Sea Grant. "Offshore Renewable Energy Improves Habitat, Increases Fish." Rhode Island Sea Grant, 29 July 2020, https://seagrant.gso.uri.edu/offshore-renewable-energy-improves-habitat-increases-fish/.

[13] Inger, Richard, et al. "Marine Renewable Energy: Potential Benefits to Biodiversity? an Urgent Call for Research." *Journal of Applied Ecology*, vol. 46, no. 6, 2009, pp. 1145–1153., https://doi.org/10.1111/j.1365-2664.2009.01697.x.

[14] Fisheries, NOAA. "NOAA Fisheries." | NOAA Fisheries, https://www.fisheries.noaa.gov/topic/offshore-wind-energy/protecting-marine-life.

[15] Browning, Ella, et al. *Acoustic Monitoring Guide - the World Wildlife Fund*. WWF-UK, 2017, https://www.wwf.org.uk/sites/default/files/2019-04/Acousticmonitoring-WWF-guidelines.pdf.

[16] "WOC MSP Case Studies (Mar 2016)." *World Ocean Council*, 2016, https://www.oceancouncil.org/woc-msp-case-studies-mar-2016/.

species list with a large population off the coast of California, comprising about 20% of the remaining species. Orca whales can be found off the coast of California year round. To avoid potential interactions with these various species of whales, we recommend RCAM try to plan construction around the time frame in which transient or migratory species of whales heavily reside in the waters.

Sound communication is extremely important for the survival of whales. Noise pollution can interrupt their behavior as a disturbed ocean leaves less communication space for whales to hear each other.[17] According to the NOAA fisheries species directory, "noise can also cause marine mammals to change the frequency or amplitude of calls, decrease foraging behavior, become displaced from preferred habitat, or increase the level of stress hormones in their bodies." Impacts to mammals from ocean noise can be immediate, or they may happen over a period of time after repeated exposure. This presents another good reason why RCAM would want to plan construction around the whales migration patterns as this would also avoid the chances of noise pollution from RCAM's technology affecting these animals.

BOEM recently conducted a study on the impacts of offshore wind in California on seabirds and mammals. The study area was focused from Monterey Bay to the California-Mexico border. When looking at the impact of sound and noise on mammals specifically, researchers found that during the operational phase of offshore floating wind, noise is low intensity and "generally expected to add to the normal background acoustic environment over time."[18] Operational noise is largely regarded as a secondary concern compared to noise during construction and site assessment. Although operational noise is a lower frequency and less physically damaging, modeling on the Hornsea 3 offshore wind farm in the U.K. showed that operational noise would cause injury to mammals within 10 meters. Floating offshore wind is expected to generate considerably less noise due to the lack of foundations coming into contact with the seafloor, which RCAM should take into consideration since the spheres will in fact be located on the ocean floor. Researchers found that mammals with the highest level of vulnerability were low-frequency cetaceans and pinnipeds: baleen whales, seals, and sea lions, with ranges from 7 Hz to 86 kHz.

In addition to mammals, fish can also be affected by underwater noise pollution. Certain species of fish have a swim bladder that is connected to the ear, increasing their sensitivity to noise and sound pressure. The most noise-sensitive fish are those in the Clupeidae family that possess this trait. These fish are especially vulnerable to any increase in noise activity that can cause damage or even death at a much lower frequency than other species.[19] [20]

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[17] "Noise Pollution." *National Geographic Society*, https://education.nationalgeographic.org/resource/noise-pollution.

[18] BOEM. "Seabird and Marine Mammal Surveys Near Potential Renewable Energy Sites Offshore Central and Southern California (PC-17-01)." 2022.

[19] Popper, A.N. *et al.* (2014). Sound Exposure Guidelines. In: ASA S3/SC1.4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. SpringerBriefs in Oceanography. Springer, Cham. https://doi.org/10.1007/978-3-319-06659-2_7

[20] Thomsen, Frank, et al. "Potential Effects of Offshore Wind Farm Noise on Fish." *Bioacoustics*, vol. 17, no. 1-3, 2008, pp. 221–223., https://doi.org/10.1080/09524622.2008.9753825.

Overall, the study concluded that when it comes to noise and sound pollution, humpback whales, killer whales, and pelagic fish (fish in the open water column) have the highest level of vulnerability due to the whale's reliance on echolocation and increased sound sensitivity of pelagic fish. For whales specifically, researchers stated, "low-frequency operational noise from turbines may cause masking and limit communication." Furthermore, the study listed the humpback whale as the species with the lowest recovery potential out of all marine mammal species in California.

Electromagnetic Impact and Mitigation:

All electrical equipment can generate electromagnetic fields(EMFs) at run-time. This radiation is called artificial industrial frequency type radiation.[21] As natural magnetic, electric, and electromagnetic fields provide important ecological cues to magneto-receptive and electro-receptive species to locate predators or prey and navigate and orient through water, these anthropogenic electromagnetic fields may possibly cause effects on the biological rhythms and habits of some marine species, including the benthos that are sensitive to electromagnetic fields.[22]

The spheres in the M-PHES has a power output capacity of 5 MW and will generate an electromagnetic field. However, the strength and the nature of the electromagnetic field may be reduced as the pump is located inside the sphere and therefore shielded/isolated from the surrounding environment. The potential affected species in the research area include sea turtles and whales, marine demersal species, elasmobranchs, shellfish and benthic invertebrates. The affected range for electromagnetic field varies greatly among species, from 1μT- 4000μT[23] (Table 1). For benthic invertebrates, they could be physiologically affected by magnetic fields of below 100μT, down to just 1μT. However, though there is evidence that EMFs sensitive species will respond to anthropogenic EMFs, the speculation that EMFs will affect the marine species significantly is speculative.[24]

Though the affect from EMF to marine life could be reverse, the impact of electromagnetic fields on marine life does exist. Currently, there are no clear regulations specifying the thresholds for electromagnetic fields in offshore wind energy, only recommendations for the materials and mitigation methods to be adopted for the cables. A report of restrictions on renewable structures has mentioned that: EMF during operation may be mitigated by use of armored cable for inter-array and export cables which should be buried at a sufficient depth. Some research has shown that where cables are buried at depths greater than 1.5m below the sea bed impacts are likely to be negligible. However sufficient depth to mitigate impacts will depend on the geology of the sea bed.[25]

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[21] Zheng, Lina, Liying Zheng, and Li Wei. "Environmental Impact and Control Measures of New Wind Power Projects." Procedia Environmental Sciences 10 (2011): 2788-91. Print.
[22] Hutchison, Zoë L., et al. "Anthropogenic electromagnetic fields (EMF) influence the behaviour of bottom-dwelling marine species." Scientific reports 10.1 (2020): 4219.
[23] Gill, Andrew B., et al. "Marine renewable energy, electromagnetic (EM) fields and EM-sensitive animals." Marine renewable energy technology and environmental interactions (2014): 61-79.
[24] Tricas, Timothy, and Andrew B. Gill. "Effects of EMFs from Undersea Power Cables on Elasmobranchs and Other Marine Species." (2011).
[25] DECC. "National Policy Statements for Energy Infrastructure." (2011).

For RCAM case, because of the depth of the ocean where the M-PHES is located, it is difficult to have no impact on benthic organisms, considering some species are extremely sensitive to EMF. To mitigate the impact, a report has suggested that if the magnetic field remains below 300µT, then some less mobile species such as crustaceans and shellfishthe. To reduce the impact of EMFs, burying the source of EMFs below the sea floor or covering the source of EMFs with 6- to 12-inch thick concrete mattresses, rock berms.

Table 1

Affected EMFs Range for Marine Life

Species group	Lowest published detection levels		Lowest published behavioural response levels		Lowest published physiological change levels	
	Induced electric fields (iE-field) (µV/m)	Magnetic field (B-field) (µT)	Induced electric fields (iE-field) (µV/m)	Magnetic field (B-field) (µT)	Induced electric fields (iE-field) (µV/m)	Magnetic field (B-field) (µT)
Salmonids	8µV/m	No data identified	No data identified	600-1000µT	7,000µV/m	2000µT (improvements at low magnetic fields 0.1-50µT)
European eel*	8µV/m	No data identified	No data identified	5µT	7,000µV/m	12.6µT*
Lampreys	8µV/m	No data identified	No data identified	No data identified	No data identified	No data identified
Other marine pelagic species	8µV/m	No data identified	No data identified	No data identified	No data identified	>10,000µT
Other marine demersal species	8µV/m	No data identified	No data identified	No data identified	No data identified	>3,700µT
Elasmobranchs	0.0061µV/m	0.000037µT	<600µV/m (attraction) >400µV/m (avoidance)	25µT	No data identified	No data identified
Shellfish: Crustaceans	No data identified	No data identified	No data identified	314µT	No data identified	>3,700µT

Morro Bay Final Environmental Assessment

Marine Life

BOEM conducted an environmental assessment (EA) of the Morro Bay wind energy area in 2022. The EA includes sections about Marine and Coastal Habitats and Associated Biotic Assemblages, Marine Mammals and Sea Turtles, Coastal and Marine Birds, and Commercial Fishing.

With regards to marine and coastal habitats, the wind energy lease area does not include any Area of Special Biological Significance, National Park, or National Marine Sanctuary. However, there are still several key habitats which need to be considered.

First, the outer shelf and upper slope habitats are important and defined as “soft and hard substrates at depths between 100 m and 1500 m.”[26] The seafloor of the wind energy area is confined between 900 to 1300 meters of upper slope habitats. Species inhabiting this area include echinoderms (e.g., sea cucumbers, sea stars, brittle stars, urchins, and crinoids), cnidarians (e.g., sea pens and anemones), and a variety of crustaceans, molluscs, brachiopods,

[26] US Department of the Interior, Bureau of Ocean Management Pacific Region. Commercial Wind Lease and Grant Issuance and Site Assessment Activities on the Pacific Outer Continental Shelf Morro Bay Wind Energy Area, California Final Environmental Assessment. Morro Bay Wind Energy Area, 2022.

and sponges.[27] Corals and sponges were also present along with rockfishes. The EA found that in this area organisms could be crushed by anchors placed and the anchor could cause turbidity in the water, which should be a concern for RCAM since the proposed sphere diameter is around 30 meters with a weight that could exceed thousands of tons.

Second, the pelagic environment consists of open ocean and is home to many fish species. The EA found that noise could alter fish behavior within the wind energy area, but this is expected to only be a temporary effect. As stated in their report, "Noise impacts from HRG(high-resolution geophysical) surveys and project vessels to EFH(essential fish habitat) and fishes would be minimal and temporary in duration." RCAM should expect any sound impact to be short lived due to the fact that sphere installation of RCAM's technology is temporary and the EA found noise to be a temporary impact as well.

Looking at marine mammals and sea turtles, BOEM examined species likely to be present within the wind energy area based on current and expected range of occurrence. The following species with critical habitats were identified within the proposed area: North Pacific Right Whales, Blue Whales, Fin Whales, Humpback Whales, Gray Whales, Harbor Porpoise, Northern Elephant Seals, and Leatherback Sea Turtles. Density during the summer and fall for the whale species can be found in figures 1, 2, and 3 below. The EA found that impacts for mammals and sea turtles within the area would be noise impact, collision with vessels, and entanglement in mooring systems. Acoustic thresholds for noise disturbance can be found in Table 2 below.[28] Permanent threshold shift results in permanent hearing loss while temporary threshold shift is a temporary loss in hearing function related to the exposure level and durations.

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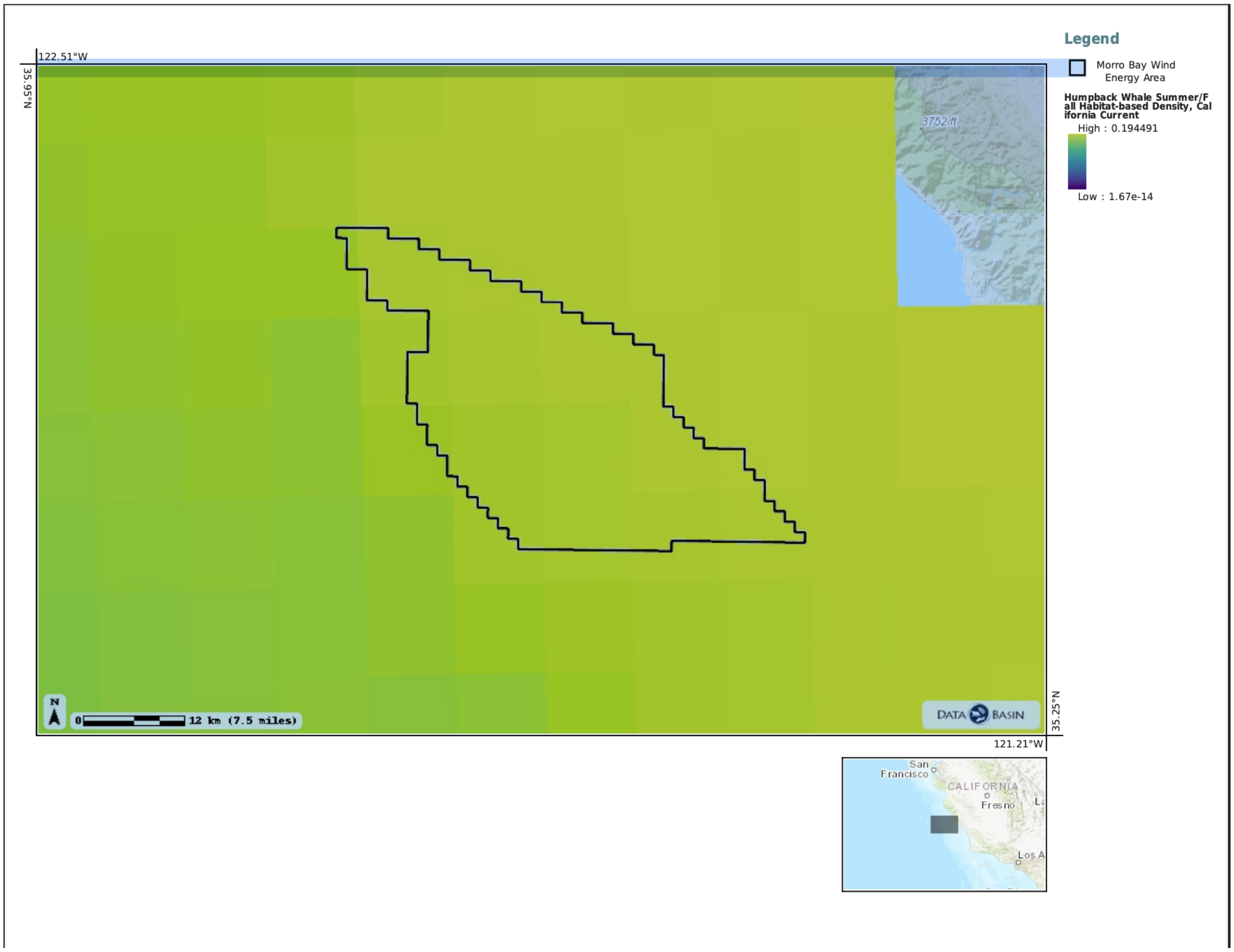
[27] Cochrane, G. R., Kuhnz, L. A., Gilbane, L., Dartnell, P., Walton, M. A. L., & Paull, C. K. (2022). California Deepwater Investigations and Groundtruthing (Cal DIG) I, volume 3 — Benthic habitat characterization offshore Morro Bay, California (2022-1035). Retrieved from Reston, VA: http://pubs.er.usgs.gov/publication/ofr20221035

[28] US Department of the Interior, Bureau of Ocean Management Pacific Region. Commercial Wind Lease and Grant Issuance and Site Assessment Activities on the Pacific Outer Continental Shelf Morro Bay Wind Energy Area, California Final Environmental Assessment. Morro Bay Wind Energy Area, 2022.

Figure 1

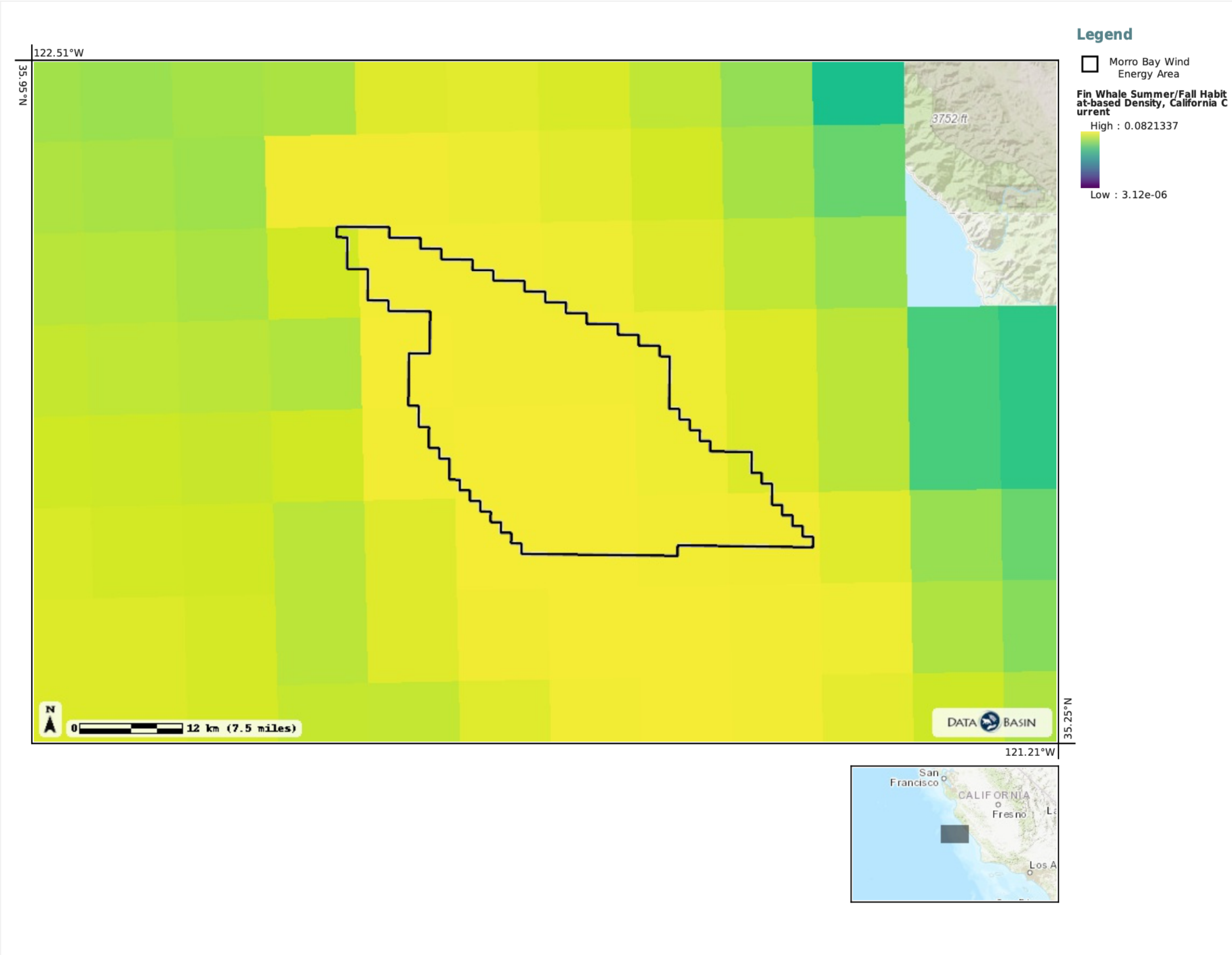
Summer/Fall Habitat based density of the Humpback Whale



Note. This map shows Humpback Whale density within the Morro Bay WEA.

Figure 2

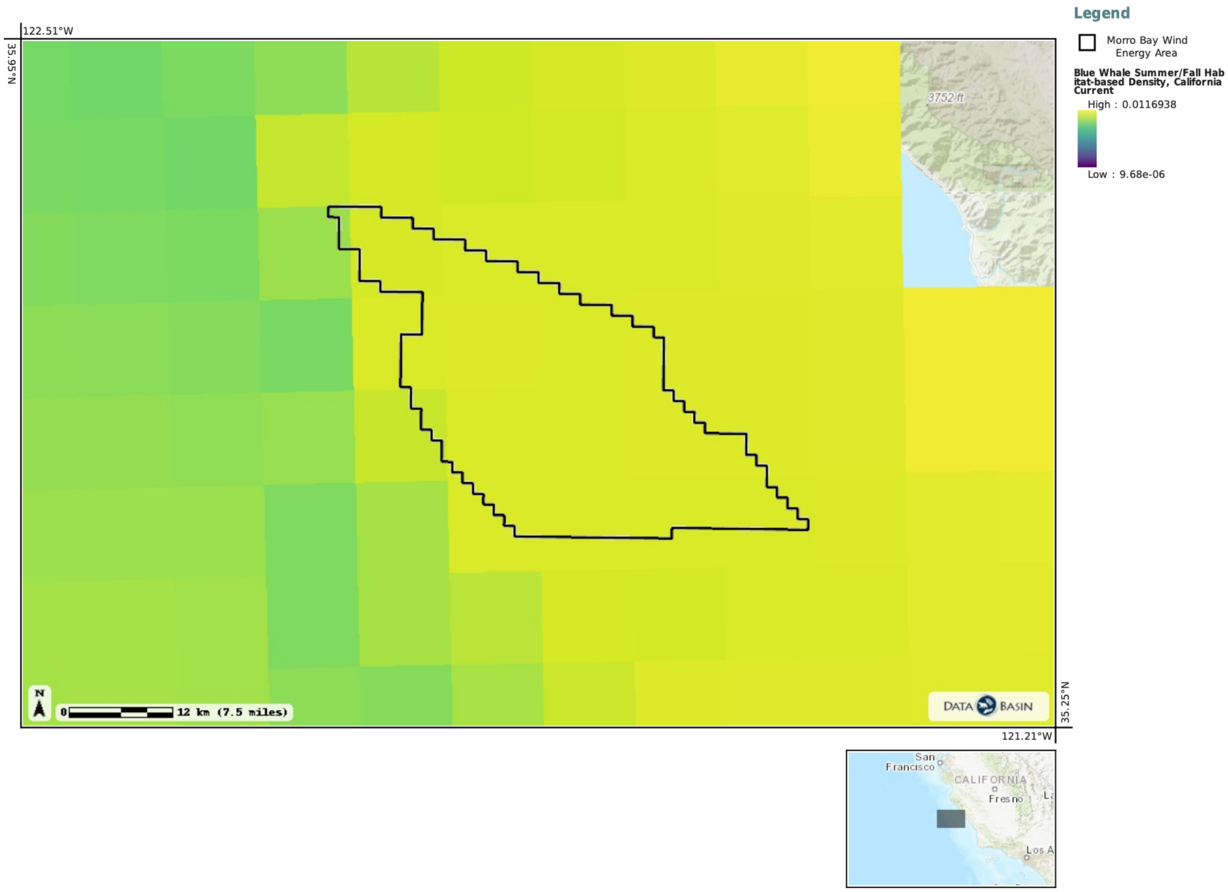
Summer/Fall Habitat based density of the Fin Whale



Note. This map shows Fin Whale density within the Morro Bay WEA.

Figure 3

Summer/Fall Habitat based density of the Blue Whale



Note. This map shows Blue Whale density within the Morro Bay WEA.

Table 2

Impulsive Acoustic Thresholds

Hearing Group	Generalized Hearing Range	Permanent Threshold Shift Onset	Temporary Threshold Shift Onset
Low frequency (e.g., Baleen Whales)	7 Hz to 35 kHz	219 dB Peak 183 dB cSEL	213 dB Peak 179 dB cSEL
Mid-frequency (e.g., Dolphins and Sperm Whales)	150 Hz to 160 kHz	230 dB Peak 185 dB cSEL	224 dB Peak 178 dB cSEL
High frequency (e.g., Porpoise)	275 Hz to 160 kHz	202 dB Peak 155 dB cSEL	148 dB Peak 153 dB cSEL
Phocid pinnipeds (True Seals) (underwater)	50 Hz to 86 kHz	218 dB Peak 185 dB cSEL	212 dB Peak 181 dB cSEL
Otariid pinnipeds (Sea Lions and Fur Seals) and Sea Otters (underwater)	60 Hz to 39 kHz	232 dB Peak 203 dB cSEL	226 dB Peak 199 dB cSEL
Sea Turtles	30 Hz to 2 kHz	230 dB Peak 204 dB cSEL	226 dB Peak 189 dB cSEL

Notes:
cSEL = cumulative sound exposure level   dB = decibels   Hz = hertz   kHz = kilohertz
Sources: mammals: NMFS (2018); sea turtles: U.S. Navy (2017)

Note. These thresholds identify the onset of PTS and TTS for Marine Mammals and Sea Turtles

Overall, the results of the environmental assessment from BOEM in regards to marine mammals found that impact would be negligible. This was looking specifically at the Morro Bay proposed lease area and based upon consultation with federal statutes and regulations as well as the research mentioned above. Although this report is speaking in regards to offshore wind, given what we know about RCAM's technology we can infer that it will not cause significant impacts as long as RCAM proceeds judiciously and cautiously. This could include obtaining outside environmental consultation from marine specialists before full development and during prototype testing.

Water Quality

The potential impact to the water quality from spheres could happen during the construction and installation stage of spheres. Since the installation of spheres is similar to that of gravity base foundation of wind turbine, it may require seabed preparation, which is essential to installation of gravity base foundation to identify soil with enough bearing capacity and level the base to accommodate the infrastructure.[29] Some process during the seabed preparation like dredging will decrease water quality due to the increase of suspended sediment and exposure of contaminants within the sediment.[30] During the construction phase, soil erosion and sedimentation can occur, leading to an increase in suspended solids and turbidity. This can reduce light penetration,

[29] Esteban, M. D., et al. "Gravity based support structures for offshore wind turbine generators: Review of the installation process." Ocean Engineering 110 (2015): 281-291.
[30] Esteban, M. D., et al. "Gravity based support structures for offshore wind turbine generators: Review of the installation process." Ocean Engineering 110 (2015): 281-291.

affecting aquatic plants and fish that rely on surface light. Runoff from the construction site can also carry pollutants such as oil, grease, and chemicals to nearby water bodies, leading to water quality degradation. However, The effects of increased suspended sediment concentration and down-current deposition are restricted to the surrounding of the foundation,they do not regionally affect suspended sediment concentrations if spheres are adequately spaced to reduce cumulative effects.[31]

As for the exposure of contaminants within the sediment, in the National Coastal Condition Report IV, the overall rating for the West Coast coastal waters was “Good” including coastal waters in the Morro Bay Region. However, the sediment quality index rating for coastal waters around the Morro Bay region was rated as “Poor,” due to measurements of sediment toxicity.[32] The other two sediment quality indicators, sediment contaminants and sediment total organic carbon, were both rated “Good” for coastal waters in the Morro Bay region. Based on this, the exposure of contaminants within the sediment and the release of toxic sediments during the construction stage could cause the decline in water quality.

Geology

Marine benthic habitats are often defined by the geological structure as well as depth (or bathymetry) and chemistry. Also, the geological characterization of the seafloor is crucial to the construction of infrastructure like turbines and spheres in offshore wind farms. A proper understanding of the seafloor's characteristics, such as sediment type, hardness, and stability is necessary to determine the optimal location for wind turbine installation to maximize energy output and minimize the risk of structural failure or damage.

The Holocene marine geology of the Morro Bay Wind Energy Area reflects the Cenozoic regional tectonics and depositional stages unique to the offshore Santa Maria Basin.[33] As shown in Figure 4, The entire WEA is located at the active continental margin zone and lies west of the continental shelf break on the gently sloping shelf in water depths ranging from 800 to 1,300 meters. The region is mainly composed of two geomorphic forms: nearly 90% of the area is characterized by terraces, while around 5% is covered by canyons (Figure 5). Submarine canyons have complex bathymetry with high, ridge-like features that provide habitat for a variety of species and can also affect local bottom currents. The substrate type of most areas in the WEA is classified as Soft according to Coastal and Marine Ecological Classification Standard,[34] and the predominant component of sediment is mud or Rock/Mud (Figure 6).

An interesting feature of the seafloor in the Morro Bay WEA are thousands of distinct pockmarks averaging around 5 m (16 ft) deep and approximately 175 m (574 ft) in

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[31] Horwath, ED Sarah, et al. "Comparison of Environmental Effects from Different Offshore Wind Turbine Foundations." Rep. ICF Int. Rep. ICF Int., no. OCS Study BOEM 41 (2020): 53.
[32] Waters, O. C. U. C., et al. "National Coastal Condition Report IV." Environmental Protection Agency: Washington, DC, USA (2012).
[33] US Department of the Interior, Bureau of Ocean Management Pacific Region. Commercial Wind Lease and Grant Issuance and Site Assessment Activities on the Pacific Outer Continental Shelf Morro Bay Wind Energy Area, California Final Environmental Assessment. Morro Bay Wind Energy Area, 2022.
[34] Cochrane, Guy R., et al. California Deepwater Investigations and Groundtruthing (Cal DIG) I, volume 3—Benthic habitat characterization offshore Morro Bay, California. No. 2022-1035. US Geological Survey, 2022.

diameter,which can be seen in Figure 7.[35] These pockmarks were found across two physiographic regions near the Morro Bay WEA in water depths ranging from about 500 to 1,400 m. The pockmarks cover an area that totals nearly 1,300 km^2 (579 mi2) making this one of the largest known pockmark fields in North America (Walton et al., 2021). However, there is no evidence showing that pockmarks have any threat to the seabed stability (Paull et al., 2002).

Considering the similarity between spheres and gravity-base foundations, the suitable geology conditions for spheres will be site with low slope, less than 1 degree, and the geomorphologies including trenches,spreading ridges, rift valleys, canyons,seamounts, escarpments and fans are not suitable.[36] The existence of pockmarks and canyons could lead to difficulties when installing the spheres, and the potential seabed preparation to fill the pockmarks could be geologically harmful.

According to the Environment Assessment created by BOEM, the anticipated impact on the local geologic resources by activities performed as part of a Site Assessment Plan (SAP) and site characterization activities would be negligible. No marine geophysical data acquisition would impact the seafloor or subseafloor geology, and any shallow geotechnical sampling within the WEA would result in only minor, temporary disturbance of the upper 25 m (82 ft) of Quaternary sediment that underlies the seafloor. The installation of MPHES, with the assistance of two tugs, a crane vessel and ROV, could prove to be harmless to the geology.

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[35] Cochrane, Guy R., et al. California Deepwater Investigations and Groundtruthing (Cal DIG) I, volume 3—Benthic habitat characterization offshore Morro Bay, California. No. 2022-1035. US Geological Survey, 2022.
[36] Puchta, M., et al. "Development and testing of a novel offshore pumped storage concept for storing energy at sea− Stensea." Journal of Energy Storage 14 (2017): 271-275.

Figure 4

Seafloor Geology of Morro Bay WEA

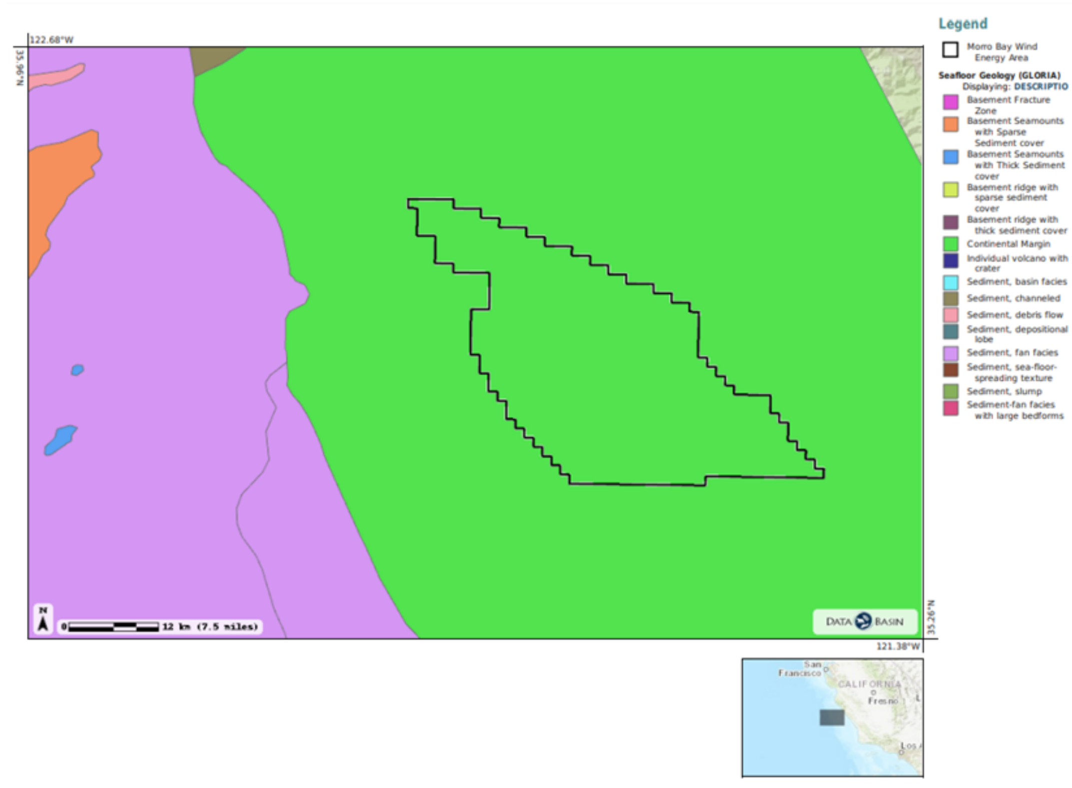
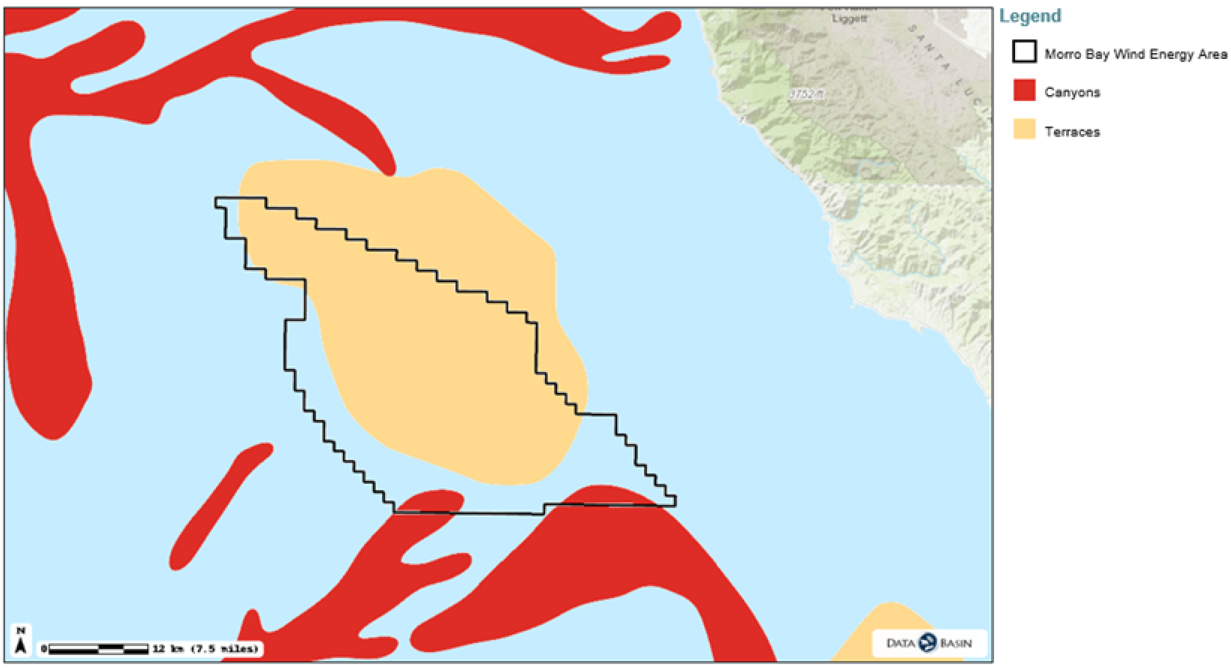
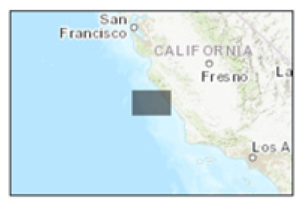


Figure 5

Geomorphic Form of Morro Bay WEA





Sources: Morro Bay WEA, Bureau of Ocean Energy Management
Seafloor Geomorphology, US West Coast, Blue Habitats: Home to the global seafloor geomorphic features map.
Created by: DataBasin
MapLayout: Shiyu Ding

Figure 6

Sediment Type of Morro Bay WEA

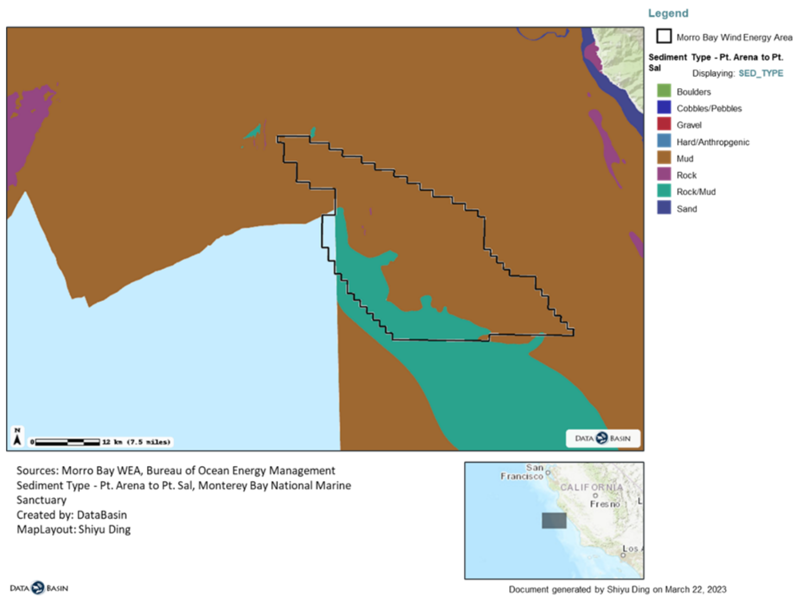
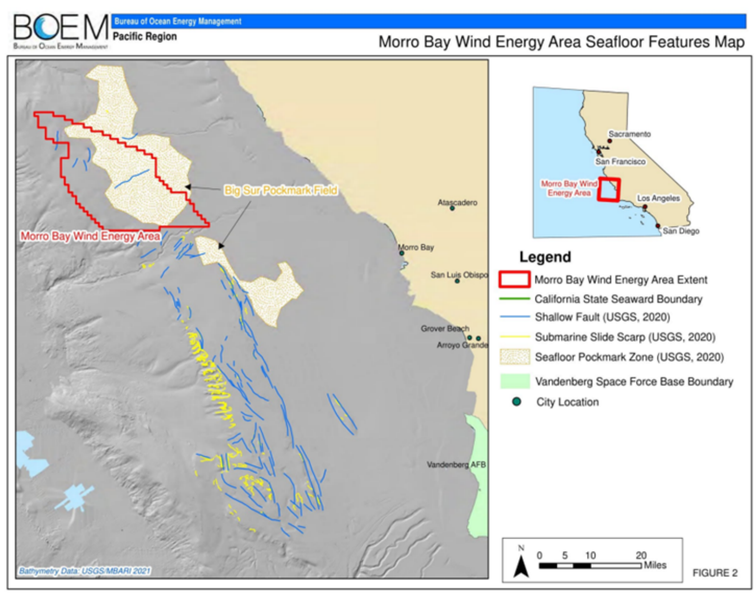


Figure 7

Pockmark in Morro Bay WEA



Humboldt Final Environmental Assessment

Marine Life

Similarly to the Morro Bay Environmental Assessment, BOEM also conducted an Environmental Assessment for the Humboldt WEA. The EA includes sections about Marine and Coastal Habitats and Associated Biotic Assemblages, Marine Mammals and Sea Turtles, Coastal and Marine Birds, and Commercial Fishing.

The outer shelf and upper slope habitats contain a variety of benthic species as well as flatfishes, rays, and rockfishes. Additionally, a rock ridge towards the middle of the WEA provides a habitat for invertebrates like coral and sponges. Similar to the Morro Bay EA, the Humboldt EA found that organisms in these outer shelf and upper slope habitats are at risk of being crushed by anchors from buoys, which RCAM should consider during the installation of concrete spheres.[37] The EA also noted any impacts to benthic species in the coastal and intertidal habitats would occur due to accidental events like a vessel grounding (when a ship is no longer floating and comes into contact with the seabed), for example, which should not be a concern for RCAM since the technology will be installed at much greater depths. With regard to endangered species, the EA did not propose any additional conservation measures as adverse impacts are not expected. Furthermore, any noise impacts are expected to be minimal and temporary.

The pelagic zone contains phytoplankton, zooplankton, jellyfish, krill, squid, tuna, sharks, and many other large animals. In regards to this area, the EA states “noise from HRG surveys and Project vessels may alter fish behavior within the WEA, but the effect will be temporary, and is not expected to affect viability of regional populations” (Staaterman, unpublished data). Although it is possible to assume that the installation of RCAM’s technology will have minimal impact as well, additional consultation of relevant government agencies and environmental consultants is recommended.

When looking at mammals, many of the findings of this EA were extremely similar to the Morro Bay EA. To avoid entanglement with mammals, the EA states, “BOEM will review each buoy design to ensure that reasonable low risk mooring designs are used.”[38] The Humboldt wind energy area overlaps with the humpback whale critical habitat, but any displacement is expected to be temporary and not expected to modify any part of the critical habitat. Species density for several whale species can be seen in the figures below. Overall, the EA finds the risk to mammals from site assessment and characterization to range from negligible to minor. As stated above, we would expect any sound impact to be short lived due to the fact that sphere installation of RCAM’s technology is temporary and the EA found noise to be a temporary impact as well.

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[37] US Department of the Interior, Bureau of Ocean Management Pacific Region. Commercial Wind Lease and Grant Issuance and Site Assessment Activities on the Pacific Outer Continental Shelf Humboldt Bay Wind Energy Area, California Final Environmental Assessment. Humboldt Bay Wind Energy Area, 2022.

[38] US Department of the Interior, Bureau of Ocean Management Pacific Region. Commercial Wind Lease and Grant Issuance and Site Assessment Activities on the Pacific Outer Continental Shelf Humboldt Bay Wind Energy Area, California Final Environmental Assessment. Humboldt Bay Wind Energy Area, 2022.

Similarly, we recommend that RCAM plan its construction timeline around the whales' migration patterns.

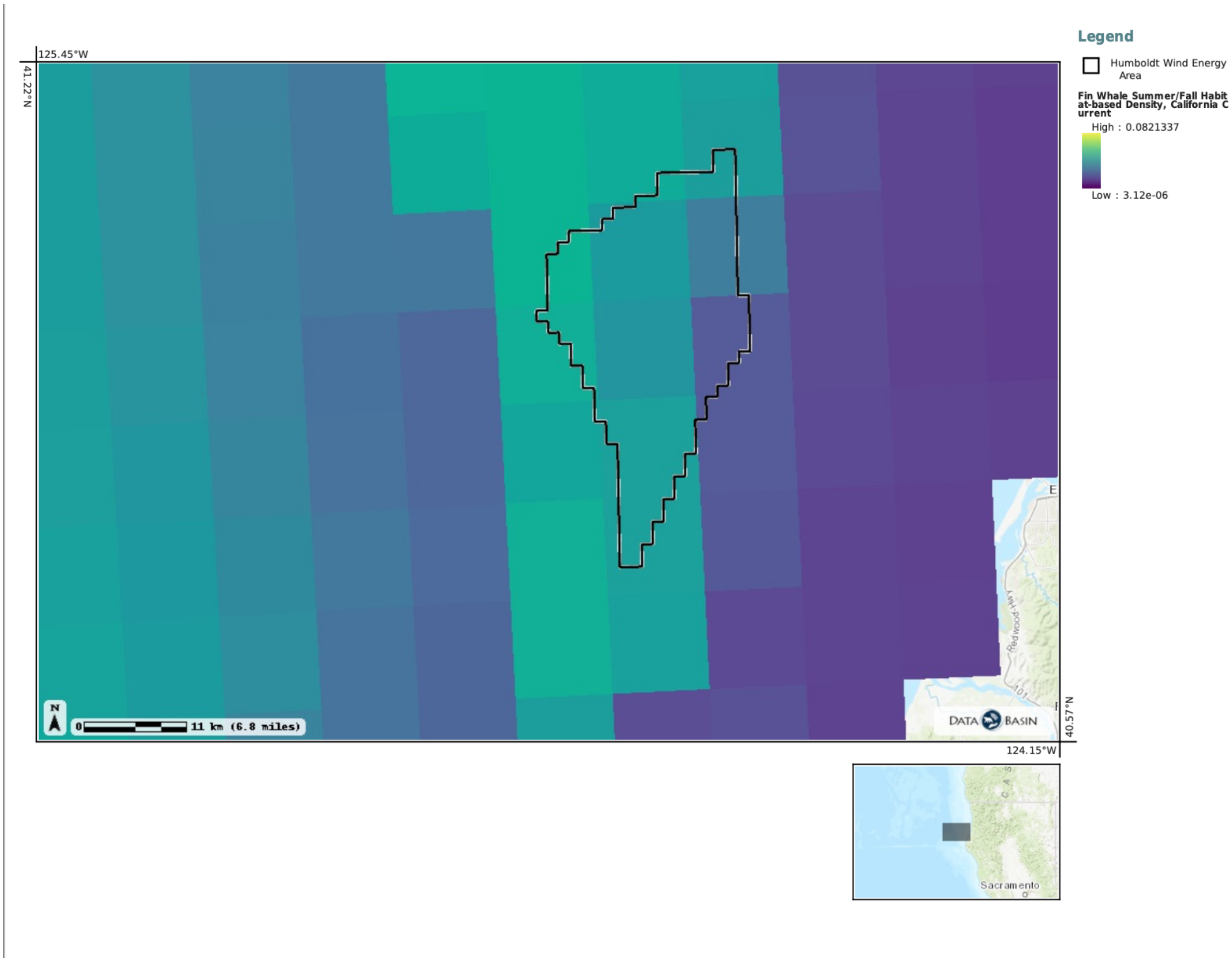
Figure 8

Summer/Fall Habitat based density of the Humpback Whale

Note. This map shows Humpback Whale density within the Humboldt Bay WEA.

Figure 9

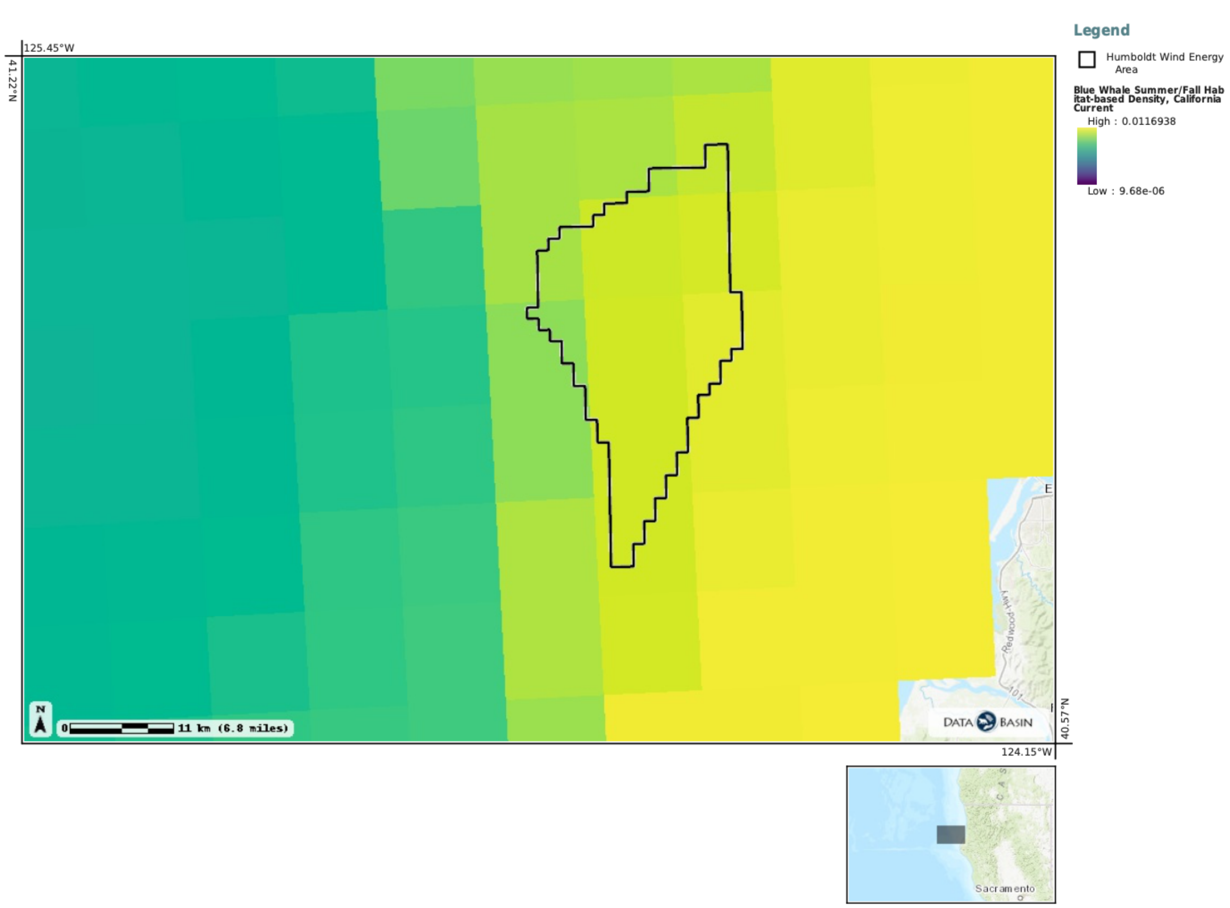
Summer/Fall Habitat based density of the Fin Whale



Note. This map shows Fin Whale density within the Humboldt Bay WEA.

Figure 10

Summer/Fall Habitat based density of the Blue Whale



Note. This map shows Blue Whale density within the Humboldt Bay WEA.

Geology

Like the Morro Bay WEA, the Humboldt Bay WEA is located at the continental slope (Figure 11). The water depths of the Humboldt WEA are primarily between 550 and 1,000 m, with increasing depths exceeding 1,100 m toward the western boundary. This is where the slope can exceed 4 degrees, which increases the slope instability and submarine landslides. The Morro Bay WEA has deeper water depths between 800 and 1300 meters. In terms of geomorphology, the two areas are also very similar. Humboldt also consists of terraces and canyons, with a few basins along the western boundary (Figure 12). The predominant soil type of Humboldt WEA is mud/ Muddy Sand, which has a soft texture and would be considered good material for building foundations.

Similar to Morro Bay, the current foreseeable actions would not cause permanent damage to the geology of Humboldt. However, the installation of spheres and potential seabed preparation actions should also be considered.

Figure 11

Seafloor Feature of Humboldt WEA

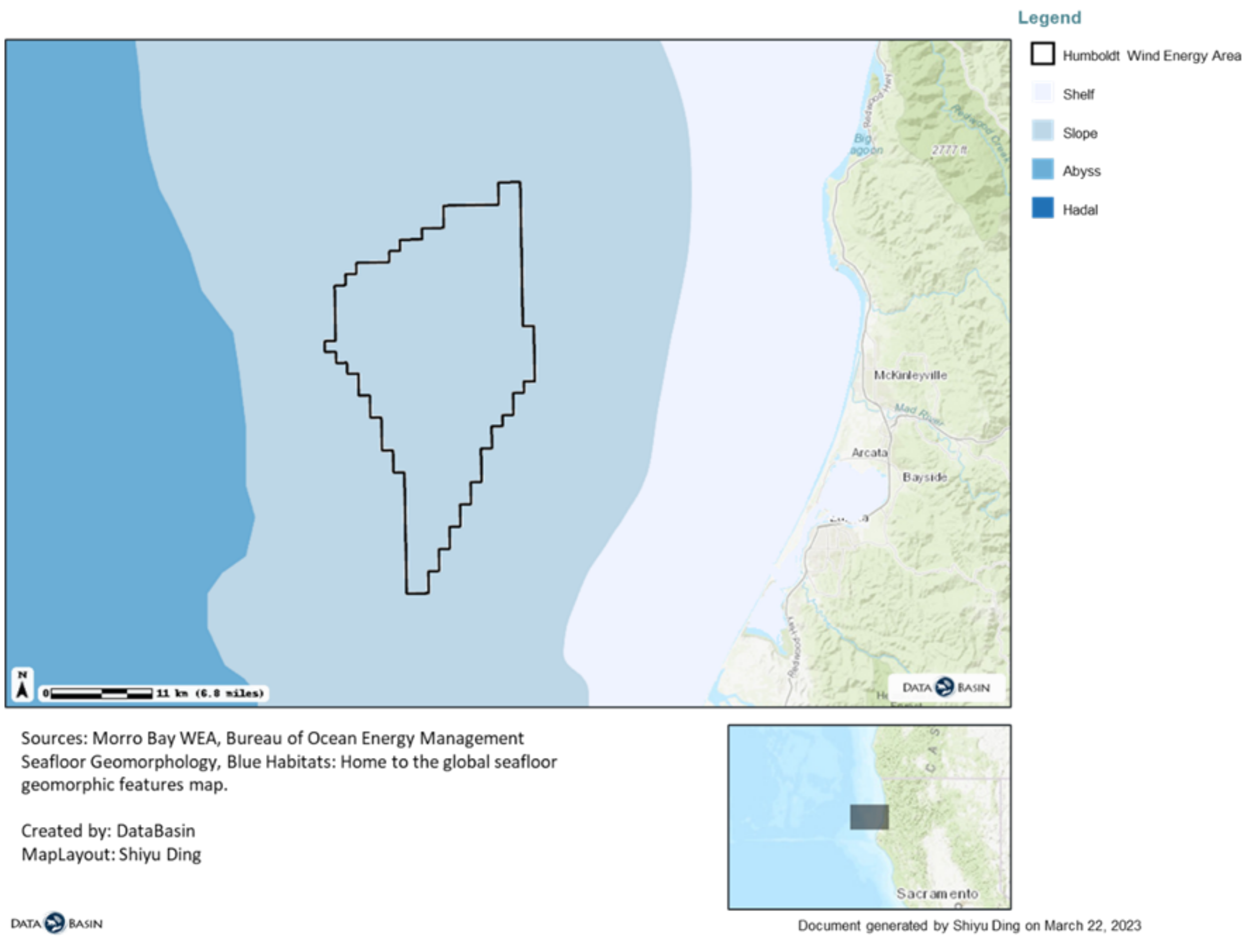


Figure 12

Geomorphology of Humboldt WEA

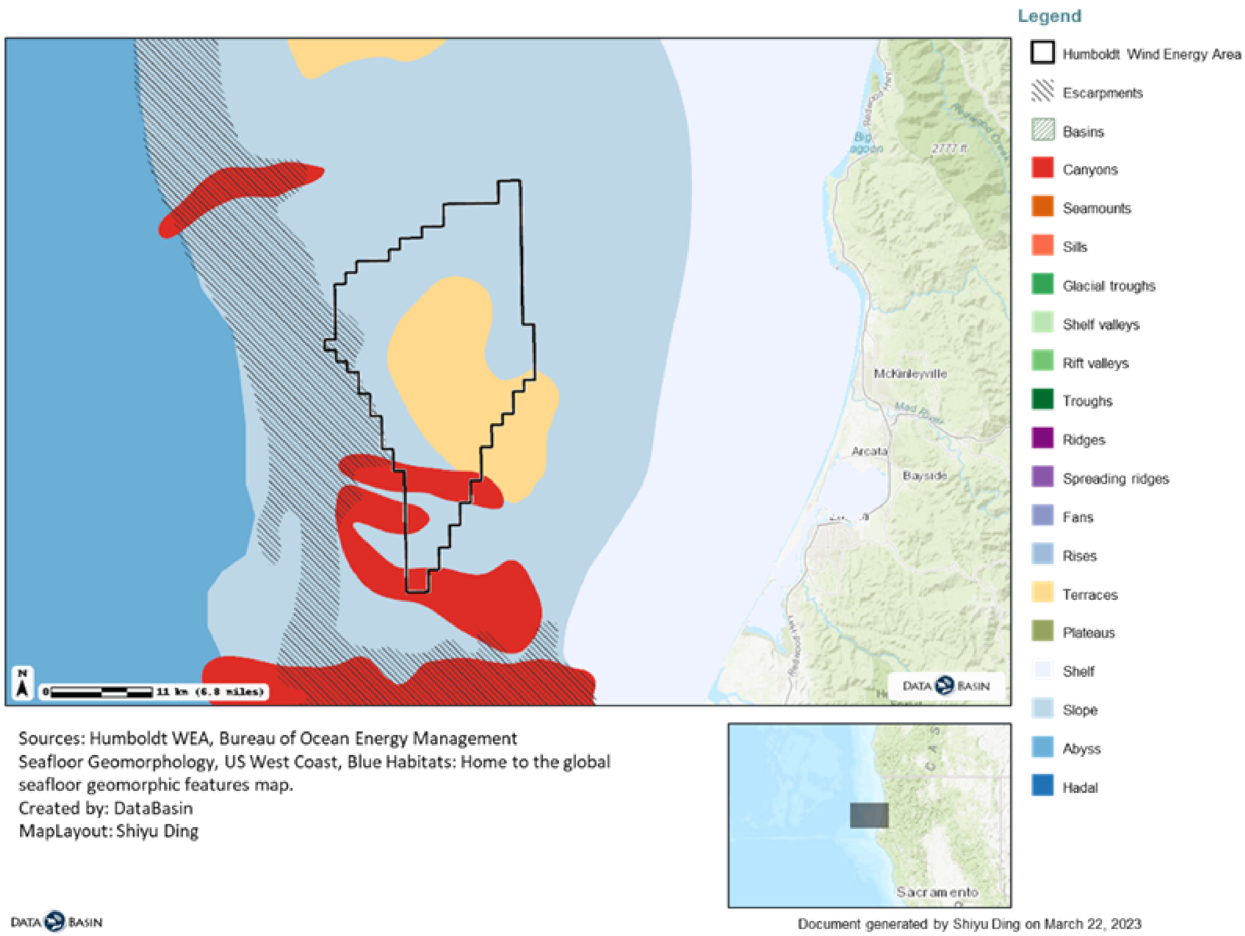
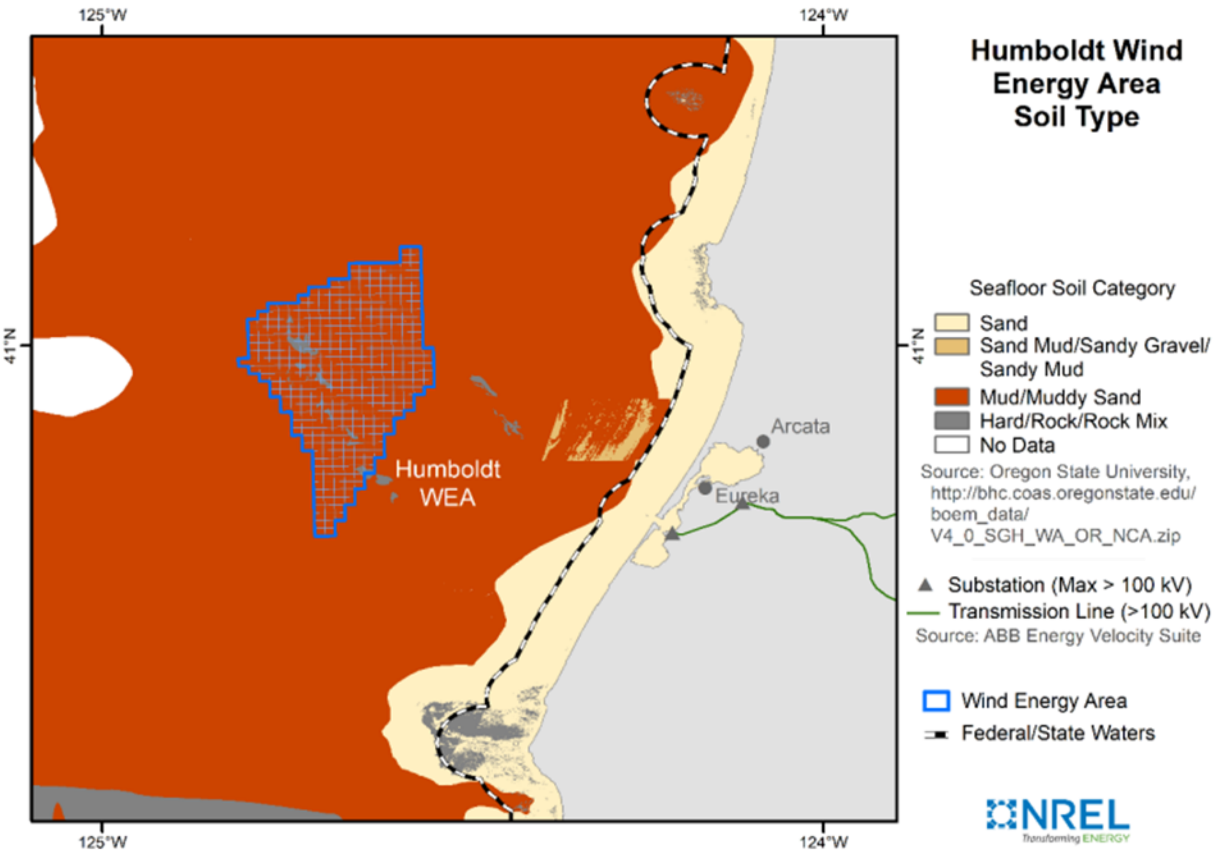


Figure 13

Soil Type of the Humboldt WEA (Cooperman et al, 2022)



M-PHES PRICE TAKER MODELING DOCUMENTATION FOR RCAM TECHNOLOGIES

By: Mike Storch
Published: April 10, 2023

UM SEAS and RCAM Technologies Capstone Partnership

Contents

Introduction

RCAM Technologies' novel Marine Pumped HydroElectric Energy Storage (M-PHES) product is a long duration energy storage device currently under development. The RCAM team needed to understand the revenue potential of this product in the California Independent System Operator (CAISO) regulatory market in order to make informed business decisions. To help RCAM in this effort, three different cases were modeled that represent potential market opportunities for their technology, specifically in the CAISO market. The first case is a standalone case in which the M-PHES was assumed to be connected only to the grid to participate in energy arbitrage. The next two cases are hybrid cases where the M-PHES was assumed to be solely charged using energy from simulated offshore wind farms that were constrained by the resources and characteristics of the Morro Bay and Humboldt California offshore Wind Energy Areas (WEAs). All three cases followed price taker modeling assumptions and were modeled in the linear optimization software GAMS (General Algebraic Modeling System). All three models were run using Day Ahead Market (DAM) and Real Time Market (RTM) pricing for the full years of 2020 and 2021. The wind farm modeling for the hybrid cases was conducted in the same years. The rest of this document includes background, key research questions curated by the RCAM team, all methods used to perform the modeling, results, analyses, and next steps. The results indicate that standalone storage may be better than hybrid systems in terms of overall revenue optimization potential, increasing energy storage capacity has a limit, and the Humboldt hybrid system has higher revenue potential than Morro Bay.

Problem Statement

RCAM Technologies needed to understand the revenue potential for different commercial deployment pathways for its M-PHES device. These pathways include standalone and hybrid systems across different wholesale markets because their product development and business decisions are dependent on whether they can make money with this product. More specifically, the following research questions were investigated:

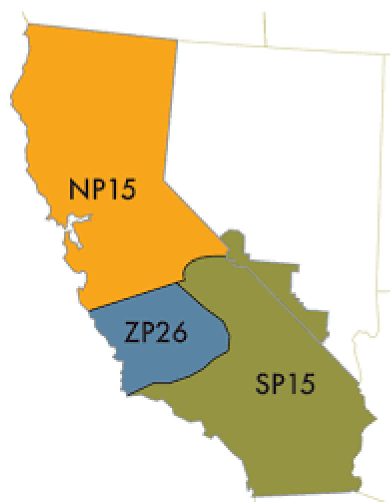
1. How does the ratio of storage to wind capacity impact profitability in a hybrid system?
2. How does the time duration of the storage impact the profitability of the storage technology?
3. How does the profitability of the storage technology differ in a standalone case vs. a hybrid system?
4. How does the profitability of the technology change with increases in efficiency?
5. How does the profitability differ between Morro Bay and Humboldt?
6. How does the profitability differ between DAM and RTM?

Background

The first step in this research project was to investigate the California markets and offshore wind lease areas in question. CAISO maintains the reliability of the power grid in California by facilitating the bidding and dispatching of generating resources throughout the state, thus allowing for transparent access to a competitive wholesale energy market.[1] In order to provide transparency, CAISO has developed the Open Access Same-time Information System (OASIS), which displays current and historical pricing data for the entire state on a nodal and zonal basis. There are over 5,000 nodes in the CAISO system, with each representing a location where transmission lines and generation interconnect.

Figure 1 depicts how the CAISO system is simplified into three different zones. The zonal prices are an average of all nodal pricing in the respective zones. Both WEAs were assumed to be interconnected into zone NP-15 in this research because this is the closest zone to the WEAs and previous BOEM documentation made similar indications in late-2021 (these BOEM documents are currently unavailable).

Figure 1
CAISO zone map



A primary reference used to understand the different types of market data available for download from OASIS was the CAISO Business Practice Manual 2022 and the *OASIS Interface Specification API v7.0.0 dated 06-30-2022*. The Locational Marginal Prices (DAM) and the Interval Locational Marginal Pricing (RTM) datasets were selected for implementation in the modeling after review of the API and BPM. Using real time and day ahead pricing in price taker

[1] OASIS Staff. (2013). About Us - A reliable and accessible power grid. Retrieved from http://www.caiso.com/about/Pages/default.aspx

modeling is a common practice in estimating revenues for energy storage arbitrage.[2] The LMP in CAISO consists of "hourly locational marginal prices for all Pricing nodes and aggregated nodes in $/MWh" while the Interval LMP consists of "Five-minute Locational Marginal Prices for all PNodes and all APNodes in $/MWh, for each five-minute interval RTM". The prices in DAMs are determined through the process of generators bidding to CAISO their available capacity of MWs for each hour of every day. CAISO then uses this information to determine the least cost generators to dispatch to meet forecasted demand in the system. There is inherent inaccuracy in DAMs due to forecasting errors of both supply and demand. The RTM pricing reflects the actual valuation of electricity supply and demand within the CAISO system every five minutes; this data is a more accurate representation of actual system dynamics including transmission line congestion, high renewables production, and potential constraints of traditional generation units.

In the future, floating offshore wind turbines will be connected to the CAISO operated grid. These floating offshore wind turbines will reside in two WEAs sold by the Bureau of Ocean and Energy Management (BOEM). Morro Bay consists of 3 leased parcels that make up ~975 sq-km with an NREL maximum capacity estimate of 5045 MW while Humboldt consists of 2 leased parcels that make up ~536 sq-km with an NREL maximum capacity estimate of 3045 MW.[3] The five provisional lease winners were published on December 7, 2022 and are shown in Figure 2.[4]

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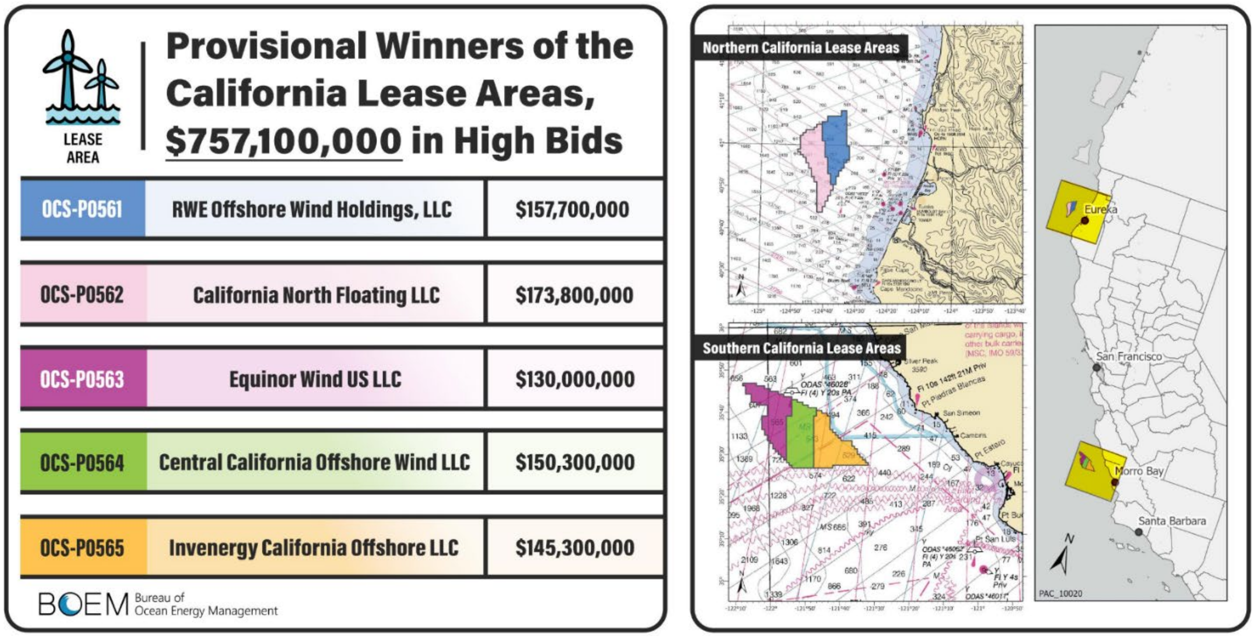
[2] Krishnamurthy, D., Uckun, C., Zhou, Z., Thimmpuram, P., Botterud, A. (2017). Energy Storage Arbitrage Under Day-Ahead and Real-Time Price Uncertainty. Published in IEEE. Retrieved from https://www.osti.gov/servlets/purl/1358239/、

[3] Cooperman, Aubryn, Patrick Duffy, Matt Hall, Ericka Lozon, Matt Shields, and Walter Musial. 2022. Assessment of Offshore Wind Energy Leasing Areas for Humboldt and Morro Bay Wind Energy Areas, California. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-82341. https://www.nrel.gov/docs/fy22osti/82341.pdf.

[4] Department of Interior Staff. (December 7, 2022). Biden-Harris Administration Announces Winners of California Offshore Wind Energy Auction. Published by the U.S. Department of Interior. Retrieved from https://doi.gov/pressreleases/biden-harris-administration-announces-winners-california-offshore-wind-energy-auction

Figure 2

BOEM Summary of CA Provisional Winners.



Note: *Central California Offshore Wind is a joint venture between Ocean Winds and sponsors EDPR and Engie* *while California North Floating is a joint venture between Copenhagen Infrastructure Partners and RWE Offshore Wind Energy Holdings*.

Methods

The methods for this research comprise of 1) price taker modeling formulation that is used to generate results to answer the above questions, 2) the development of wholesale market price files used as inputs for the price taker model, and 3) the development of the modeled wind capacity factor files for both Morro Bay and Humboldt used as inputs to the price taker model.

1. Price Taker Modeling Formulation

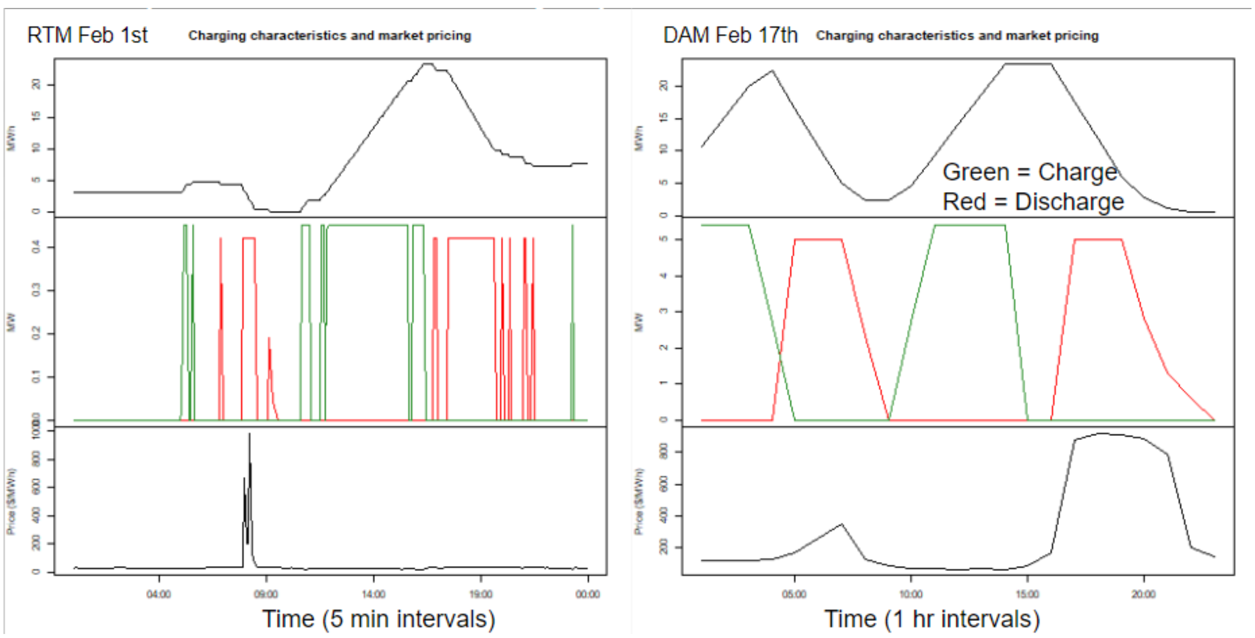
To estimate the potential revenues that can be earned through using the M-PHES, linear optimization models were developed and run in the software GAMS. The appropriate model type to use was a price taker model. A price taker model assumes that the generation or storage facility being investigated does not affect wholesale market prices because the small size of the facility does not have the capacity to influence market prices; when selling electricity into the market, the facility must take the prevailing price. In general, the objective function of this model is to maximize the potential revenues in the market through consideration of the facility characteristics, market dynamics, and market pricing information.

The objective function of the wind without storage model is simply to pump electricity into the grid and be paid at the rate available during generation. The wind is constrained by its maximum power output capacity and the capacity factor of the wind turbine at each time interval.

The objective function of the standalone model is to maximize the difference in sum of total discharge values and the sum of total charge values; the model seeks to operate the battery in a way that discharges at higher prices and charges at lower prices — energy arbitrage (see Figure 3 for example battery operational profile for select time periods in 2021). The battery is constrained to its own charge and discharge capacities, round trip efficiency that helps determine its state of charge after charging and discharging, and its maximum energy storage amount that governs the maximum state of charge the battery can hold. In this model, the M-PHES draws its power from the grid, which has a 100% capacity factor.

Figure 3

Battery operational profile for RTM on Feb 1st, 2021 (left) and DAM on Feb 17th, 2021 (right).



Note that green means charging and red means discharging.

The objective function of the hybrid case is to maximize the battery discharge and charge values while considering the production of wind energy that is not used to charge the battery. The hybrid model accounts for all the constraints in the standalone storage and wind without storage models, including the important constraint that the battery may only charge from electricity generated from the wind farm.

At the request of RCAM Technologies, and to simplify the modeling process, there were several assumptions accepted for both the standalone and hybrid cases as well as assumptions specific to the hybrid case. The assumptions are as follows:

Both Cases:

- Energy storage participation in the market does not affect prices.
- No operational or capital costs are assumed for the storage technology, wind facilities, and the grid. This is done to provide a best-case scenario for RCAM to understand their profitability potential compared to costs that are still in discovery through the design development and sourcing of materials.
- 1:1 pump-turbine to sphere
- All storage units are placed at a 1000m depth.
- The storage is 100% operational for a full year.
- The storage operates purely in wholesale markets.
- No inverter losses or efficiencies are considered for conversion from DC to AC power.

Standalone Case:

- The battery can charge from the grid whenever it is capable as the grid is set to have a capacity factor of 1 for the entire year.

Hybrid Case:

- The wind farm generation does not affect market prices, which realistically would not be the case.
- The storage can only be charged from the wind farm generation (this is one of many possible scenarios that can be used in a wind-storage hybrid system, see Appendix A for schematic diagram of assumed system)[5]

Overall, six different modeling files were produced: one for the standalone DAM case, one for the standalone RTM case, one for the hybrid DAM case, one for the just wind DAM (to be able to calculate differences between having storage), and two models replicated for the RTM case (please see Appendix B for the formulation of each model and Appendix C for the raw GAMS code). Input parameters to the models were changed to investigate the key research questions (please see Appendices D-F for input tables for the standalone case, the Humboldt hybrid case, and the Morro Bay hybrid case).

2. Wholesale Market Prices

The daily RTM and DAM pricing data for 2020 and 2021 were extracted using an R-Script developed by Michael Craig with edits from Eamon Espey (see Appendix G for R-Script). The downloaded Excel files were then consolidated into single, annual files that retained the price information, the date, and the operating hour (see Appendix H for Python script developed by Charles Song). The final DAM 2021 file contains 8,760 rows of price data while the DAM 2020 contains 8,784 rows of price data. The RTM 2021 file contains 105,120 rows of pricing data

[5] Reilly, Jim, Ram Poudel, Venkat Krishnan, Ben Anderson, Jayaraj Rane, Ian BaringGould, and Caitlyn Clark. 2022. Hybrid Distributed Wind and Battery Energy Storage Systems. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-77662. https://www.nrel.gov/docs/fy22osti/77662.pdf.

while the RTM 2020 file contains 105,408 rows of pricing data. See Table 1 for summary statistics of each data file.

Table 1: DAM and RTM Summary Statistics in $/MWh for 2021 and 2020

Market	DAM 2021	DAM 2020	RTM 2021	RTM 2020
Avg.	52.36	32.23	45.65	27.87
Max	921.88	957.9	1878.68	1095.98
Min.	-0.57	-10.33	-12.01	-42.07
Std. Dev.	36.49	33.40	39.42	43.45
Var.	1331.79	1115.45	1553.56	1887.88

Overall, the DAM prices were higher than the RTM prices, the RTM maximum prices were higher than the DAM prices, the RTM minimum prices were less than the DAM prices, and the RTM had much more variability in pricing than the DAM prices. The high maximum prices in the RTMs are most likely due to system supply constraints or unmet demand while the minimums are reflective of forecasting errors in the DAM because in RTM there was much more renewable generation than expected. The volatility in RTM prices is reflected in the variance, which means that a lot can happen in the market every five minutes compared to an hourly basis (see Appendix I for plots of the annual price comparisons of each market).

3. Wind Modeling

a. Wind Speed Data

To ensure as much accuracy as possible in the wind modeling efforts, it was important to match the wind data to the same years as the pricing data. The National Renewable Energy Laboratory (NREL) Wind Integration National Dataset Toolkit has available offshore wind speed datasets up to 2013. In 2020, NREL developed the CA20 dataset that covers offshore and onshore wind speeds up to 2020, however at the time of modeling the 2020 dataset was not available.[6] Instead of using NREL datasets, the ERA 5 dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) was used to obtain vertical and horizontal components of 100 m offshore wind speeds for a 30km grid in the years 2020 and 2021.[7] The ECMWF is a research

[6] Offshore CA Data Download. NREL Staff (2022). Published by the National Renewable Energy Laboratory. Retrieved from https://developer.nrel.gov/docs/wind/wind-toolkit/offshore-ca-download/

[7] ECMWF Reanalysis v5 (ERA5). ECMWF Staff. (2023). Published by the European Center for Medium Ranged Weather Forecasts. Retrieved from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

institute and operational service that uses advanced modeling to predict atmospheric conditions globally.[8] The inputs used to extract the netCDF file from the website can be seen in Appendix J. With the help of Eamon Espey, an R-Script was developed to extract the 100 m wind speed components from the NetCDF download file at the coordinates for Humboldt (41N, 124.75W) and Morro Bay (35.5N, 121.75W), which can be seen in Figure 4.

Figure 4

30 km grid selections for wind speed data from ERA 5 for Morro Bay (left) and Humboldt (right).

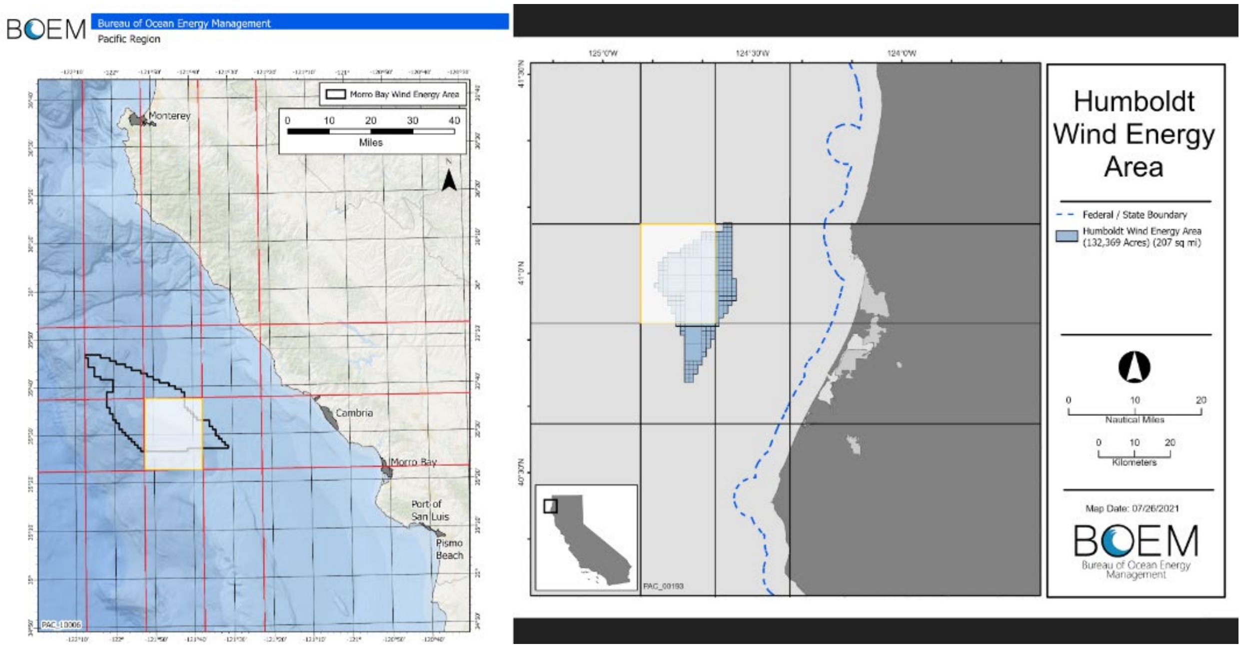


Table 2: Comparison of 100 m Hub Height Mean Annual Wind Speeds

ERA 5 Specific Values		NREL 2020 CA 2020 values (m/s)	Percent difference	NREL April 2022 20-year 100 m ranges (m/s)
Location - year	Speed (m/s)			
Humboldt 2020	9.33	10.41*	-10.37	10.4-10.7*
Humboldt 2021	10.46	10.41*	0.48	10.4-10.7*
Morro Bay 2020	8.40	9.52*	-11.76	9.4-9.7*
Morro Bay 2021	8.60	9.52*	-9.66	9.4-9.7*

*Note that these values are not specific to the years 2020 and 2021.

[8] About us. ECMWF Staff. (2023). Published by the European Center for Medium Range Weather Forecasts. Retrieved from (https://www.ecmwf.int/en/about

Table 2 provides a comparison of 100 m wind speeds from the ERA 5 datasets and two different NREL studies. Overall, 3 of the 4 chosen ERA 5 wind speed datasets are less than the NREL estimates, but are still within an acceptable range of percent difference. The ERA 5 datasets are conservative valuations of wind speeds compared to NREL estimates:

> NREL developed the CA20 resource data for this analysis, **which indicated extremely high average wind speeds at Humboldt** and excellent resource characteristics at Morro Bay. In subsequent comparisons with the limited lidar measurements obtained from buoys deployed at Morro Bay and Humboldt, **we found a relatively high bias, indicating that the CA20 data may overestimate actual wind speeds at hub height. The reader is cautioned that the uncertainty in the data is higher than expected.**

The R-Script calculates hourly 150 m wind speeds (in m/s) for each site in 2020 and 2021 (see Appendix K for full R-Script). The 150 m hub height is assumed in accordance with NREL 2022, which assumes the use of the IEA 15 MW Offshore Reference Wind turbine.[9] The R-Script calculates the magnitude of the 100 m wind speeds using the vector components then uses the power law formula for wind shear to determine final 150 m wind speeds. The wind shear constants, 0.1153 for Humboldt and 0.1112 for Morro Bay, assumed for these calculations were interpolated from NREL 2020 Resource Assessment Figure 9 (see Appendix L for interpolation).[10] These wind shear values are within the range of expected values of 0.10 - 0.15 for the temperate offshore wind type as seen in Figure 5. Appendix M contains histograms of the annual 150 m wind speeds for each lease area.

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[9] Gaertner, Evan, Jennifer Rinker, Latha Sethuraman, Frederik Zahle, Benjamin Anderson, Garrett Barter, Nikhar Abbas, Fanzhong Meng, Pietro Bortolotti, Witold Skrzypinski, George Scott, Roland Feil, Henrik Bredmose, Katherine Dykes, Matt Shields, Christopher Allen, and Anthony Viselli. 2020. Definition of the IEA 15-Megawatt Offshore Reference Wind. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-75698. https://www.nrel.gov/docs/fy20osti/75698.pdf

[10] Optis, Mike, Alex Rybchuk, Nicola Bodini, Michael Rossol, and Walter Musial. 2020. 2020 Offshore Wind Resource Assessment for the California Pacific Outer Continental Shelf. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-77642. https://www.nrel.gov/docs/fy21osti/77642.pdf.

Figure 5

Table of typical wind shear exponents, courtesy of Dr. Michael Craig and AWS Truepower.

Table 10-3. Typical shear exponents for different site conditions. These estimates may not be valid for specific sites; measurement is required

Terrain type	Land cover	Approximate range of annual mean wind shear exponent
Flat or rolling	Low to moderate vegetation	0.12–0.25
Flat or rolling	Patchy woods or forest	0.25–0.40
Complex, valley (sheltered)	Varied	0.25–0.60
Complex, valley (gap or thermal flow)	Varied	0.10–0.20
Complex, ridgeline	Low to moderate vegetation	0.15–0.25
Complex, ridgeline	Forest	0.20–0.35
Offshore, temperate	Water	0.10–0.15
Offshore, tropical	Water	0.07–0.10

Source: AWS Truepower.

b. Wind Modeling

After developing the 150 m hourly wind speed datasets, the next step was to use the power curve information from the IEA 15 MW turbine to generate hourly production estimates for each site and each year. The power curve shown in yellow in Figure 6 is an adaptation of the original dataset in gray to better allocate for wind speed bins.[11] To have an accurate estimation of wind speeds between the cut-in speed and the rated power of the turbine, the quadratic function seen in Figure 7 was used to fit the data.

[11] Raw power curve data from: https://github.com/IEAWindTask37/IEA-15-240-RWT/blob/master/performance/performance_ccblade.dat

Figure 6

IEA 15 MW power curve raw data plot and adjusted data plot.

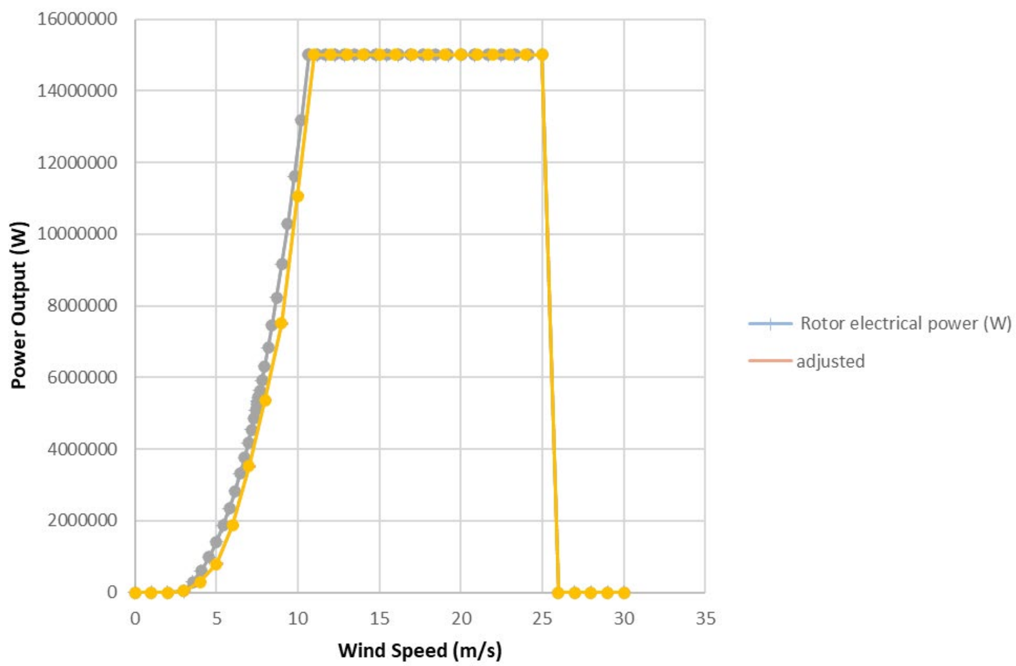
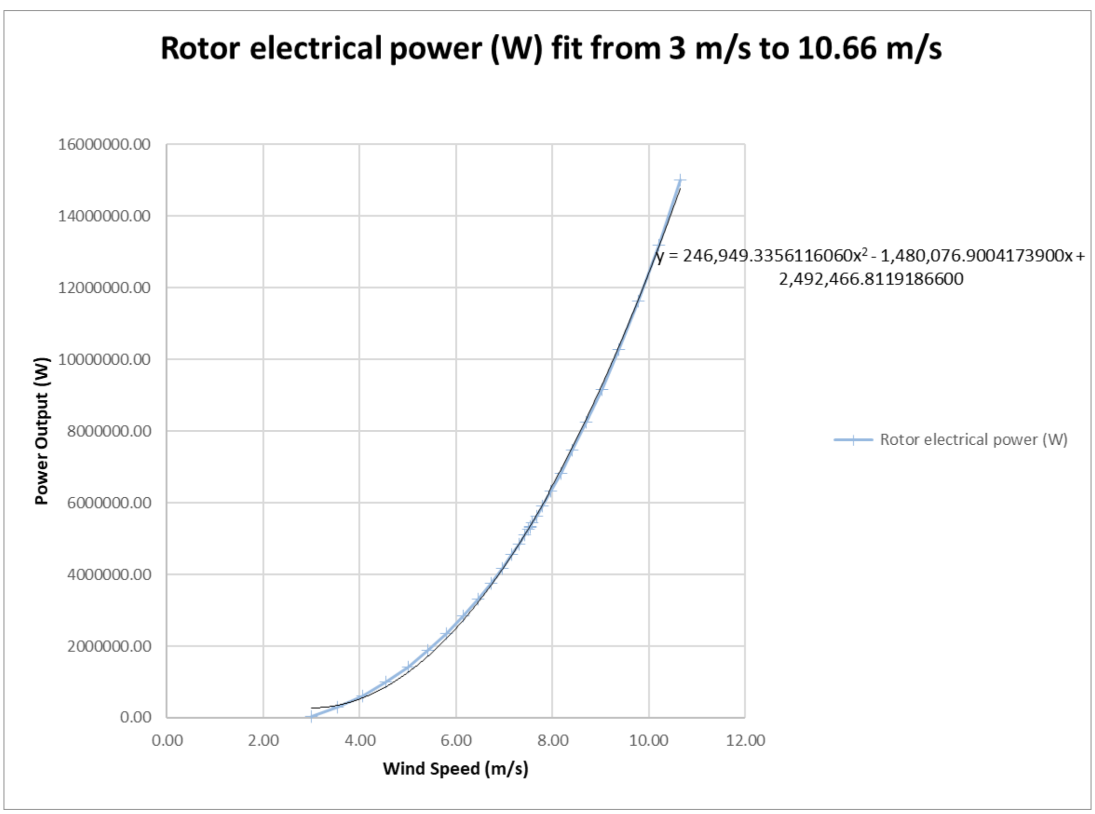


Figure 7

Rotor Electrical Power (W) Fit from 3 m/s to 10.66 m/s.



Next, an Excel file for each year and site was created. In each file, the developed 150 m wind speeds were listed for each hour and a quadratic fit equation was used to generate estimated wind generation in MW for that range of the power curve. A piecewise function was then created using an Excel formula to determine the simulated power generation in MW for each hour. In each hour, the simulated power generation was divided by the turbine capacity of 15 MW to get a gross capacity factor (GCF) in each hour. The method for calculating the net capacity factor (NCF) for each hour follows the NREL 2022 process, where assumed losses were taken as a percentage of the gross capacity factor, totaled, and then subtracted from the gross capacity factor. An added step in this methodology was to take the ratio of the net capacity factor and the gross capacity factor that can then be multiplied by the gross capacity factor in each hour to get a net capacity factor in each hour that yields the desired annual net capacity factor when averaged (please see Appendix N for process details and supporting images).

There are a few key assumptions worth noting for this process:

1. The wind farm is 100% functional at all hours of the year, therefore the simulated hourly capacity factor is what is put into the optimization model later.
2. For converting the hourly capacity factors into 5 minute intervals to be used in the RTM optimization models, the hourly capacity factors are divided by 12 and assumed equally across each 5 minute interval (ex: hour 1 has net capacity factor of 0.82, for the 12 time steps in that hour the net capacity factor will be 0.82/12).
3. The net capacity factors are calculated for one turbine, which is easier to scale because of the optimization model formulation discussed later.

The results of the wind modeling are displayed in Table 3 below. Three of the four modeled NCFs were lower than the NREL reference because of different wind speed data used as well as the fact that they increased the rated power for their power curve. Humboldt 2021 is the only larger modeled NCF than the NREL references, which can be reflective of the ERA 5 100 m wind speed data used for that year being abnormally large compared to the other ERA 5 wind speeds. The three other modeled NCF are lower than the NREL reference by less than 5% and can represent more conservative estimates when considering later optimization modeling. These modeled NCFs are well within historical values of offshore wind projects from literature and future projections collected by the NREL 2022 Offshore Wind Annual Technology Baseline report shown in Figure 8.[12]

[12] Annual Technology Baseline: Offshore wind. By NREL Staff. (2022). Published by the National Renewable Energy Lab and the U.S Department of Energy. Retrieved from https://atb.nrel.gov/electricity/2022/offshore_wind

Table 3: Comparison of Modeled Annual NCFs to NREL 2022 Reference

Site-Year	Modeled GCF	Modeled NCF	NREL Reference NCF (April 2022)*, **
Humboldt 2020	57.66%	47.4%	49.4 - 50.2%
Humboldt 2021	66.24%	54.45%	49.4 - 50.2%
Morro Bay 2020	54.26%	44.28%	46.5 - 47.8%
Morro Bay 2021	55.55%	45.33%	46.5 - 47.8%
* These values from NREL are not specified for the years 2020 or 2021. ** NREL modeled wind using IEA 15 MW power curve extends rated power from 25 m/s to 30 m/s			

Figure 8:

Historical Trends, Current Estimates, and Future Projections, R&D, CRP 30 Years.

Note: From NREL 2022 Offshore Wind ATB. Advanced scenario assumes 18 MW turbines and 51.84% NCF by 2030 with class 3 wind, Moderate scenario assumes 15 MW turbines and 50% NCF by 2030 with class 3 wind, and Conservative scenario assumes 12 MW turbines and 46% NCF by 2030 with class 3 wind.

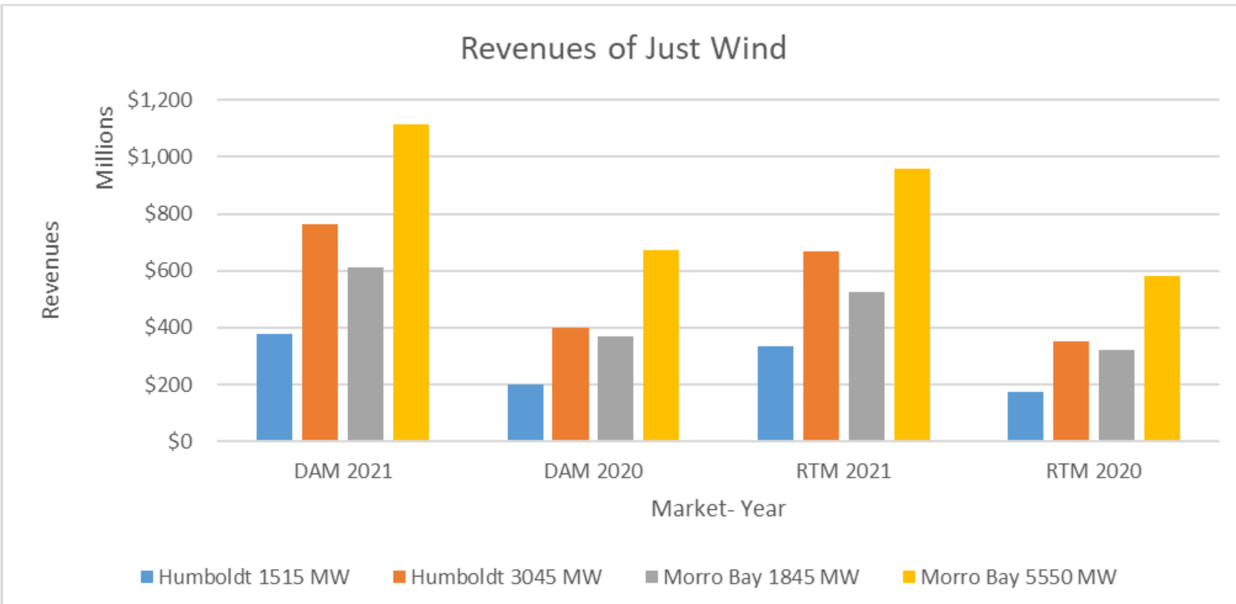
Results and Analysis

1 Revenues of Wind Without Storage: Base Case

Figure 9 below considers the revenues of wind models for Humboldt and Morro Bay across DAMs and RTMs for 2021 and 2020 so that it is easier to compare to the hybrid results later.

Figure 9

Revenues of Just Wind to serve as base case against hybrid results.



2 Hybrid System Results

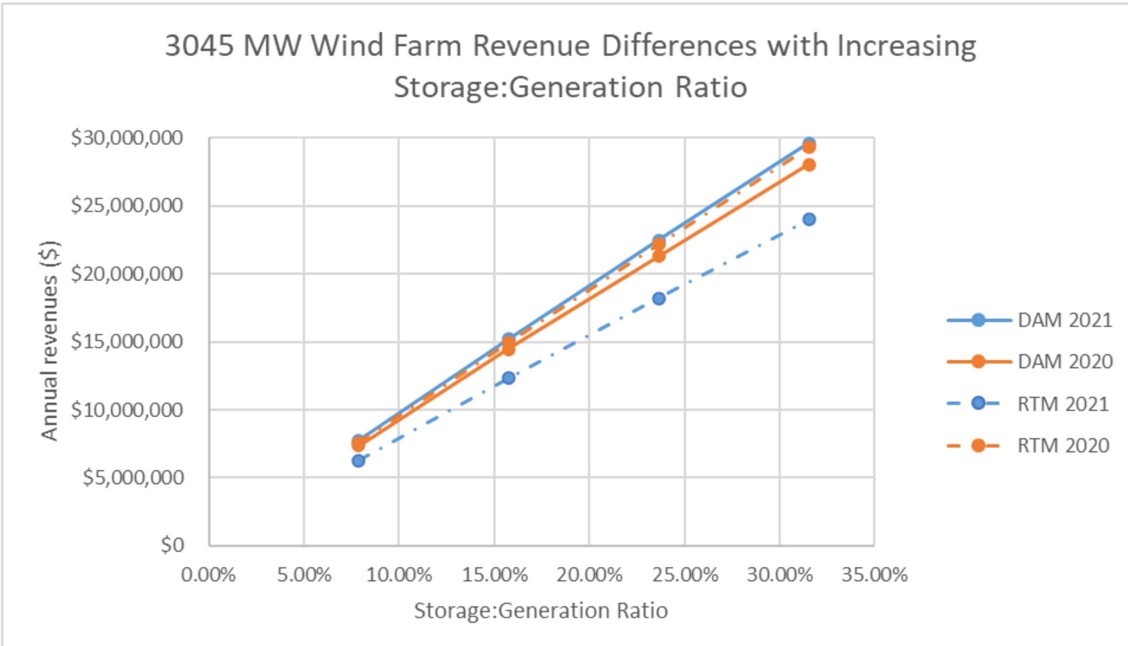
Both systems were modeled with full wind and less wind capacity scenarios and varying storage park sizes to explore an optimum storage to generation ratio. The results are displayed graphically in Figures 10-13 and in more detail via Tables 4-7. There are three key trends across all the modeled scenarios:

1. There are linear increases in revenue when increasing the storage to generation ratio.
2. The largest revenues follow the order of DAM2021, RTM2020, DAM2020, and RTM2021, except in the small hybrid case for Morro Bay where the RTM2020 surpasses DAM 2021 at a ratio of 39%.
3. The wind farm capacity plays a larger role in marginal revenue differences between Morro Bay and Humboldt scenarios, but on a 1 to 1 basis, Humboldt produces more revenues every year.

In this very simplified study, a one-to-one comparison of Humboldt and Morro Bay yielded that Humboldt could generate more revenue than Morro Bay (see Figure 14). The results of this study will vastly differ compared to a model that follows a set of assumptions that consider available spacing for the spheres in each location, the distances to each interconnect point on land, and many other important factors. Additionally, it is difficult for this type of study to determine an optimal storage to generation ratio; however, typical wind-storage hybrid systems of comparable size have a storage to generation ratio between 9.2 – 31.3% with durations of 0.4, 0.7, 1, or 2 hours.[13]

Figure 10

Revenue difference because of storage in Humboldt Large Scenario.



[13] Lawrence Berkeley Lab Electricity Markets and Policy, *Hybrid Power Plants: Status of Operating and Proposed Plants, 2022 Edition*. Retrieved from https://emp.lbl.gov/hybrid

Table 4: Results of Humboldt Large Scenario

System Characteristics					Increase in Revenues Due to Storage ($ million)			
Wind Farm Capacity (MW)	Storage to gen. ratio	Total Charge Capacity (MW)	Total Discharge Capacity (MW)	Storage Capacity (MWh)	DAM 2021	DAM 2020	RTM 2021	RTM 2020
3045*	7.88%	259.2	240	1003.88	7.8	7.4	6.3	7.6
	15.76%	518.4	480	2007.75	15.2	14.5	13.2	14.9
	23.65%	777.6	720	3011.63	22.5	21.3	18.2	22.2
	31.53%	1036.8	960	4015.51	29.6	28.1	24.0	29.3

*NREL 2022 maximum capacity estimate for the entire Humboldt WEA because of spacing design.

Figure 11

Revenue difference because of storage in Humboldt Small Scenario.

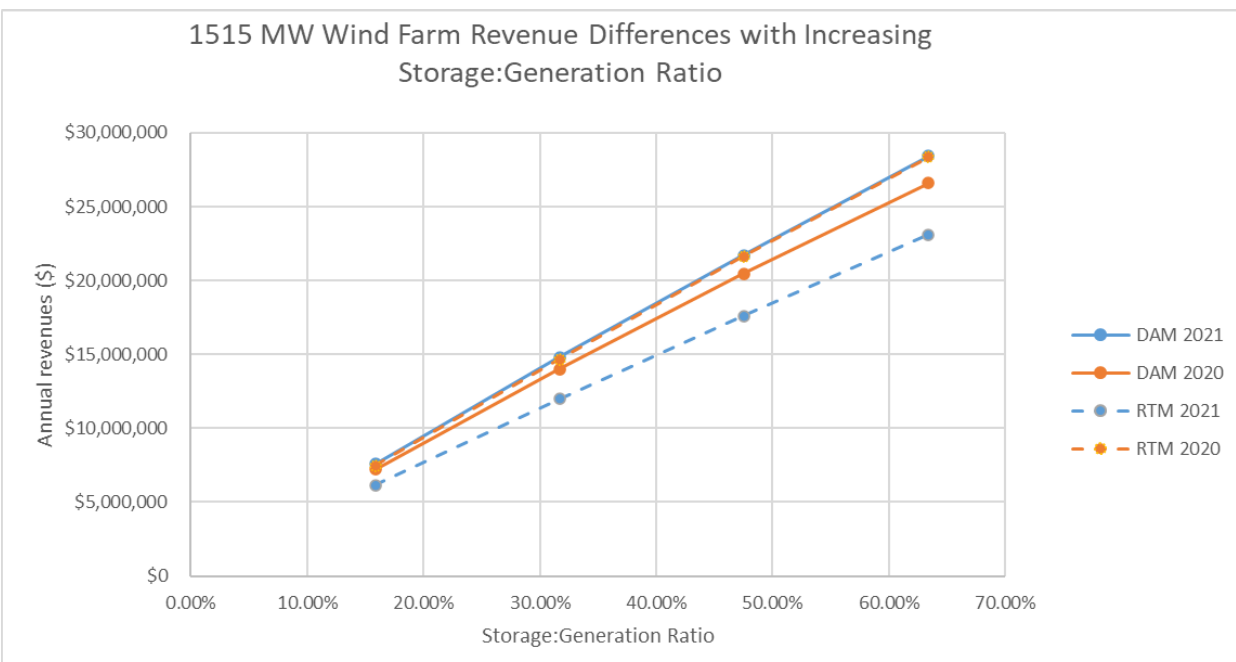


Table 5: Results of Humboldt Small Scenario

System Characteristics		Increases in Revenues Due to Storage ($ million)			
Wind Farm Capacity (MW)	Storage to gen. ratio	DAM 2021	DAM 2020	RTM 2021	RTM 2020
1515*	15.84%	7.6	7.2	6.2	7.5
	31.68%	14.8	14.0	12.0	14.7
	47.52%	21.7	20.5	17.6	21.6
	63.37%	28.4	26.6	23.1	28.3

*Half of NREL 2022 maximum capacity estimate for entire Humboldt WEA (to simulate one wind energy area).

Figure 12:

Revenue difference because of storage in Morro Bay Large Scenario.

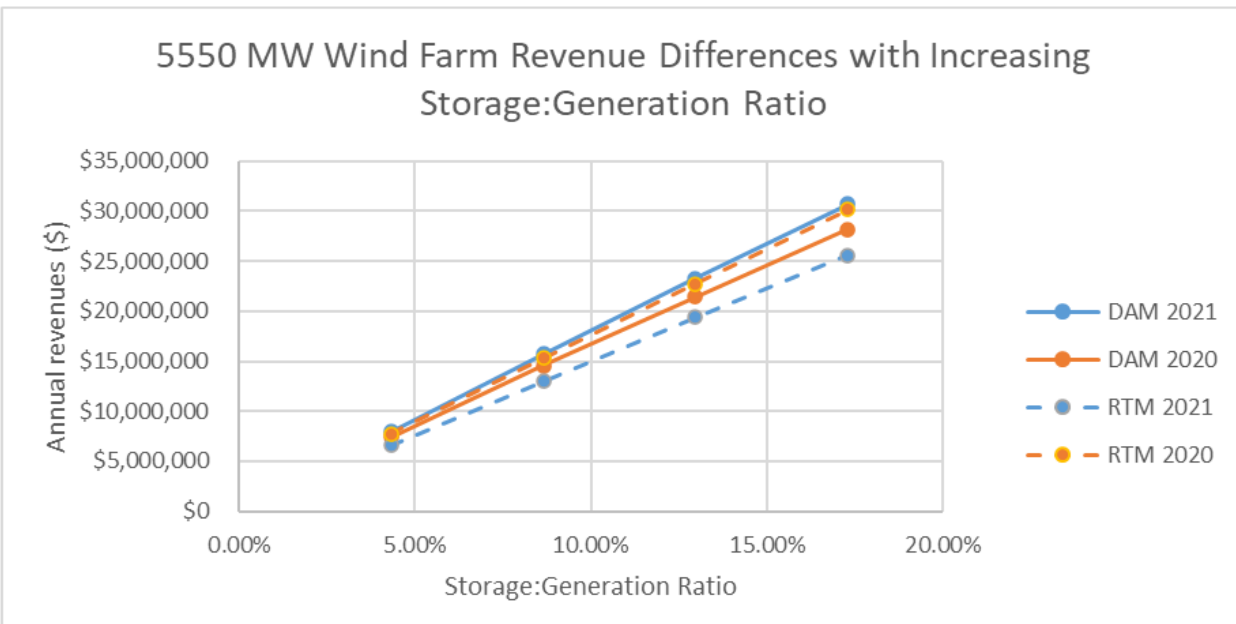


Table 6: Results of Morro Bay Large Scenario

System Characteristics		Increases in Revenues Due to Storage ($ million)			
Wind Farm Capacity (MW)	Storage to gen. ratio	DAM 2021	DAM 2020	RTM 2021	RTM 2020
5550*	4.32%	7.9	7.4	6.6	7.7
	8.65%	15.7	14.6	13.0	15.3
	12.97%	23.3	21.4	19.4	22.7
	17.30%	30.7	28.2	25.6	30.2

*NREL 2022 maximum capacity estimate for the entire Morro Bay WEA because of spacing design.

Figure 13:

Revenue difference because of storage in Morro Bay Small Scenario.

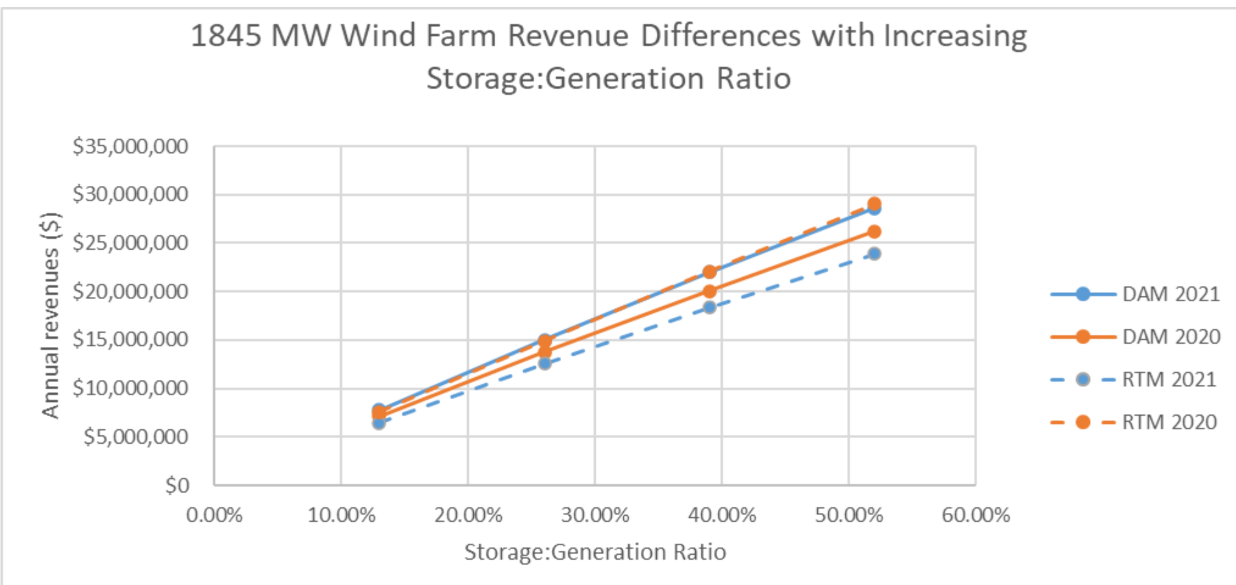


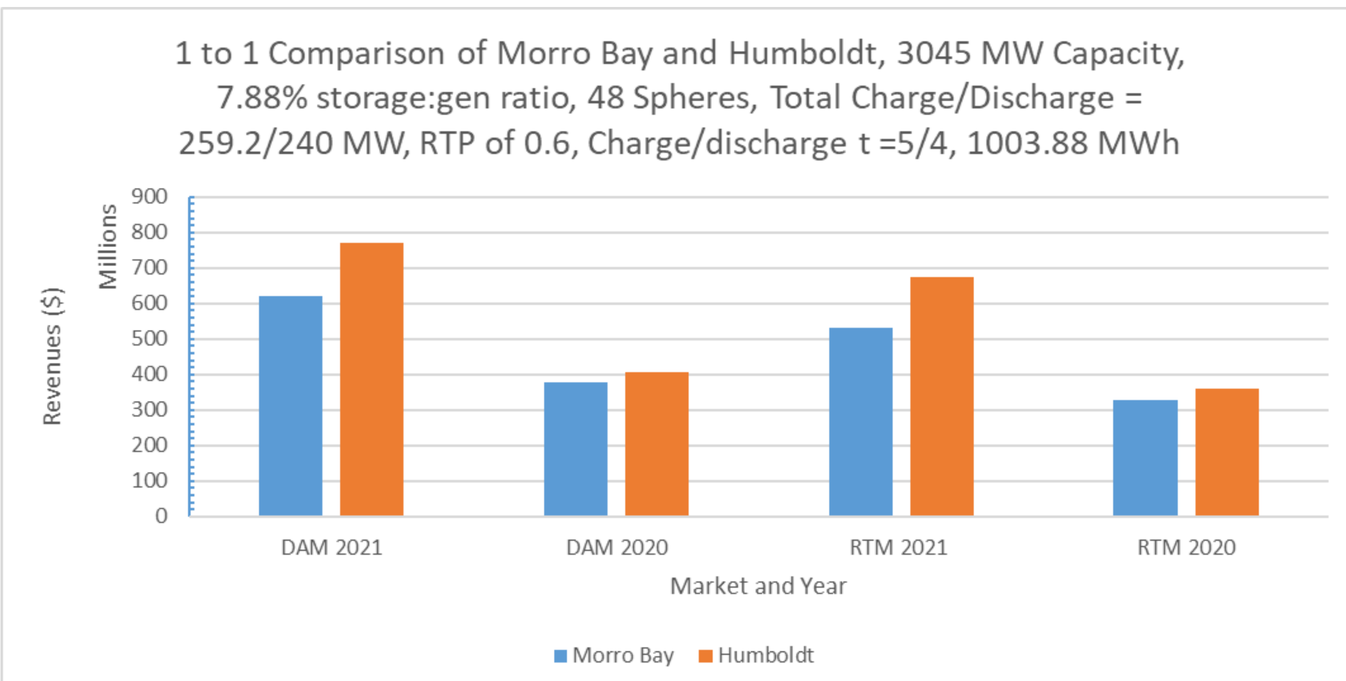
Table 7: Results of Morro Bay Small Scenario

System Characteristics		Increases in Revenues Due to Storage ($ million)			
Wind Farm Capacity (MW)	Storage to gen. ratio	DAM 2021	DAM 2020	RTM 2021	RTM 2020
1845*	13.01%	7.8	7.1	6.5	7.6
	26.02%	15.0	13.8	12.5	14.9
	39.02%	22.0	20.1	18.3	22.1
	52.03%	28.6	26.2	23.9	29.0

*~ 1/3 of NREL 2022 maximum capacity estimate for the entire Morro Bay WEA (to simulate one wind energy area).

Figure 14

Comparison of Humboldt and Morro Bay WEAs for identical storage systems and equal wind capacity ratings.

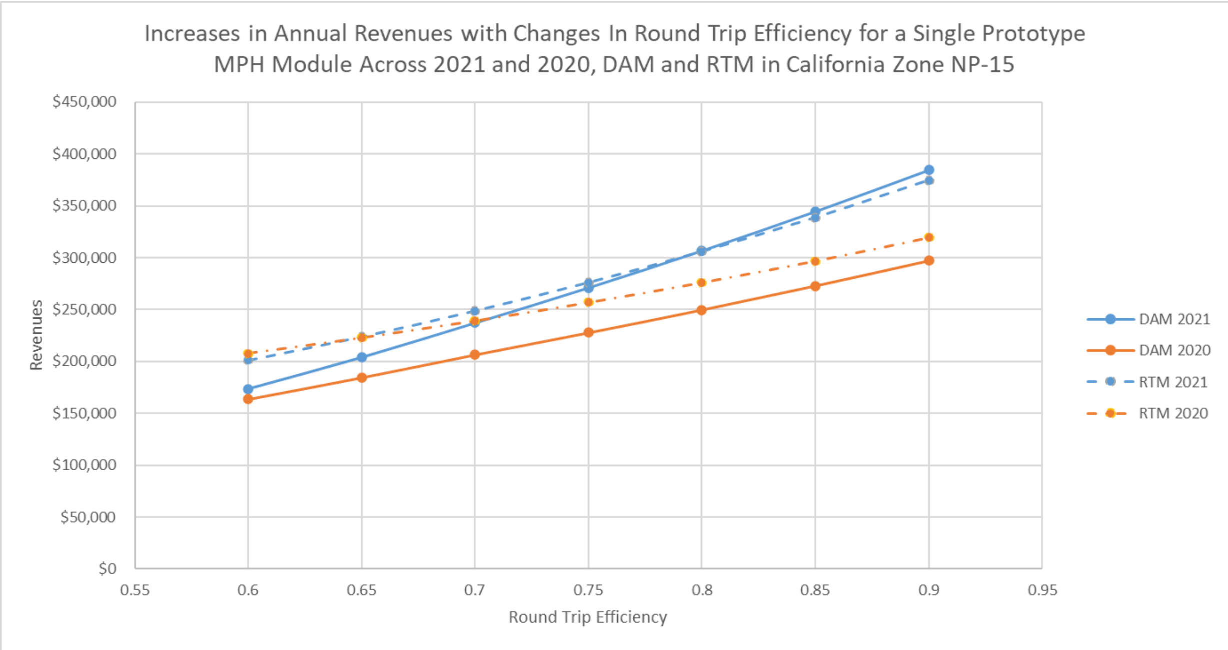


3 Standalone: Impacts of Changing Efficiency

To investigate the effects of improving round trip efficiency (RTP) on revenues from the base case assumption of 0.6, the models were executed in increasing 5% increments of RTP efficiencies. Potential ways to improve the efficiency of the system are through design improvements and more efficient cables. The results are shown in Figure 15 below.

Figure 15

Impacts on revenues with Increasing RTP efficiency



Overall, the standalone storage sensitivity to RTP efficiency is approximately linear. The rate of increase diminishes in each market except in the RTM 2020 market where each increase in revenue is only slightly larger than the previous. For the year 2021, at an efficiency of 0.8, the DAM generated more revenue than the RTM and for 2020, the RTM always generates more revenue than the DAM but the difference between the two decreases with increasing efficiency. This trend may be explained by the fact that the increasing efficiency increases the opportunity to extract revenues, and this is better captured in the less volatile DAMs.

4 Standalone: Impacts of Changing Storage Duration

To explore the impacts of increasing the size of the spheres, which relates to increasing the energy storage capacity of the spheres, various charge times and corresponding MWh's were executed via the models. To determine the MWh stored, the charging capacity was multiplied by the charge time and the square root of the efficiency. The results are shown below in Figure 16 and summarized in Table 8.

Figure 16

Impacts of increasing energy storage capacity.

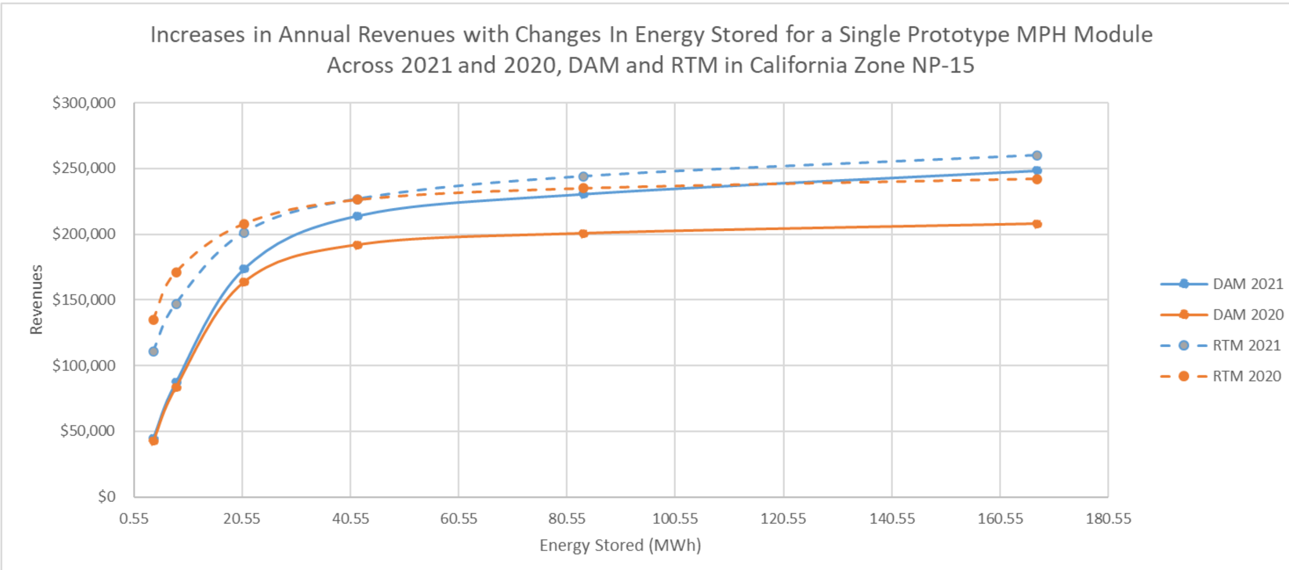


Table 8: Summary of Revenue Changes due to Increasing Energy Storage Capacity

Charge & discharge (hrs)	MWh stored	DAM 2021 ($000)	DAM 2020 ($000)	RTM 2021 ($000)	RTM 2020 ($000)
1/0.5	4.18	45	41	111	135
2/1	8.37	87	80	147	171
5/4	20.91	174	164	201	208
10/8	41.83	214	192	227	226
20/16	83.66	231	201	244	235
40/32	167.31	248	208	260	242

Overall, the standalone storage revenue increases due to storage duration increases are limited by pump:turbine capacity as can be seen with the square root curve behavior exhibited in the chart. The system cannot infinitely capitalize on having an increased storage because the system can only generate revenues based on how much the system can discharge/sell to the grid. At a certain point, increasing the sphere size most likely incurs more cost than benefit. Increasing the MWh capacity has a large impact when starting from smaller MWhs for DAMs, where improving from

4.18 MWh to 8.37, and 20.91 yields to percent increases in the 90s compared to the 20s and 30s for the RTMs. This may be due to the fact that when the model wants to discharge at times of higher prices in the DAM, it is unable to discharge as much over that desired time interval. When the energy storage capacity is greater, the system is then able to capitalize on revenues in that desired time interval, which is less volatile than the RTM. Finally, the RTMs always produce more revenues than the DAMs in their respective years.

5 Standalone: Impacts of Increasing Storage System Size

Due to the linear nature of the optimization model and its formulation, increasing the system size yields a linear increase in revenue generation as shown in Table 9. This trend, however, will not hold as the power rating of the storage system increases to infinity because the system will ultimately be constrained by the grid's ability to provide energy that will charge the system.

Table 9: Impacts of Increasing Storage System Size

# of Modules	Total Charge Capacity (MW)	Total Discharge Capacity (MW)	Energy storage (MWh)	DAM 2021	DAM 2020	RTM 2021	RTM 2020
1	5.4	5	20.91	$173,508	$163,459	$201,143	$207,857
48	259.2	240	1003.88	$8,329,216	$7,846,664	$9,655,399	$9,977,580
				Larger System Rev. on Per Module Basis			
				$173,525	$163,472	$201,154	$207,866

Summary

In response to the original research questions, the results of the study indicate the following:

1. **How does the ratio of storage to wind capacity impact profitability in a hybrid system?**

Answer: The ratio of storage to wind capacity has a minimal impact (<10% increase in revenues) on overall system revenues for both locations and markets *unless* the ratio is above 40% (produces >10% revenues) in the RTM (see Appendices O and P for full results).

2. **How does the time duration of the storage impact the profitability of the storage technology?**

Answer: There are benefits to increase energy storage duration and corresponding energy storage capacity when increasing from 1-2 hr durations to 4 hr durations. After 4 hours, the sphere size increases yield less dramatic increases due to pump:turbine capacity limitations. This does not consider the fact that having larger durations and more MWh's can have other benefits to the grid overall, such as the ability to help with load shifting.

3. **How does the profitability of the storage technology differ in a standalone case vs. a hybrid system?**

Answer: The revenues in the standalone case are higher on a per pump:turbine basis compared to the hybrid scenarios. This can be because the standalone case has fewer modeling constraints as the storage can charge/discharge solely on market conditions rather than being limited to wind capacity factors for charging in the hybrid case. Both cases, however, offer the potential of load shifting, avoiding wind/solar energy curtailments, arbitrage, and firm capacity as value options.[14]

4. **How does the profitability of the technology change with increases in efficiency?**

Answer: Revenues increase linearly with linear increases in efficiency with a trend toward DAMs when efficiencies exceed 90%.

[14] Bowen, T., Chernyakhoskiy, I., Denholm, P., NREL Staff. *Grid Scale Battery Storage: Frequently Asked Questions*. USAID and National Renewable Energy Laboratory. Retrieved from https://www.nrel.gov/docs/fy19osti/74426.pdf

5. **How does the profitability differ between Morro Bay and Humboldt?**

Answer: On a one-to-one basis, Humboldt produces more revenues than Morro Bay in all markets and all years, which is to be expected as the modeled wind NCF's for Humboldt are 2-6% larger than those of Morro Bay.

6. **How does the profitability differ between DAM and RTM?**

Answer: On a pure revenue basis, and especially in the standalone case, the RTM offers a better opportunity to maximize on energy arbitrage due to higher maximum prices and market volatility.

Conclusion and Future Research Focus

The research presented is developed upon extremely simplified assumptions, which are only meant to provide an absolute base case estimate of a single way to generate revenues for the M-PHES technology in California wholesale markets. While useful, the conclusions reached should not *alone* be used to make financial decisions about product development and commercial deployment.

Due to the oversimplified nature of this study, there are many possible options to further explore the product's profitability, including but not limited to:

1. Congestion price taker modeling
2. Ancillary service price taker modeling
3. Price taker modeling with operation costs for wind and storage facilities included
4. Dynamic wind-storage hybrid systems that can have the storage charge from both the grid and the wind farm
5. Avoided CO_2 modeling that can be done using data from CAISO
6. Including inverter losses
7. Forecasting wind generation and revenues into the future
8. Comparative study over different geographies/markets (i.e., the upcoming Gulf of Mexico auction)
9. Repeating the same analysis but assuming different depths.

Appendix A: Wind-Storage Hybrid Schematics

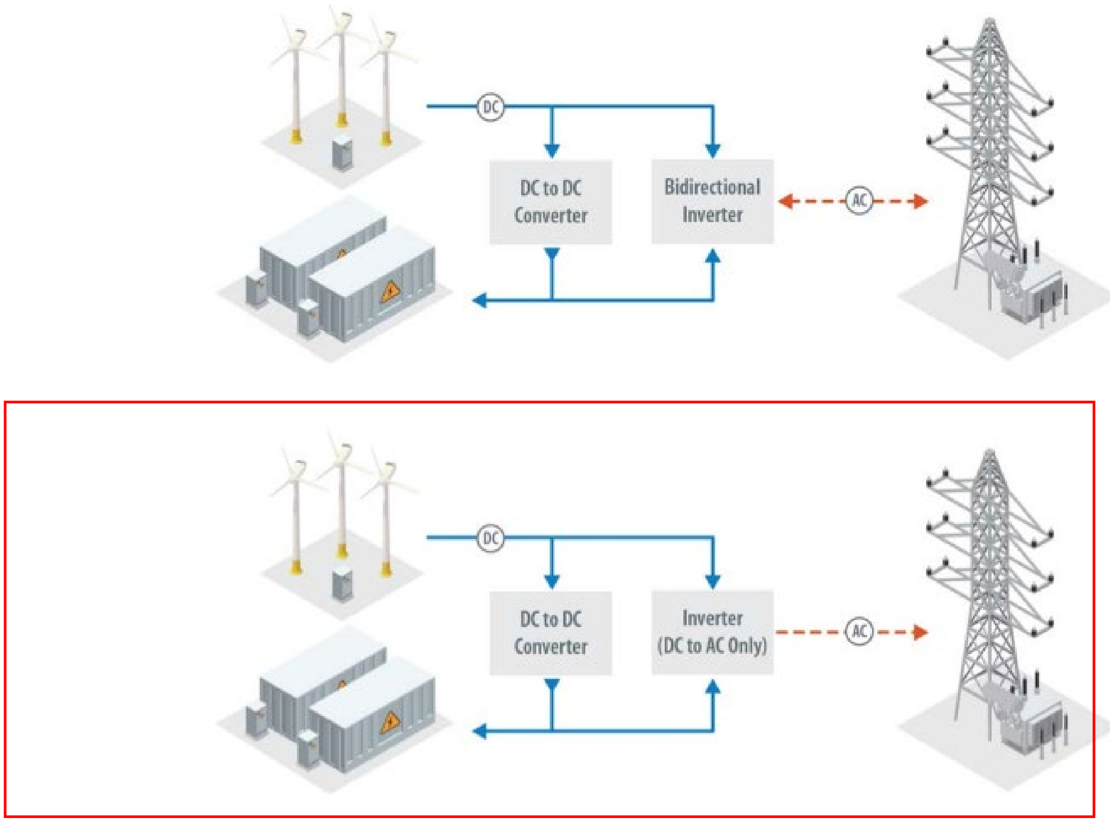


Figure 4. Schematics of DC-coupled wind-storage systems.

Source: Adapted from Denholm, Eichman, and Margolis (2017)

Appendix B: Formulation of Optimization Models

Standalone DAM

Decision Variables

vZ = the revenue of the system

Continuous Variables

$vP_{(w,t)}$ = the amount of production from the grid, *w*, at time *t*

$vDischarge_{(stor,t)}$ = the amount of energy discharged from the storage, *stor*, at time *t*

$vCharge_{(stor,t)}$ = the amount of energy charged to the storage in time *t*

$vSOC_{(stor,t)}$ = the state of charge in the storage at time *t*

Parameters and Sets:

g is a set for generators which consists of *w (the grid)* and PHS, which has a subset *stor*

t is the time in hours of a year, there are 8760 instances of t in 2021 and 8784 in 2020

$pCapacity_g$ = the maximum power output in MW of any generator *g*

pCf_w = the simulated capacity factor of the grid, *w*

pE_{stor} = the maximum amount energy that can be stored in the storage in MWh

pCR_{stor} = the maximum charge rate of the storage in MW

$pEFF_{stor}$ = the round-trip efficiency of the storage

$pLBMP_t$ = the locational based marginal price for DAM in zone NP-15 for 2020 or 2021 (inserted as an external csv file into the model)

Objective Function

Charge and discharge the battery such that revenues are maximized:

Maximize $vZ = \Sigma_{(stor,t)} (pLBMP_t \times vDischarge_{(stor,t)} - pLBMP_t \times vCharge_{(stor,t)})$

Constraints

The maximum production from the grid is restricted by its corresponding capacity:

$$vP_{(w,t)} \leq pCapacity_w$$

The maximum discharge amount from the storage at anytime is restricted by its discharge capacity:

$$vDischarge_{(stor,t)} \leq pCapacity_{stor}$$

The maximum discharge amount from the storage at any time is restricted by its state of charge at time t :

$$vDischarge_{(stor,t)} \leq vSOC_{(stor,t)}$$

The maximum state of charge in the storage at any time is limited by the maximum energy storage:

$$vSOC_{(stor,t)} \leq pE_{stor}$$

The ability to charge the storage at any time is limited by the maximum charge rate of the storage:

$$vCharge_{(stor,t)} \leq pCR_{stor}$$

The state of charge in the battery at any time is dependent on the previous state of charge in *t-1* and the charge and discharge actions of the storage in time *t*:

$$vSOC_{(stor,t)} = vSOC_{(stor,\ t-1)} – [vDischarge_{(stor,t)} / sqrt(pEFF_{stor})] + [vCharge_{(stor,t)} \text{ x } sqrt(pEFF_{stor})]$$

The generation of the grid is restricted to the capacity factor of the grid:

$$vP_{(w,t)} \leq pCf_{w} \text{ x } pCapacity_{w}$$

The sum of all energy charged to the battery must be less than or equal to all the energy produced from the grid:

$$\Sigma_{(stor)}\ vCharge_{(stor,t)} \leq \Sigma_{(w)}\ vP_{(w,t)}$$

Standalone RTM – Main differences from DAM are highlighted in yellow

Decision Variables

vZ = the revenue of the system

Continuous Variables

$vP_{(w,t)}$ = the amount of production from the grid, *w*, at time *t*

$vDischarge_{(stor,t)}$ = the amount of energy discharged from the storage, *stor*, at time *t*

$vCharge_{(stor,t)}$ = the amount of energy charged to the storage in time *t*

$vSOC_{(stor,t)}$ = the state of charge in the storage at time *t*

Parameters and Sets:

g is a set for generators which consists of *w (the grid)* and PHS, which has a subset *stor*

t is the time in 5 minute intervals in a year, there are 105120 instances of t in 2021 and 105408 in 2020

$pCapacity_g$ = the maximum power output in MW of any generator *g*, this value is divided by 12 for the storage value

pCf_w = the simulated capacity factor of the grid, *w*, divided by 12 to convert from hourly to 5-min intervals

pE_{stor} = the maximum amount energy that can be stored in the storage in MWh

pCR_{stor} = the maximum charge rate of the storage in MW, will be divided by 12

$pEFF_{stor}$ = the round-trip efficiency of the storage

$pLBMP_t$ = the locational based marginal price for RTM in zone NP-15 for 2020 or 2021 (imported as a csv file into the model)

Objective Function

Charge and discharge the battery such that revenues are maximized:

$$\textbf{Maximize } vZ = \Sigma_{(stor,t)} (pLBMP_t \times vDischarge_{(stor,t)} - pLBMP_t \times vCharge_{(stor,t)})$$

Constraints

The maximum production from the grid is restricted by its corresponding capacity:

$$vP_{(w,t)} \leq pCapacity_w$$

The maximum discharge amount from the storage at anytime is restricted by its discharge capacity:

$$vDischarge_{(stor,t)} \leq pCapacity_{stor}$$

The maximum discharge amount from the storage at any time is restricted by its state of charge at time t :

$$vDischarge_{(stor,t)} \leq vSOC_{(stor,t)}$$

The maximum state of charge in the storage at any time is limited by the maximum energy storage:

$$vSOC_{(stor,t)} \leq pE_{stor}$$

The ability to charge the storage at any time is limited by the maximum charge rate of the storage:

$$vCharge_{(stor,t)} \leq pCR_{stor}$$

The state of charge in the battery at any time is dependent on the previous state of charge in *t-1* and the charge and discharge actions of the storage in time *t*:

$$vSOC_{(stor,t)} = vSOC_{(stor,\ t-1)} - [vDischarge_{(stor,t)} / sqrt(pEFF_{stor})] + [vCharge_{(stor,t)} \times sqrt(pEFF_{stor})]$$

The generation of the grid is restricted to the capacity factor of the grid:

$$vP_{(w,t)} \leq pCf_{w} \times pCapacity_{w}$$

The sum of all energy charged to the battery must be less than or equal to all the energy produced from the grid:

$$\Sigma_{(stor)}\ vCharge_{(stor,t)} \leq \Sigma_{(w)}\ vP_{(w,t)}$$

Wind-storage hybrid model for DAM:

Decision Variables

vZ = the revenue of the system

Continuous Variables

$vP_{(g,t)}$ = the amount of production from the wind or storage, *g*, at time *t*

$vDischarge_{(stor,t)}$ = the amount of energy discharged from the storage, *stor*, at time *t*

$vCharge_{(stor,t)}$ = the amount of energy charged to the storage in time *t*

$vSOC_{(stor,t)}$ = the state of charge in the storage at time *t*

$vWindNotStored_{t}$ = the amount energy in each hour that is not stored and sold directly to the market

Parameters and Sets:

g is a set for generators which consists of *w (the grid)* and PHS, which has a subset *stor*

t is the time in hours of a year, there are 8760 instances of t in 2021 and 8784 in 2020

$pCapacity_{g}$ = the maximum power output in MW of any generator *g*

$pCf_{(w,t)}$ = the simulated capacity factor of the wind farm in each hour *t* (an external csv file that is imported into the model from the wind modeling)

pE_{stor} = the maximum amount energy that can be stored in the storage in MWh

pCR_{stor} = the maximum charge rate of the storage in MW

$pEFF_{stor}$ = the round-trip efficiency of the storage

$pLBMP_t$ = the locational based marginal price for DAM in zone NP-15 for 2020 or 2021

Objective Function

Maximize the revenues of the system:

Maximize

$$vZ = \Sigma_{(stor,t)} (pLBMP_t \times vDischarge_{(stor,t)} - pLBMP_t \times vCharge_{(stor,t)}) + \Sigma_{(w,t)} pLBMP_t \times vWindNotStored_t$$

Constraints

The maximum production from the wind is restricted by its corresponding capacity:

$$vP_{(w,t)} \leq pCapacity_w$$

The maximum discharge amount from the storage at any time is restricted by its discharge capacity:

$$vDischarge_{(stor,t)} \leq pCapacity_{stor}$$

The maximum discharge amount from the storage at any time is restricted by its state of charge at time t :

$$vDischarge_{(stor,t)} \leq vSOC_{(stor,t)}$$

The maximum state of charge in the storage at any time is limited by the maximum energy storage:

$$vSOC_{(stor,t)} \leq pE_{stor}$$

The ability to charge the storage at any time is limited by the maximum charge rate of the storage:

$$vCharge_{(stor,t)} \leq pCR_{stor}$$

The state of charge in the battery at any time is dependent on the previous state of charge in *t-1* and the charge and discharge actions of the storage in time *t*:

$$vSOC_{(stor,t)} = vSOC_{(stor,\ t-1)} – [vDischarge_{(stor,t)} / sqrt(pEFF_{stor})] + [vCharge_{(stor,t)} \times sqrt(pEFF_{stor})]$$

The generation of the wind in each hour is restricted to the capacity factor of the wind in each hour

$$vP_{(w,t)} \leq pCf_{(w,t)} \times pCapacity_w$$

The sum of all energy charged to the battery must be less than or equal to energy produced from the wind:

$$\Sigma_{(stor)}\ vCharge_{(stor,t)} \leq \Sigma_{(w)}\ vP_{(w,t)}$$

All energy from the wind farm that is not used to charge the battery is sold to the grid:

$$\Sigma_{(w)}\ vP_{(w,t)} - \Sigma_{(stor)}\ vCharge_{(stor,t)} = vWindNotStored_t$$

Just DAM wind optimization model:

<u>Decision Variables</u>

vZ = the revenue of the system

<u>Continuous Variables</u>

$vP_{(g,t)}$ = the amount of production from the wind , *g*, at time *t*

<u>Parameters and Sets:</u>

g is a set for generators which consists of *w (the grid)*

t is the time in hours of a year, there are 8760 instances of t in 2021 and 8784 in 2020

$pCapacity_g$ = the maximum power output in MW of any generator *g*

$pCf_{(w,t)}$ = the simulated capacity factor of the wind farm in each hour *t* (an external csv file that is imported into the model from the wind modeling)

$pLBMP_t$ = the locational based marginal price for DAM in zone NP-15 for 2020 or 2021

<u>Objective Function</u>

Maximize the revenues of the system:

Maximize

$$vZ = + \Sigma_{(w,t)} pLBMP_t \text{ x } vP_{(w,t)}$$

<u>Constraints</u>

The maximum production from the wind is restricted by its corresponding capacity:

$$vP_{(w,t)} \leq pCapacity_w$$

The generation of the wind in each hour is restricted to the capacity factor of the wind in each hour

$$vP_{(w,t)} \leq pCf_{(w,t)} \text{ x } pCapacity_w$$

Wind-storage Hybrid Model for RTM:

Decision Variables

vZ = the revenue of the system

Continuous Variables

$vP_{(g,t)}$ = the amount of production from the wind or storage, *g*, at time *t*

$vDischarge_{(stor,t)}$ = the amount of energy discharged from the storage, *stor*, at time *t*

$vCharge_{(stor,t)}$ = the amount of energy charged to the storage in time *t*

$vSOC_{(stor,t)}$ = the state of charge in the storage at time *t*

$vWindNotStored_t$ = the amount energy in each hour that is not stored and sold directly to the market

Parameters and Sets:

g is a set for generators which consists of *w (the grid)* and PHS, which has a subset *stor*

t is the time in hours of a year, there are 105120 instances of t in 2021 and 105408 in 2020

$pCapacity_g$ = the maximum power output in MW of any generator *g,* divided by 12 for storage values

$pCf_{(w,t)}$ = the simulated capacity factor of the wind farm in each hour *t* (an external csv file that is imported into the model from the wind modeling)

pE_{stor} = the maximum amount energy that can be stored in the storage in MWh

pCR_{stor} = the maximum charge rate of the storage in MW, divided by 12

$pEFF_{stor}$ = the round-trip efficiency of the storage

$pLBMP_t$ = the locational based marginal price for RTM in zone NP-15 for 2020 or 2021

Objective Function

Maximize the revenues of the system:

Maximize

$$vZ = \Sigma_{(stor,t)} (pLBMP_t \times vDischarge_{(stor,t)} - pLBMP_t \times vCharge_{(stor,t)}) + \Sigma_{(w,t)} pLBMP_t \times vWindNotStored_t$$

Constraints

The maximum production from the wind is restricted by its corresponding capacity:

$$vP_{(w,t)} \leq pCapacity_{w}$$

The maximum discharge amount from the storage at any time is restricted by its discharge capacity:

$$vDischarge_{(stor,t)} \leq pCapacity_{stor}$$

The maximum discharge amount from the storage at any time is restricted by its state of charge at time t :

$$vDischarge_{(stor,t)} \leq vSOC_{(stor,t)}$$

The maximum state of charge in the storage at any time is limited by the maximum energy storage:

$$vSOC_{(stor,t)} \leq pE_{stor}$$

The ability to charge the storage at any time is limited by the maximum charge rate of the storage:

$$vCharge_{(stor,t)} \leq pCR_{stor}$$

The state of charge in the battery at any time is dependent on the previous state of charge in *t-1* and the charge and discharge actions of the storage in time *t*:

$$vSOC_{(stor,t)} = vSOC_{(stor,\ t-1)} - [vDischarge_{(stor,t)} / sqrt(pEFF_{stor})] + [vCharge_{(stor,t)} \text{ x } sqrt(pEFF_{stor})]$$

The generation of the wind in each hour is restricted to the capacity factor of the wind in each hour

$$vP_{(w,t)} \leq pCf_{(w,t)} \text{ x } pCapacity_{w}$$

The sum of all energy charged to the battery must be less than or equal to energy produced from the wind:

$$\Sigma_{(stor)}\ vCharge_{(stor,t)} \leq \Sigma_{(w)}\ vP_{(w,t)}$$

All energy from the wind farm that is not used to charge the battery is sold to the grid:

$$\Sigma_{(w)}\ vP_{(w,t)} - \Sigma_{(stor)}\ vCharge_{(stor,t)} = vWindNotStored_{t}$$

Just RTM wind optimization model:

Decision Variables

vZ = the revenue of the system

Continuous Variables

$vP_{(g,t)}$ = the amount of production from the wind , *g*, at time *t*

Parameters and Sets:

g is a set for generators which consists of *w (the grid)*

t is the time in hours of a year, there are 105120 instances of t in 2021 and 105408 in 2020

$pCapacity_g$ = the maximum power output in MW of any generator *g*

$pCf_{(w,t)}$ = the simulated capacity factor of the wind farm in each hour *t* (an external csv file that is imported into the model from the wind modeling)

$pLBMP_t$ = the locational based marginal price for RTM in zone NP-15 for 2020 or 2021

Objective Function

Maximize the revenues of the system:

Maximize

$$vZ = + \Sigma_{(w,t)} pLBMP_t \times vP_{(w,t)}$$

Constraints

The maximum production from the wind is restricted by its corresponding capacity:

$$vP_{(w,t)} \leq pCapacity_w$$

The generation of the wind in each hour is restricted to the capacity factor of the wind in each hour

$$vP_{(w,t)} \leq pCf_{(w,t)} \times pCapacity_w$$

Appendix C: Raw Optimization Code

```
*Michael Storch
*RCAM Project
*Project: Standalone Price DAM Taker Model
*Scrdir "C:\Users\Michael Storch\Documents\SEAS\RCAM\Revenue Modeling\CA\Standalone"


Sets
        g "generators" /w,PHS/
t "time in hours" /t1*t8760/
* for 2021
*t "time in hours" /t1*t8784/
* for 2020
        w(g) " the grid " /w/
        stor(g) "Pumped Hydro Storage" /PHS/
        ;

Parameters
*VOM(w) "vom of wind" /w 0/
        pCapacity(g) "maximum power output MW" /w 10000,PHS 5/
        pCf(w) "Simulated capacity of the grid" /w 1.0/
*add unlimited capacity of wind to simulate the grid
        pE(stor)  "Energy stored in battery MWh" /PHS 23.38/
        pCR(stor) "max charge rate of battery MW" /PHS 5.4/
        pEFF(stor)  "battery efficiency" /PHS 0.75/
       ;

*15 MW is for 1 turbine from reference
*Do not indent or modify any part of this parameter declaration.
Parameter pLBMP(t) "Locational Based Marginal pricing for DAM in NP-15 for 2021 or 2020"
/
$ondelim
$include LMBPDAM2021.csv
$offdelim
/
;

*Do not indent or modify any part of this parameter declaration.
*Parameter pCf(w,t)
*/
*$ondelim
*$include CFhum2021DAM.csv
*$offdelim
```

```
*/
*;

Variables
        vZ
        ;

Positive variables
        vP(w,t)
*vWindNotStored(t)
        vDischarge(stor,t)
        vCharge(stor,t)
        vSOC(stor,t)
        ;

Equations
        eObjFunc
*eMeetDemand(t)
        eMaxGen(w,t)
        eMaxGenStor(stor,t)
        eEnforceCfs(w,t)
        eMaxStorage(stor,t)
        eEnergyLimit(stor,t)
* the discharge rate and charge rate can be changed by changing the constraint for both.
        eChargeLimit(stor,t)
        eChargeDischarge(stor,t)
        eWind2Stor(t)
*eLink(t)
        ;

eObjFunc.. vZ =e= sum((stor,t),pLBMP(t)*vDischarge(stor,t)-pLBMP(t)*vCharge(stor,t));

*+ sum((w,t),pLBMP(t)*vWindNotStored(t)); not including wind farm
*+sum(t,pLBMP(t)*vP(w,t)-(pLBMP(t)+VOM(t))*vP(w,t));
*-pLBMP(t)*vCharge(stor,t)) <-- use this for the charging with the grid as a standalone system.

*eMeetDemand(t).. sum(g,vP(g,t))+vNSE(t) =e= pDemand(t)+sum(stor,vCharge(stor,t)); !! not applicable
for this model

eMaxGen(w,t).. vP(w,t) =l= pCapacity(w);
eMaxGenStor(stor,t).. vDischarge(stor,t) =l= pCapacity(stor);

eMaxStorage(stor,t).. vDischarge(stor,t) =l= vSOC(stor,t);
eEnergyLimit(stor,t).. vSOC(stor,t) =l= pE(stor);
```

```
eChargeLimit(stor,t)..vCharge(stor,t)=l= pCR(stor);

eChargeDischarge(stor,t)..vSOC(stor,t)=e=vSOC(stor,t-1)-
vDischarge(stor,t)/sqrt(pEFF(stor))+vCharge(stor,t)*sqrt(pEFF(stor));

eEnforceCfs(w,t).. vP(w,t) =l= pCf(w)*pCapacity(w);
eWind2Stor(t)..sum((stor),vCharge(stor,t)) =l= sum((w),vP(w,t));
*this just allows the storage to charge from the "grid" which is available all the time per the eEnforceCfs

*need to allow the storage to buy and sell to the grid by linking charge and discharge decisions to LMPs, I
believe this is handled in the obj. function

*eLink(t)..sum(w,vP(w,t))-sum(stor,vCharge(stor,t))=e= vWindNotStored(t);
* ^for a standalone system, remove the link constraining charging to justthe wind farm.

Model dispatch includes all equations /all/;
Solve dispatch using lp Maximizing vZ;

execute_unload "results.gdx" vP.l vCharge.l vSOC.l vDischarge.l
*vWindNotStored.l
execute 'gdxxrw.exe results.gdx o=results.xlsx var=vP.l rng=Generation!a1'
execute 'gdxxrw.exe results.gdx o=results.xlsx var=vDischarge.l rng=Generation!a1'
*execute 'gdxxrw.exe results.gdx o=results.xlsx par=pOC rng=OpCost!a1'
*execute 'gdxxrw.exe results.gdx o=results.xlsx equ=eMeetDemand.m rng=Prices!a1'
execute 'gdxxrw.exe results.gdx o=results.xlsx var=vCharge.l rng=Charge!a1'
*execute 'gdxxrw.exe results.gdx o=results.xlsx var=vWindNotStored.l rng=Leftoverwind!a1'
execute 'gdxxrw.exe results.gdx o=results.xlsx var=vSOC.l rng=Stateofcharge!a1'

File gen / generation.csv /;
gen.pc = 5;
put gen;
loop((w,t),
  put w.tl, t.tl, vP.l(w,t) /
);
putclose;

File discharge / discharge.csv /;
discharge.pc = 5;
put discharge;
loop((stor,t),
  put stor.tl, t.tl, vDischarge.l(stor,t) /
);
putclose;
```

```
File charge / Charge.csv /;
charge.pc = 5;
put charge;
loop((stor,t),
  put stor.tl, t.tl, vCharge.l(stor,t) /
);
putclose;

File SOC / Stateofcharge.csv /;
SOC.pc = 5;
put SOC;
loop((stor,t),
  put stor.tl, t.tl, vSOC.l(stor,t) /
);
putclose;
```

```
*Michael Storch
*RCAM Project
*Project: Standalone Price RTM Taker Model
*Scrdir "C:\Users\Michael Storch\Documents\SEAS\RCAM\Revenue Modeling\CA\Standalone"


Sets
        g "generators" /w,PHS/
t "time in 5 minute intervals" /t1*t105120/
* for 2021
*t "time in 5-min intervals" /t1*t105408/
* for 2020
        w(g) "the grid" /w/
        stor(g) "Pumped Hydro Storage" /PHS/
        ;

Parameters
*VOM(w) "vom of wind" /w 0/
        pCapacity(g) "maximum power output MW" /w 10000,PHS 0.41666/
        pCf(w) "Simulated capacity of the grid" /w 0.083333/
*add unlimited capacity of wind to simulate the grid, for RTM, CF must be 1/12 for five minute intervals
in an hour
        pE(stor)  "Energy stored in battery MWh" /PHS 24.89/
        pCR(stor) "max charge rate of battery MW" /PHS 0.45/
        pEFF(stor)  "battery efficiency" /PHS 0.85/
       ;

*15 MW is for 1 turbine from reference
```

```
*Do not indent or modify any part of this parameter declaration.
Parameter pLBMP(t) "Locational Based Marginal pricing for RTM in NP-15 for either 2020 or 2021"
/
$ondelim
$include LMBPRTM2021.csv
$offdelim
/
;

*Do not indent or modify any part of this parameter declaration.
*Parameter pCf(w,t)
*/
*$ondelim
*$include CFhum2021DAM.csv
*$offdelim
*/
*;

Variables
        vZ
        ;

Positive variables
        vP(w,t)
*vWindNotStored(t)
        vDischarge(stor,t)
        vCharge(stor,t)
        vSOC(stor,t)
        ;

Equations
        eObjFunc
*eMeetDemand(t)
        eMaxGen(w,t)
        eMaxGenStor(stor,t)
        eEnforceCfs(w,t)
        eMaxStorage(stor,t)
        eEnergyLimit(stor,t)
* the discharge rate and charge rate can be changed by changing the constraint for both.
        eChargeLimit(stor,t)
        eChargeDischarge(stor,t)
        eWind2Stor(t)
*eLink(t)
        ;
```

```
eObjFunc.. vZ =e= sum((stor,t),pLBMP(t)*vDischarge(stor,t)-pLBMP(t)*vCharge(stor,t));

*+ sum((w,t),pLBMP(t)*vWindNotStored(t)); not including wind farm
*+sum(t,pLBMP(t)*vP(w,t)-(pLBMP(t)+VOM(t))*vP(w,t));
*-pLBMP(t)*vCharge(stor,t)) <-- use this for the charging with the grid as a standalone system.

*eMeetDemand(t).. sum(g,vP(g,t))+vNSE(t) =e= pDemand(t)+sum(stor,vCharge(stor,t)); !! not applicable
for this model

eMaxGen(w,t).. vP(w,t) =l= pCapacity(w);
eMaxGenStor(stor,t).. vDischarge(stor,t) =l= pCapacity(stor);

eMaxStorage(stor,t).. vDischarge(stor,t) =l= vSOC(stor,t);
eEnergyLimit(stor,t).. vSOC(stor,t) =l= pE(stor);
eChargeLimit(stor,t)..vCharge(stor,t)=l= pCR(stor);

eChargeDischarge(stor,t)..vSOC(stor,t)=e=vSOC(stor,t-1)-
vDischarge(stor,t)/sqrt(pEFF(stor))+vCharge(stor,t)*sqrt(pEFF(stor));

eEnforceCfs(w,t).. vP(w,t) =l= pCf(w)*pCapacity(w);
eWind2Stor(t)..sum((stor),vCharge(stor,t)) =l= sum((w),vP(w,t));
*this just allows the storage to charge from the "grid" which is available all the time per the eEnforceCfs

*need to allow the storage to buy and sell to the grid by linking charge and discharge decisions to LMPs, I
believe this is handled in the obj. function

*eLink(t)..sum(w,vP(w,t))-sum(stor,vCharge(stor,t))=e= vWindNotStored(t);
* ^for a standalone system, remove the link constraining charging to justthe wind farm.

Model dispatch includes all equations /all/;
Solve dispatch using lp Maximizing vZ;

execute_unload "results.gdx" vP.l vCharge.l vSOC.l vDischarge.l
*vWindNotStored.l
execute 'gdxxrw.exe results.gdx o=results.xlsx var=vP.l rng=Generation!a1'
execute 'gdxxrw.exe results.gdx o=results.xlsx var=vDischarge.l rng=Generation!a1'
*execute 'gdxxrw.exe results.gdx o=results.xlsx par=pOC rng=OpCost!a1'
*execute 'gdxxrw.exe results.gdx o=results.xlsx equ=eMeetDemand.m rng=Prices!a1'
execute 'gdxxrw.exe results.gdx o=results.xlsx var=vCharge.l rng=Charge!a1'
*execute 'gdxxrw.exe results.gdx o=results.xlsx var=vWindNotStored.l rng=Leftoverwind!a1'
execute 'gdxxrw.exe results.gdx o=results.xlsx var=vSOC.l rng=Stateofcharge!a1'

File gen / generation.csv /;
```

```
gen.pc = 5;
put gen;
loop((w,t),
  put w.tl, t.tl, vP.l(w,t) /
);
putclose;

File discharge / discharge.csv /;
discharge.pc = 5;
put discharge;
loop((stor,t),
  put stor.tl, t.tl, vDischarge.l(stor,t) /
);
putclose;

File charge / Charge.csv /;
charge.pc = 5;
put charge;
loop((stor,t),
  put stor.tl, t.tl, vCharge.l(stor,t) /
);
putclose;

File SOC / Stateofcharge.csv /;
SOC.pc = 5;
put SOC;
loop((stor,t),
  put stor.tl, t.tl, vSOC.l(stor,t) /
);
putclose;
```

```
*Michael Storch
*RCAM Project
*Project: Price Taker of PHS+Wind for DAM
*Scrdir "C:\Users\Michael Storch\Documents\SEAS\RCAM\Revenue Modeling\CA\MPH+Wind DAM Modeling"


Sets
        g "generators" /w,PHS/
t "time in hours" /t1*t8760/
* for 2021
*t "time in hours" /t1*t8784/
```

```
* for 2020
        w(g) "wind generators" /w/
        stor(g) "Pumped Hydro Storage" /PHS/
        ;

Parameters
        VOM(w) "vom of wind" /w 0/
        pCapacity(g) "maximum power output MW" /w 1845,PHS 240/
        pE(stor)  "Energy stored in battery MWh" /PHS 1003.88/
        pCR(stor) "max charge rate of battery MW" /PHS 259.2/
        pEFF(stor)  "battery efficiency" /PHS 0.6/
       ;

*15 MW is for 1 turbine from reference
*Do not indent or modify any part of this parameter declaration.
Parameter pLBMP(t) "Locational Based Marginal pricing for DAM in NP-15 for 2021 or 2020"
/
$ondelim
$include LMBPDAM2021.csv
$offdelim
/
;

*Do not indent or modify any part of this parameter declaration.
Parameter pCf(w,t)
/
$ondelim
$include CFmorr2021DAM.csv
$offdelim
/
;
* change between years 2021 and 2020, as well as site,
*i.e. CFmorr2021DAM, CFmorr2020DAM, or CFhum2021DAM, CFhum2020DAM
Variables
        vZ
        ;

Positive variables
        vP(w,t)
        vWindNotStored(t)
        vDischarge(stor,t)
        vCharge(stor,t)
        vSOC(stor,t)
        ;
```

```
Equations
        eObjFunc
*eMeetDemand(t)
        eMaxGen(w,t)
        eMaxGenStor(stor,t)
        eEnforceCfs(w,t)
        eMaxStorage(stor,t)
        eEnergyLimit(stor,t)
* the discharge rate and charge rate can be changed by changing the constraint for both.
        eChargeLimit(stor,t)
        eChargeDischarge(stor,t)
        eWind2Stor(t)
        eLink(t)
        ;

eObjFunc.. vZ =e= sum((stor,t),pLBMP(t)*vDischarge(stor,t)) +
sum((w,t),pLBMP(t)*vWindNotStored(t));
*+sum(t,pLBMP(t)*vP(w,t)-(pLBMP(t)+VOM(t))*vP(w,t));
*-pLBMP(t)*vCharge(stor,t)) <-- use this for the charging with the grid as a standalone system.

*eMeetDemand(t).. sum(g,vP(g,t))+vNSE(t) =e= pDemand(t)+sum(stor,vCharge(stor,t));

eMaxGen(w,t).. vP(w,t) =l= pCapacity(w);
eMaxGenStor(stor,t).. vDischarge(stor,t) =l= pCapacity(stor);

eMaxStorage(stor,t).. vDischarge(stor,t) =l= vSOC(stor,t);
eEnergyLimit(stor,t).. vSOC(stor,t) =l= pE(stor);
eChargeLimit(stor,t)..vCharge(stor,t)=l= pCR(stor);

eChargeDischarge(stor,t)..vSOC(stor,t)=e=vSOC(stor,t-1)-
vDischarge(stor,t)/sqrt(pEFF(stor))+vCharge(stor,t)*sqrt(pEFF(stor));
eEnforceCfs(w,t).. vP(w,t) =l= pCf(w,t)*pCapacity(w);

eWind2Stor(t)..sum((stor),vCharge(stor,t)) =l= sum((w),vP(w,t));
eLink(t)..sum(w,vP(w,t))-sum(stor,vCharge(stor,t))=e= vWindNotStored(t);
* for a standalone system, remove the link constraining charging to justthe wind farm.

Model dispatch includes all equations /all/;
Solve dispatch using lp Maximizing vZ;

*execute_unload "results.gdx" vP.l vCharge.l vSOC.l vDischarge.l vWindNotStored.l
*execute 'gdxxrw.exe results.gdx o=results.xlsx var=vP.l rng=Generation!a1'
*execute 'gdxxrw.exe results.gdx o=results.xlsx var=vDischarge.l rng=Generation!a1'
```

```
**execute 'gdxxrw.exe results.gdx o=results.xlsx par=pOC rng=OpCost!a1'
**execute 'gdxxrw.exe results.gdx o=results.xlsx equ=eMeetDemand.m rng=Prices!a1'
*execute 'gdxxrw.exe results.gdx o=results.xlsx var=vCharge.l rng=Charge!a1'
*execute 'gdxxrw.exe results.gdx o=results.xlsx var=vWindNotStored.l rng=Leftoverwind!a1'
*execute 'gdxxrw.exe results.gdx o=results.xlsx var=vSOC.l rng=Stateofcharge!a1'
*
*File gen / generation.csv /;
*gen.pc = 5;
*put gen;
*loop((w,t),
*  put w.tl, t.tl, vP.l(w,t) /
*);
*putclose;
*
*File discharge / discharge.csv /;
*discharge.pc = 5;
*put discharge;
*loop((stor,t),
*  put stor.tl, t.tl, vDischarge.l(stor,t) /
*);
*putclose;
*
*File charge / Charge.csv /;
*charge.pc = 5;
*put charge;
*loop((stor,t),
*  put stor.tl, t.tl, vCharge.l(stor,t) /
*);
*putclose;
*
*File SOC / Stateofcharge.csv /;
*SOC.pc = 5;
*put SOC;
*loop((stor,t),
*  put stor.tl, t.tl, vSOC.l(stor,t) /
*);
*putclose;
```

```
*Michael Storch
*RCAM just wind for comparison
*Project: Price Taker of Wind DAM
Sets
        g "generators" /w,PHS/
t "time in hours" /t1*t8760/
```

```
* for 2021
*t "time in hours" /t1*t8784/
* for 2020
        w(g) "wind generators" /w/
*stor(g) "Pumped Hydro Storage" /PHS/
        ;

Parameters
        VOM(w) "vom of wind" /w 0/
        pCapacity(g) "maximum power output MW" /w 1845/
*,PHS 10/
*pE(stor)  "Energy stored in battery MWh" /PHS 100/
*pCR(stor) "max charge rate of battery MW)" /PHS 10/
*pEFF(stor)  "battery efficiency" /PHS 0.73/
       ;


*Do not indent or modify any part of this parameter declaration.
Parameter pLBMP(t) "Locational Based Marginal pricing in NP 15 for 2020 or 2021"
/
$ondelim
$include LMBPDAM2021.csv
$offdelim
/
;

*Do not indent or modify any part of this parameter declaration.
Parameter pCf(w,t)
/
$ondelim
$include CFmorr2021DAM.csv
$offdelim
/
;
* change between years 2021 and 2020, as well as site, i.e.
*CFmorr2021DAM, CFmorr2020DAM, or CFhum2021DAM, CFhum2020DAM
Variables
        vZ
        ;

Positive variables
        vP(w,t)
*vDischarge(stor,t)
*vCharge(stor,t)
```

```
*vSOC(stor,t)
        ;

Equations
        eObjFunc
*eMeetDemand(t)
        eMaxGen(w,t)
*eMaxGenStor(stor,t)
        eEnforceCfs(w,t)
*eMaxStorage(stor,t)
*eEnergyLimit(stor,t)
*eChargeLimit(stor,t)
*eChargeDischarge(stor,t)
*eWind2Stor
        ;

eObjFunc.. vZ =e= sum((w,t),pLBMP(t)*vP(w,t));
*sum((stor,t),pLBMP(t)*vCharge(stor,t)-pLBMP(t)*vDischarge(stor,t))+sum(t,pLBMP(t)*vP(w,t)-
(pLBMP(t)+VOM(t))*vP(w,t));

*eMeetDemand(t).. sum(g,vP(g,t))+vNSE(t) =e= pDemand(t)+sum(stor,vCharge(stor,t));

eMaxGen(w,t).. vP(w,t) =l= pCapacity(w);
*eMaxGenStor(stor,t).. vDischarge(stor,t) =l= pCapacity(stor);

*eMaxStorage(stor,t).. vDischarge(stor,t) =l= vSOC(stor,t);
*eEnergyLimit(stor,t).. vSOC(stor,t) =l= pE(stor);
*eChargeLimit(stor,t)..vCharge(stor,t)=l= pCR(stor);

*eChargeDischarge(stor,t)..vSOC(stor,t)=e=vSOC(stor,t-1)-
vDischarge(stor,t)/sqrt(pEFF(stor))+vCharge(stor,t)*sqrt(pEFF(stor));
eEnforceCfs(w,t).. vP(w,t) =l= pCf(w,t)*pCapacity(w);

*eWind2Stor..sum((stor,t),vCharge(stor,t)) =l= sum((w,t),vP(w,t));

Model dispatch includes all equations /all/;
Solve dispatch using lp Maximizing vZ;

*execute_unload "results.gdx" vP.l
*execute 'gdxxrw.exe results.gdx o=results.xlsx var=vP.l rng=Generation!a1'
**execute 'gdxxrw.exe results.gdx o=results.xlsx var=vDischarge.l rng=Generation!a1'
**execute 'gdxxrw.exe results.gdx o=results.xlsx par=pOC rng=OpCost!a1'
**execute 'gdxxrw.exe results.gdx o=results.xlsx equ=eMeetDemand.m rng=Prices!a1'
**execute 'gdxxrw.exe results.gdx o=results.xlsx var=vCharge.l rng=Charge!a1'
```

```
**execute 'gdxxrw.exe results.gdx o=results.xlsx var=vSOC.l rng=Stateofcharge!a1'
*
*File gen / generation.csv /;
*gen.pc = 5;
*put gen;
*loop((w,t),
*  put w.tl, t.tl, vP.l(w,t) /
*);
*putclose;
*
**File charge / Charge.csv /;
**charge.pc = 5;
**put charge;
**loop((stor,t),
**  put stor.tl, t.tl, vCharge.l(stor,t) /
**);
**putclose;
*
**File SOC / Stateofcharge.csv /;
**SOC.pc = 5;
**put SOC;
**loop((stor,t),
**put stor.tl, t.tl, vSOC.l(stor,t) /
**);
**putclose;
```

```
*Michael Storch
*RCAM Project
*Project: Price Taker of PHS+Wind for RTM
*Scrdir "C:\Users\Michael Storch\Documents\SEAS\RCAM\Revenue Modeling\CA\MPH+Wind RTM Modeling"


Sets
        g "generators" /w,PHS/
t "time in 5 minute intervals" /t1*t105120/
* for 2021
*t "time in 5-min intervals" /t1*t105408/
* for 2020
        w(g) "wind generators" /w/
        stor(g) "Pumped Hydro Storage" /PHS/
        ;

Parameters
```

```
      VOM(w) "vom of wind" /w 0/
      pCapacity(g) "maximum power output MW" /w 1845,PHS 20/
        pE(stor)  "Energy stored in battery MWh" /PHS 1003.88/
        pCR(stor) "max charge rate of battery MW" /PHS 21.6/
        pEFF(stor)  "battery efficiency" /PHS 0.6/
       ;

*15 MW is for 1 turbine from reference
*Do not indent or modify any part of this parameter declaration.
Parameter pLBMP(t) "Locational Based Marginal pricing for DAM in NP-15 for 2021 or 2020"
/
$ondelim
$include LMBPRTM2021.csv
$offdelim
/
;

*Do not indent or modify any part of this parameter declaration.
Parameter pCf(w,t)
/
$ondelim
$include CFmorr2021RTM.csv
$offdelim
/
;
* change between years 2021 and 2020, as well as site, i.e. CFmorr2021RTM, CFmorr2020RTM,
* or CFhum2021RTM, CFhum202RTM

Variables
        vZ
        ;

Positive variables
        vP(w,t)
        vWindNotStored(t)
        vDischarge(stor,t)
        vCharge(stor,t)
        vSOC(stor,t)
        ;

Equations
        eObjFunc
*eMeetDemand(t)
        eMaxGen(w,t)
```

```
        eMaxGenStor(stor,t)
        eEnforceCfs(w,t)
        eMaxStorage(stor,t)
        eEnergyLimit(stor,t)
        eChargeLimit(stor,t)
        eChargeDischarge(stor,t)
        eWind2Stor(t)
        eLink(t)
        ;

eObjFunc.. vZ =e= sum((stor,t),pLBMP(t)*vDischarge(stor,t)-pLBMP(t)*vCharge(stor,t)) +
sum((w,t),pLBMP(t)*vWindNotStored(t));
*+sum(t,pLBMP(t)*vP(w,t)-(pLBMP(t)+VOM(t))*vP(w,t));

*eMeetDemand(t).. sum(g,vP(g,t))+vNSE(t) =e= pDemand(t)+sum(stor,vCharge(stor,t));

eMaxGen(w,t).. vP(w,t) =l= pCapacity(w);
eMaxGenStor(stor,t).. vDischarge(stor,t) =l= pCapacity(stor);

eMaxStorage(stor,t).. vDischarge(stor,t) =l= vSOC(stor,t);
eEnergyLimit(stor,t).. vSOC(stor,t) =l= pE(stor);
eChargeLimit(stor,t)..vCharge(stor,t)=l= pCR(stor);

eChargeDischarge(stor,t)..vSOC(stor,t)=e=vSOC(stor,t-1)-
vDischarge(stor,t)/sqrt(pEFF(stor))+vCharge(stor,t)*sqrt(pEFF(stor));
eEnforceCfs(w,t).. vP(w,t) =l= pCf(w,t)*pCapacity(w);

eWind2Stor(t)..sum((stor),vCharge(stor,t)) =l= sum((w),vP(w,t));
eLink(t)..sum(w,vP(w,t))-sum(stor,vCharge(stor,t))=e= vWindNotStored(t);

Model dispatch includes all equations /all/;
Solve dispatch using lp Maximizing vZ;

*execute_unload "results_e.gdx" vP.l vCharge.l vSOC.l vDischarge.l vWindNotStored.l
*execute 'gdxxrw.exe results_e.gdx o=results.xlsx var=vP.l rng=Generation!a1'
*execute 'gdxxrw.exe results_e.gdx o=results.xlsx var=vDischarge.l rng=Generation!a1'
**execute 'gdxxrw.exe results.gdx o=results.xlsx par=pOC rng=OpCost!a1'
**execute 'gdxxrw.exe results.gdx o=results.xlsx equ=eMeetDemand.m rng=Prices!a1'
*execute 'gdxxrw.exe results_e.gdx o=results.xlsx var=vCharge.l rng=Charge!a1'
*execute 'gdxxrw.exe results_e.gdx o=results.xlsx var=vWindNotStored.l rng=Leftoverwind!a1'
*execute 'gdxxrw.exe results_e.gdx o=results.xlsx var=vSOC.l rng=Stateofcharge!a1'
*
*File gen / generation_e.csv /;
*gen.pc = 5;
```

```
*put gen;
*loop((w,t),
*  put w.tl, t.tl, vP.l(w,t) /
*);
*putclose;
*
*File discharge / discharge_e.csv /;
*discharge.pc = 5;
*put discharge;
*loop((stor,t),
*  put stor.tl, t.tl, vDischarge.l(stor,t) /
*);
*putclose;
*
*File charge / Charge_e.csv /;
*charge.pc = 5;
*put charge;
*loop((stor,t),
*  put stor.tl, t.tl, vCharge.l(stor,t) /
*);
*putclose;
*
*File SOC / Stateofcharge_e.csv /;
*SOC.pc = 5;
*put SOC;
*loop((stor,t),
*  put stor.tl, t.tl, vSOC.l(stor,t) /
*);
*putclose;
```

```
*Michael Storch
*RCAM just wind for comparison
*Project: Price Taker of Wind RTM
Sets
        g "generators" /w,PHS/
t "time in hours" /t1*t105120/
*for 2021
*t "time in 5-min intervals" /t1*t105408/
* for 2020
        w(g) "wind generators" /w/
*stor(g) "Pumped Hydro Storage" /PHS/
        ;

Parameters
```

```
	VOM(w) "vom of wind" /w 0/
	pCapacity(g) "maximum power output MW" /w 1845/
*,PHS 10/
*pE(stor)  "Energy stored in battery MWh" /PHS 100/
*pCR(stor) "max charge rate of battery MW)" /PHS 10/
*pEFF(stor)  "battery efficiency" /PHS 0.73/
	;


*Do not indent or modify any part of this parameter declaration.
Parameter pLBMP(t) "Locational Based Marginal pricing in NP-15 for 2021 or 2020"
/
$ondelim
$include LMBPRTM2021.csv
$offdelim
/
;

*Do not indent or modify any part of this parameter declaration.
Parameter pCf(w,t)
/
$ondelim
$include CFmorr2021RTM.csv
$offdelim
/
;
* change between years 2021 and 2020, as well as site, i.e. CFmorr2021RTM, CFmorr2020RTM,
* or CFhum2021RTM, CFhum202RTM
Variables
	vZ
	;

Positive variables
	vP(w,t)
*vDischarge(stor,t)
*vCharge(stor,t)
*vSOC(stor,t)
	;

Equations
	eObjFunc
*eMeetDemand(t)
	eMaxGen(w,t)
*eMaxGenStor(stor,t)
```

```
        eEnforceCfs(w,t)
*eMaxStorage(stor,t)
*eEnergyLimit(stor,t)
*eChargeLimit(stor,t)
*eChargeDischarge(stor,t)
*eWind2Stor
        ;

eObjFunc.. vZ =e= sum((w,t),pLBMP(t)*vP(w,t));
*sum((stor,t),pLBMP(t)*vCharge(stor,t)-pLBMP(t)*vDischarge(stor,t))+sum(t,pLBMP(t)*vP(w,t)-
(pLBMP(t)+VOM(t))*vP(w,t));

*eMeetDemand(t).. sum(g,vP(g,t))+vNSE(t) =e= pDemand(t)+sum(stor,vCharge(stor,t));

eMaxGen(w,t).. vP(w,t) =l= pCapacity(w);
*eMaxGenStor(stor,t).. vDischarge(stor,t) =l= pCapacity(stor);

*eMaxStorage(stor,t).. vDischarge(stor,t) =l= vSOC(stor,t);
*eEnergyLimit(stor,t).. vSOC(stor,t) =l= pE(stor);
*eChargeLimit(stor,t)..vCharge(stor,t)=l= pCR(stor);

*eChargeDischarge(stor,t)..vSOC(stor,t)=e=vSOC(stor,t-1)-
vDischarge(stor,t)/sqrt(pEFF(stor))+vCharge(stor,t)*sqrt(pEFF(stor));
eEnforceCfs(w,t).. vP(w,t) =l= pCf(w,t)*pCapacity(w);

*eWind2Stor..sum((stor,t),vCharge(stor,t)) =l= sum((w,t),vP(w,t));

Model dispatch includes all equations /all/;
Solve dispatch using lp Maximizing vZ;

*execute_unload "results.gdx" vP.l
*execute 'gdxxrw.exe results.gdx o=results.xlsx var=vP.l rng=Generation!a1'
**execute 'gdxxrw.exe results.gdx o=results.xlsx var=vDischarge.l rng=Generation!a1'
**execute 'gdxxrw.exe results.gdx o=results.xlsx par=pOC rng=OpCost!a1'
**execute 'gdxxrw.exe results.gdx o=results.xlsx equ=eMeetDemand.m rng=Prices!a1'
**execute 'gdxxrw.exe results.gdx o=results.xlsx var=vCharge.l rng=Charge!a1'
**execute 'gdxxrw.exe results.gdx o=results.xlsx var=vSOC.l rng=Stateofcharge!a1'
*
*File gen / generation.csv /;
*gen.pc = 5;
*put gen;
*loop((w,t),
*  put w.tl, t.tl, vP.l(w,t) /
*);
```

```
*putclose;
*
**File charge / Charge.csv /;
**charge.pc = 5;
**put charge;
**loop((stor,t),
**  put stor.tl, t.tl, vCharge.l(stor,t) /
**);
**putclose;
*
**File SOC / Stateofcharge.csv /;
**SOC.pc = 5;
**put SOC;
**loop((stor,t),
**put stor.tl, t.tl, vSOC.l(stor,t) /
**);
**putclose;
```

Appendix D: Standalone Case Input Table

Comments	Name or type of storage	Storage Characteristics: assume no VOM for storage, assume 1:1 tank to pump-turbine									
		# of Modules	1 gross module charge capacity	1 module discharge capacity	Total Charge Capacity (MW)	Total Discharge Capacity (MW)	Roundtrip Efficiency	Charge time	discharge time	Overall charge discharge capacity (Hrs)	Corresponding energy storage (MWh)
	Base case - Single Prototype Module (taken from STORE Deliverable 1D), assuming 1000m depth	1	5.4	5	5.4	5	0.6	5	4	9	20.91
these changes would come from improving pump-turbine, tank, and electrical designs	Prototype changing roundtrip efficiency, assuming 1000m depth	1	5.4	5	5.4	5	0.65	5	4	9	21.77
		1	5.4	5	5.4	5	0.7	5	4	9	22.59
		1	5.4	5	5.4	5	0.75	5	4	9	23.38
		1	5.4	5	5.4	5	0.8	5	4	9	24.15
		1	5.4	5	5.4	5	0.85	5	4	9	24.89
		1	5.4	5	5.4	5	0.9	5	4	9	25.61
so making a larger system increases revenues as a multiple of the pump-turbine tank system	System of 48 prototypes, assuming 1000m depth	48	5.4	5	259.2	240	0.6	5	4	9	1003.88
		1	5.4	5	5.4	5	0.6	1	0.5	1.5	4.18
		1	5.4	5	5.4	5	0.6	2	1	3	8.37
	replicate of base case	1	5.4	5	5.4	5	0.6	5	4	9	20.91
potentially increases because of increases to size of the tanks	single prototype, 2x energy stored, assuming 1000m depth	1	5.4	5	5.4	5	0.6	10	8	18	41.83
	single prototype, 4x energy stored, assuming 1000m depth	1	5.4	5	5.4	5	0.6	20	16	36	83.66
	single prototype, 8x energy stored, assuming 1000m depth	1	5.4	5	5.4	5	0.6	40	32	72	167.31

MWh stored = Charge capacity x Charge Time x sqrt(efficiency)

Appendix E: Humboldt Hybrid Case Input Table

Comments	Name or type of storage	Wind Farm Characteristics		Storage Characteristics: assume no VOM for storage, assume 1:1 tank to pump-turbine, assume 1000m depth									
		Capacity (MW)	storage to wind ratio	# of Modules	1 gross module charge capacity	1 module discharge capacity	Total Charge Capacity (MW)	Total Discharge Capacity (MW)	Roundtrip Efficiency	Charge time	discharge time	Overall charge discharge capacity (Hrs)	Corresponding energy storage (MWh)
	this is a TLP wind farm and the max size according to NREL 2022 report	3045	0.16%	1	5.4	5	5.4	5	0.6	5	4	9	20.91
The DAM/RTM 2020 results are normal compared to the standalone system, but stands out in the W+S system	small demonstration area	15	33.33%	1	5.4	5	5.4	5	0.6	5	4	9	20.91
on a per module basis, the amount of revenues actually decrease in this scheme		3045	7.88%	48	5.4	5	259.2	240	0.6	5	4	9	1003.88
		3045	15.76%	96	5.4	5	518.4	480	0.6	5	4	9	2007.75
		3045	23.65%	144	5.4	5	777.6	720	0.6	5	4	9	3011.63
		3045	31.53%	192	5.4	5	1036.8	960	0.6	5	4	9	4015.51
roughly 101 15 MW turbines, half the size of the full lease area to simulate each subdivision	one subdivision	1515	15.84%	48	5.4	5	259.2	240	0.6	5	4	9	1003.88
		1515	31.68%	96	5.4	5	518.4	480	0.6	5	4	9	2007.75
		1515	47.52%	144	5.4	5	777.6	720	0.6	5	4	9	3011.63
		1515	63.37%	192	5.4	5	1036.8	960	0.6	5	4	9	4015.51

MWh stored = Charge capacity x Charge Time x sqrt(efficiency)

Appendix F: Morro Bay Hybrid Case Input Table

Comments	Name or type of storage	Wind Farm Characteristics		Storage Characteristics: assme no VOM for storage, assume 1:1 tank to pump-turbine, assume 1000m depth									
		Capacity (MW)	storage to wind ratio	# of Modu les	1 gross module charge capacity	1 module discharge capacity	Total Charge Capacity (MW)	Total Discharge Capacity (MW)	Roundtrip Efficiency	Charge time	discharge time	Overall charge discharge capacity (Hrs)	Corresponding energy storage (MWh)
	this is a TLP wind farm and the max size according to NREL 2022 report	5550	0.09%	1	5.4	5	5.4	5	0.6	5	4	9	20.91
	small demonstration area	15	33.33%	1	5.4	5	5.4	5	0.6	5	4	9	20.91
		5550	4.32%	48	5.4	5	259.2	240	0.6	5	4	9	1003.88
		5550	8.65%	96	5.4	5	518.4	480	0.6	5	4	9	2007.75
		5550	12.97%	144	5.4	5	777.6	720	0.6	5	4	9	3011.63
		5550	17.30%	192	5.4	5	1036.8	960	0.6	5	4	9	4015.51
123 15 MW turbines in a subdivision	one third of the lease area	1845	13.01%	48	5.4	5	259.2	240	0.6	5	4	9	1003.88
		1845	26.02%	96	5.4	5	518.4	480	0.6	5	4	9	2007.75
		1845	39.02%	144	5.4	5	777.6	720	0.6	5	4	9	3011.63
		1845	52.03%	192	5.4	5	1036.8	960	0.6	5	4	9	4015.51

MWh stored = Charge capacity x Charge Time x sqrt(efficiency)

Appendix G: R-Script to Acquire Price Data from OASIS

```
#install.packages('xlsx') #make sure package installed!

library(xlsx)


#SET PARAMETERS

inputMarket <-"RTM5"

#"DAM", "RTM15", "RTM5", "DAMAS", "RTMAS"

inputNode <- "TH_NP15_GEN-APND"

#"TH_SP15_GEN-APND"

#LMPs:  "EMRYSVE_1_N003". AS prices: "AS_CAISO","AS_CAISO_EXP"

inputYear <- 2020

# rootDir = "C:/Users/mcraig/Desktop/Natel/Prices"

rootDir = "C:/Users/Michael Storch/Documents/SEAS/RCAM/Revenue Modeling/CA/Real Time
Pricing"



#Set and create dir to write to

if (grepl("NP15",inputNode)) {

  nodeAbbrev="NP15"

} else if (grepl("SP15",inputNode)) {

  nodeAbbrev="SP15"

} else {

  nodeAbbrev=inputNode

}

writeDir = file.path(rootDir,inputMarket,nodeAbbrev,inputYear)

dir.create(writeDir,showWarnings = FALSE, recursive = TRUE)

dir.create(file.path(rootDir,'trash'))

setwd(file.path(rootDir,'trash'))


#Call function for each month
```

```
year <- inputYear*10000

jan <- getCAISOlmp(startdate=year+0101, enddate=year+0131, market_run_id=inputMarket,
node=inputNode, writeDir=writeDir)

if (inputYear == 2004 || inputYear == 2008 || inputYear == 2012 || inputYear == 2016 || inputYear ==
2020) { #leap years

  feb <- getCAISOlmp(startdate=year+0201, enddate=year+0229, market_run_id=inputMarket,
node=inputNode, writeDir=writeDir)

} else { #non-leap years

  feb <- getCAISOlmp(startdate=year+0201, enddate=year+0228, market_run_id=inputMarket,
node=inputNode, writeDir=writeDir)

}

mar <- getCAISOlmp(startdate=year+0301, enddate=year+0331, market_run_id=inputMarket,
node=inputNode, writeDir=writeDir)

apr <- getCAISOlmp(startdate=year+0401, enddate=year+0430, market_run_id=inputMarket,
node=inputNode, writeDir=writeDir)

may <- getCAISOlmp(startdate=year+0501, enddate=year+0531, market_run_id=inputMarket,
node=inputNode, writeDir=writeDir)

jun <- getCAISOlmp(startdate=year+0601, enddate=year+0630, market_run_id=inputMarket,
node=inputNode, writeDir=writeDir)

jul <- getCAISOlmp(startdate=year+0701, enddate=year+0731, market_run_id=inputMarket,
node=inputNode, writeDir=writeDir)

aug <- getCAISOlmp(startdate=year+0801, enddate=year+0831, market_run_id=inputMarket,
node=inputNode, writeDir=writeDir)

sep <- getCAISOlmp(startdate=year+0901, enddate=year+0930, market_run_id=inputMarket,
node=inputNode, writeDir=writeDir)

oct <- getCAISOlmp(startdate=year+1001, enddate=year+1031, market_run_id=inputMarket,
node=inputNode, writeDir=writeDir)

nov <- getCAISOlmp(startdate=year+1101, enddate=year+1130, market_run_id=inputMarket,
node=inputNode, writeDir=writeDir)

dec <- getCAISOlmp(startdate=year+1201, enddate=year+1231, market_run_id=inputMarket,
node=inputNode, writeDir=writeDir)


# fetch CAISO LMP data from OASIS (see "Interface Specification for OASIS API")

getCAISOlmp <- function(startdate, enddate, market_run_id, node, writeDir){

  require(xlsx)
```

```
options(timeout = 6000)

#Set query based on whether RT or DA market
if (market_run_id == "DAM") {
  query <- "PRC_LMP"
  mktId <- "DAM"
} else if (market_run_id == "RTM15") {
  query <- "PRC_RTPD_LMP"
  mktId <- "RTPD"
} else if (market_run_id == "RTM5") {
  query <- "PRC_INTVL_LMP"
  mktId <- 'RTM'
} else if (market_run_id == 'DAMAS') {
  query <- "PRC_AS"
  mktId <- 'DAM'
} else if (market_run_id == 'RTMAS') {
  query <- "PRC_INTVL_AS"
  mktId <- 'RTM'
}

#Set special URL fields for AS prices
if (market_run_id == 'RTMAS' | market_run_id == 'DAMAS') {
  ancTag = '&anc_type=ALL'
  nodeTag = '&anc_region='
} else {
  ancTag = ''
  nodeTag = "&node="
}

# convert CAISO format to POSIXct dates
```

```
  start <- startdate
  end <- enddate

  # Initialize data frame with starting day
  activeDay <- start

  #define base URL
  baseURL <- "http://oasis.caiso.com/oasisapi/SingleZip?"

  #Set counter
  count <- 1

   while(activeDay <= end){
    activeNode <- node
    # assemble url for LMP
    if ((activeDay == end) && (start%%10000 == 1201)) { #%% is mod division
      getURL <-
paste(baseURL,"resultformat=6&queryname=",query,"&startdatetime=",activeDay,"T08:00-0000",
                 "&enddatetime=",start%/%10000+1,"0101T08:00-0000","&version=1",
                 "&market_run_id=",mktId,ancTag,nodeTag,activeNode,sep="")
    #Add 1 to month entry of start date so go to day 1 of next month!
    } else if (activeDay == end) {
      getURL <-
paste(baseURL,"resultformat=6&queryname=",query,"&startdatetime=",activeDay,"T08:00-0000",
                "&enddatetime=",startdate+100,"T08:00-0000","&version=1","&market_run_id=",mktId,
                ancTag,nodeTag,activeNode,sep="")
    } else {
      getURL <-
paste(baseURL,"resultformat=6&queryname=",query,"&startdatetime=",activeDay,"T08:00-0000",
                 "&enddatetime=",activeDay+1,"T08:00-0000","&version=1","&market_run_id=",mktId,
                 ancTag,nodeTag,activeNode,sep="")
```

```
}

temp <- tempfile() #create temp file

# Download file and re-try if failure
r <- NULL
attempt <- 0
while(is.null(r) && attempt <= 20) {
  attempt <- attempt + 1
  if (attempt > 1) {
    Sys.sleep(5)
  }
  try(
    #if successfully downloads, r becomes integer; data goes into 'temp'
    r <- download.file(getURL,temp,mode="wb",quiet=TRUE)
  )
  if (attempt == 21) {
    stop()
  }
}
print(paste("Downloaded",activeDay))
print(getURL)

#Read data from file
tempdata <- read.table(unzip(temp), sep = ",", header=TRUE)
unlink(temp) #deletes 'temp' file

#Write raw data for single day
write.csv(x=tempdata,file=file.path(writeDir,paste(activeNode,activeDay,".csv",sep="")))
```

```
      activeDay <- activeDay + 1
      count <- count + 1

      #CAISO enforces 5 second wait time
      Sys.sleep(5)
    }
}
```

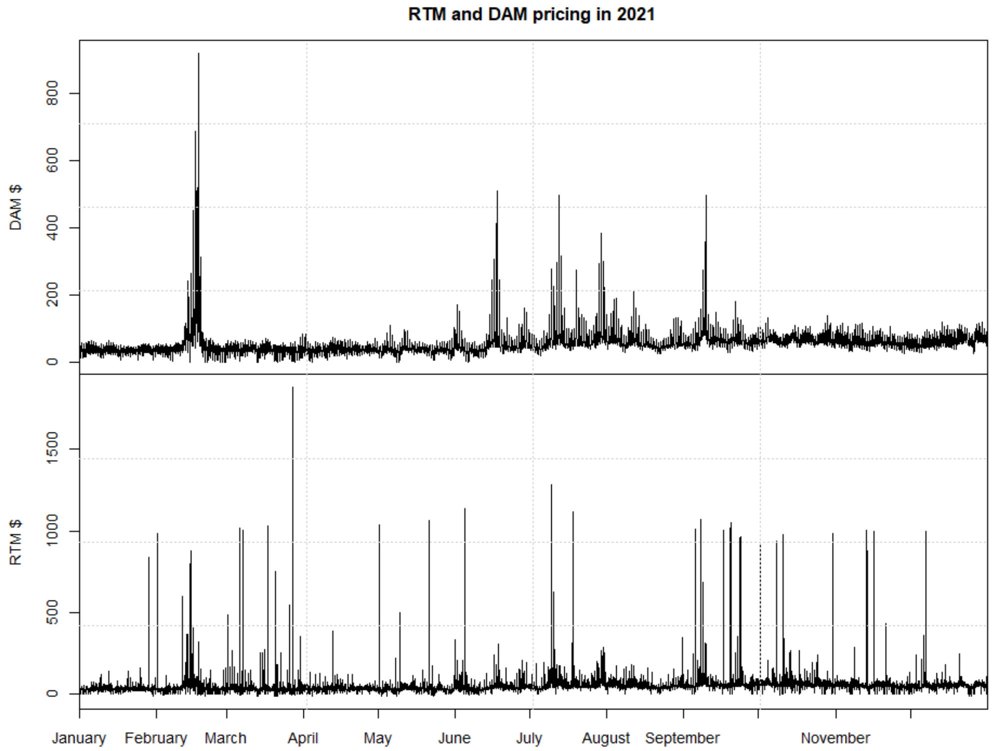
Appendix H: Python Code to Consolidate Pricing Data

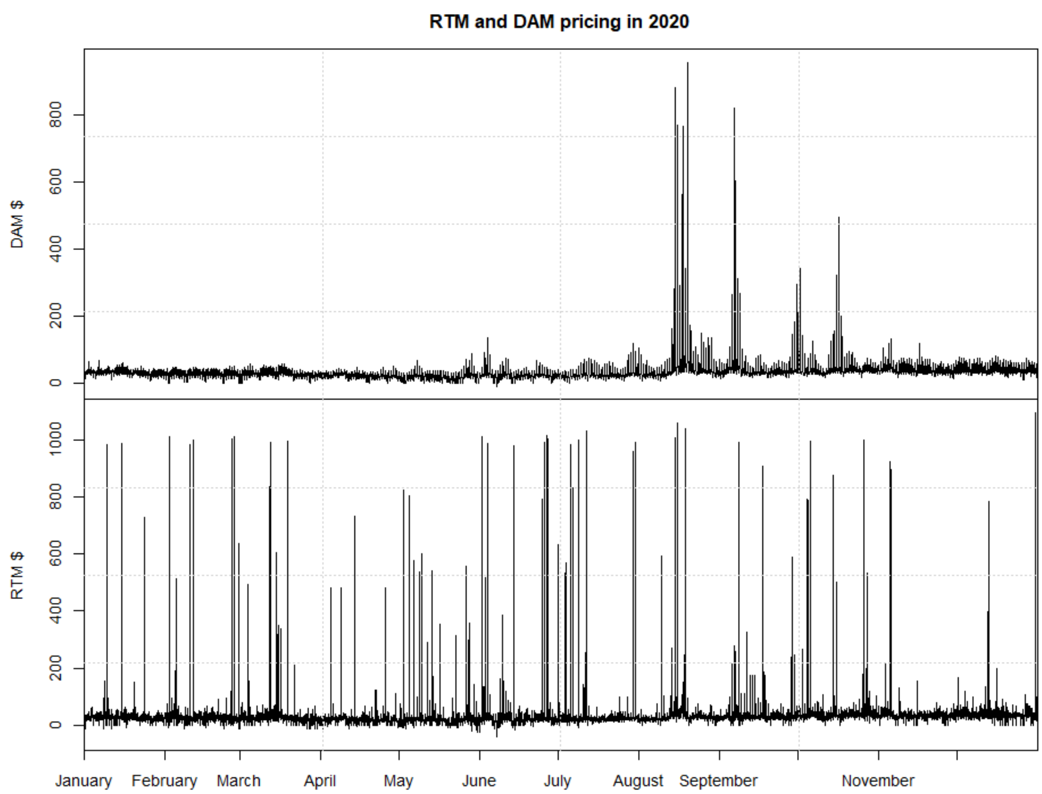
```
import os

import csv


dir = "CAISO DAM and RTM Prices/"

dir_dap = dir + "Day Ahead Pricing/DAM/NP15/2021"

dir_rtp = dir + "Real Time Pricing/RTM5/NP15/2021"


def read_csv_to_dicts(filepath, encoding='utf-8-sig', newline='', delimiter=','):
    """Accepts a file path, creates a file object, and returns a list of
    dictionaries that represent the row values using the cvs.DictReader().

    Parameters:
        filepath (str): path to file
        encoding (str): name of encoding used to decode the file
        newline (str): specifies replacement value for newline '\n'
                       or '\r\n' (Windows) character sequences
        delimiter (str): delimiter that separates the row values

    Returns:
        list: nested dictionaries representing the file contents
    """

    with open(filepath, 'r', newline=newline, encoding=encoding) as file_obj:
        reader = csv.DictReader(file_obj, delimiter=delimiter)
        data = [line for line in reader]

        return data
```

```
def write_dicts_to_csv(filepath, data, fieldnames, encoding='utf-8', newline=''):
    """
    Uses csv.DictWriter() to write a list of dictionaries to a target CSV file as row data.
    The passed in fieldnames list is used by the DictWriter() to determine the order
    in which each dictionary's key-value pairs are written to the row.

    Parameters:
        filepath (str): path to target file (if file does not exist it will be created)
        data (list): dictionary content to be written to the target file
        fieldnames (seq): sequence specifing order in which key-value pairs are written to each row
        encoding (str): name of encoding used to encode the file
        newline (str): specifies replacement value for newline '\n'
                       or '\r\n' (Windows) character sequences

    Returns:
        None
    """

    with open(filepath, 'w', encoding=encoding, newline=newline) as file_obj:
        writer = csv.DictWriter(file_obj, fieldnames=fieldnames)
        writer.writeheader() # first row
        writer.writerows(data)



def main():
    new_data = []
    for filename in os.listdir(dir_rtp):
        filepath = os.path.join(dir_rtp, filename)
        # # checking if it is a file
        # if os.path.isfile(f):
```

```
        #     print(f)
        data = read_csv_to_dicts(filepath)
        try:
            for line in data:
                if line['XML_DATA_ITEM'] == 'LMP_PRC':
                    new_line = {}
                    new_line['OPR_DT'] = line['OPR_DT']
                    new_line['OPR_HR'] = line['OPR_HR']
                    new_line['XML_DATA_ITEM'] = line['XML_DATA_ITEM']
                    new_line['MW'] = line['MW']
                    new_data.append(new_line)
        except KeyError:
            print(filepath)

    filednames = [key for key in new_data[0].keys()]
    write_dicts_to_csv('CAISO RTP 2021.csv', new_data, fieldnames)



if __name__ == '__main__':
    main()
```

Appendix I: Plot Comparisons of Annual Price Data for DAM and RTM





Appendix J: ERA 5 Input Receipt

ERA5 hourly data on single levels from 1979 to present | 2022-06-14 22:45:21 | 2022-06-14 23:32:40 | 0:47:18 | 79.7 MB | Download

Open request form
Request ID: f04859f8-f2fc-4b29-9afc-2c845dbdd672

Product type:	Reanalysis
Variable:	100m u-component of wind, 100m v-component of wind, 10m u-component of wind, 10m v-component of wind
Year:	2020, 2021
Month:	January, February, March, April, May, June, July, August, September, October, November, December
Day:	01, 02, 03, 04, 05, 06, 07, 08, 09, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31
Time:	00:00, 01:00, 02:00, 03:00, 04:00, 05:00, 06:00, 07:00, 08:00, 09:00, 10:00, 11:00, 12:00, 13:00, 14:00, 15:00, 16:00, 17:00, 18:00, 19:00, 20:00, 21:00, 22:00, 23:00
Sub-region extraction:	North 41.5°, West -125.5°, South 35°, East -120.5°
Format:	NetCDF (experimental)

Appendix K: R-Script to Extract Wind Speed Data and Calculate 150m Wind Speeds

```
library(ncdf4)

library(xlsx)

#setwd('C:/Users/eespey/Documents/RCAM/code/revenue_modeling')

setwd('C:/Users/Michael Storch/Documents/SEAS/RCAM/Revenue Modeling/CA/Wind Data and Gen
Calcs')

ncid = nc_open('adaptor.mars.internal-1655263424.030747-3218-14-f04859f8-f2fc-4b29-9afc-
2c845dbdd672.nc')

# returns time series of wind speed at height h for the point with indices x and y

pythagorate = function(a,b) {return (sqrt(a^2+b^2))}

calc_ws = function(x, y, h, alpha) {

  #v10 = ncvar_get(ncid, var='v10')[x,y,]

  v100 = ncvar_get(ncid, var='v100')[x,y,]

  #u10 = ncvar_get(ncid, var='u10')[x,y,]

  u100 = ncvar_get(ncid, var='u100')[x,y,]

 # ws10 = pythagorate(v10,u10)

  ws100 = pythagorate(v100,u100)

#log10(ws100/ws10)/log10(100/10)

  return (ws100*(h/100)^alpha)

}

# lat = ncvar_get(ncid, var='latitude')

# long = ncvar_get(ncid, var='longitude')    only need these lines when trying to figure out what indices

# Humboldt

ws150_hum = calc_ws(4,3,150,0.1153)

write.xlsx(ws150_hum, file = 'ws150_hum.xlsx', sheetName = 'Sheet1', row.names = F, col.names = T,
append = F)

# Morro Bay

ws150_mor = calc_ws(16,25,150, 0.1112)

write.xlsx(ws150_mor, file = 'ws150_mor.xlsx', sheetName = 'Sheet1', row.names = F, col.names = T,
append = F)
```

Appendix L: Method to Determine Assumed Wind Shear Values

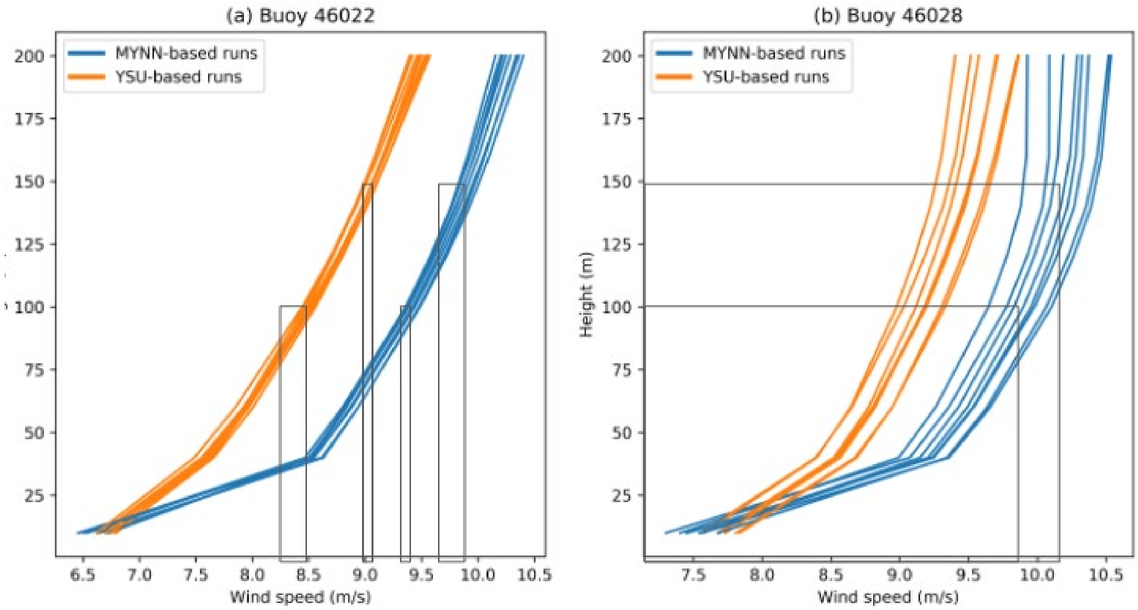


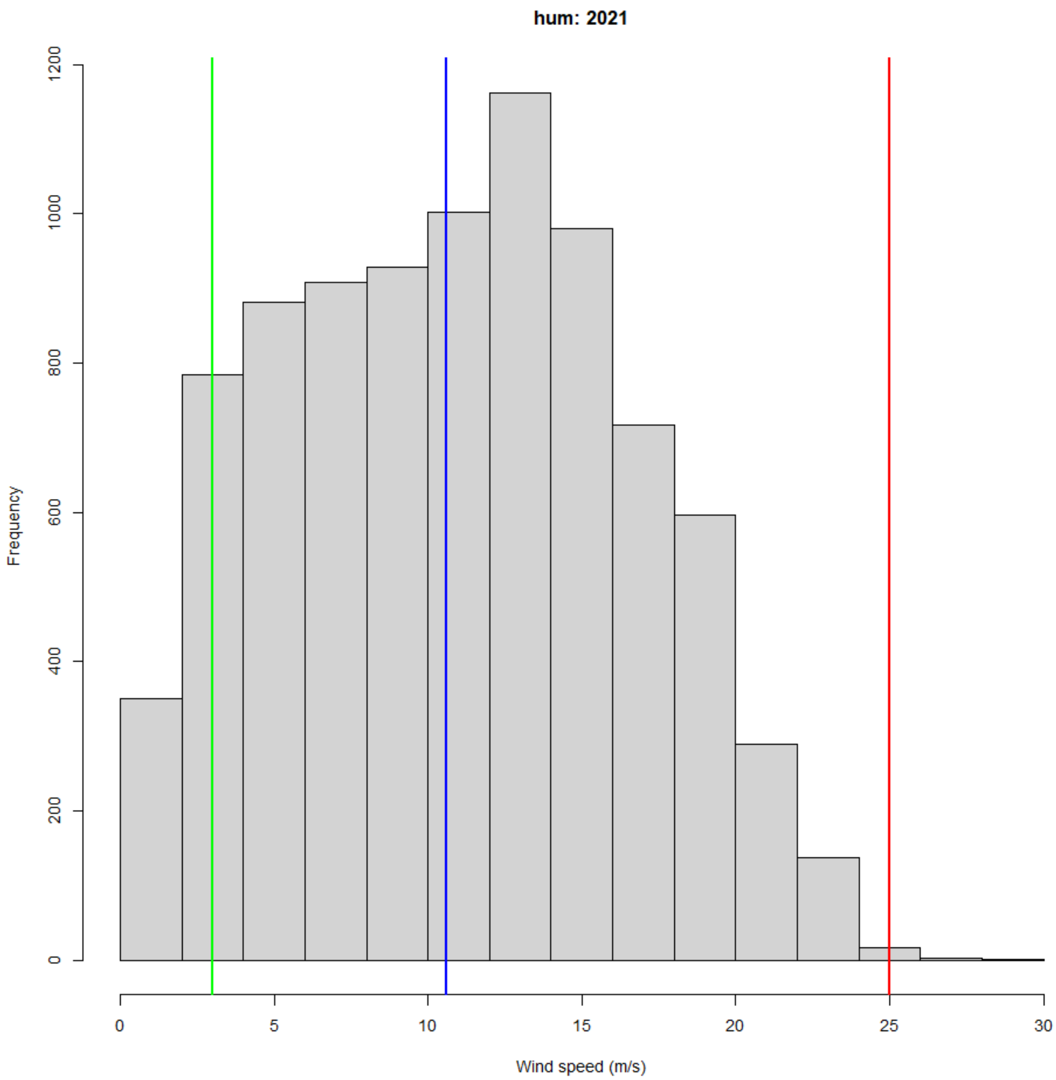
Figure 9. Mean modeled wind profiles at Buoy 46022 (a) and Buoy 46028 (b), which are adjacent to the Humboldt and Morro Bay Call Areas, respectively. MYNN-based profiles are in blue and YSU-based profiles are in orange.

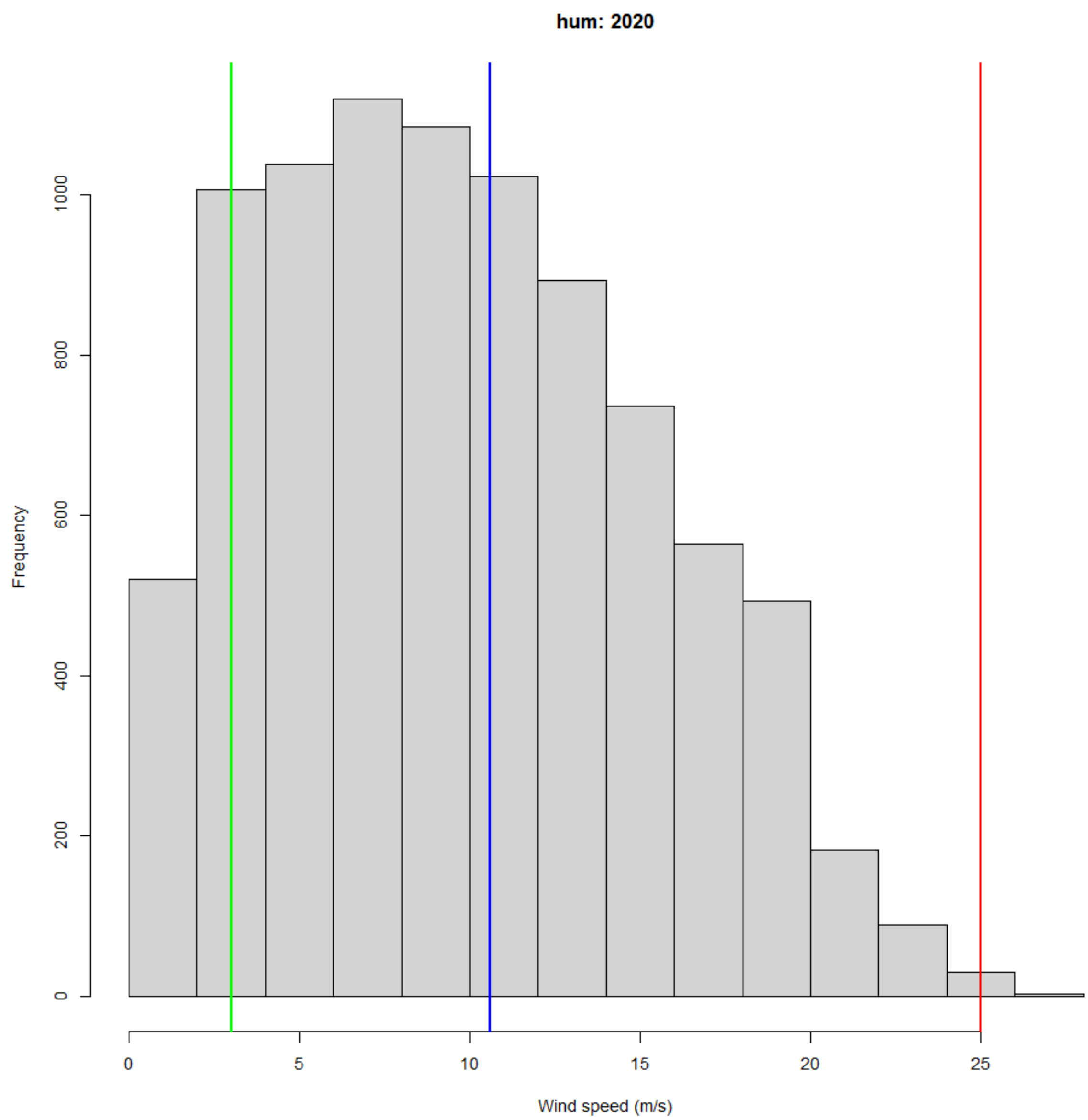
CA 20 (Blue) Humboldt: 100 m → 9.4 m/s & 150m → 9.85 m/s yields wind shear = 0.1153

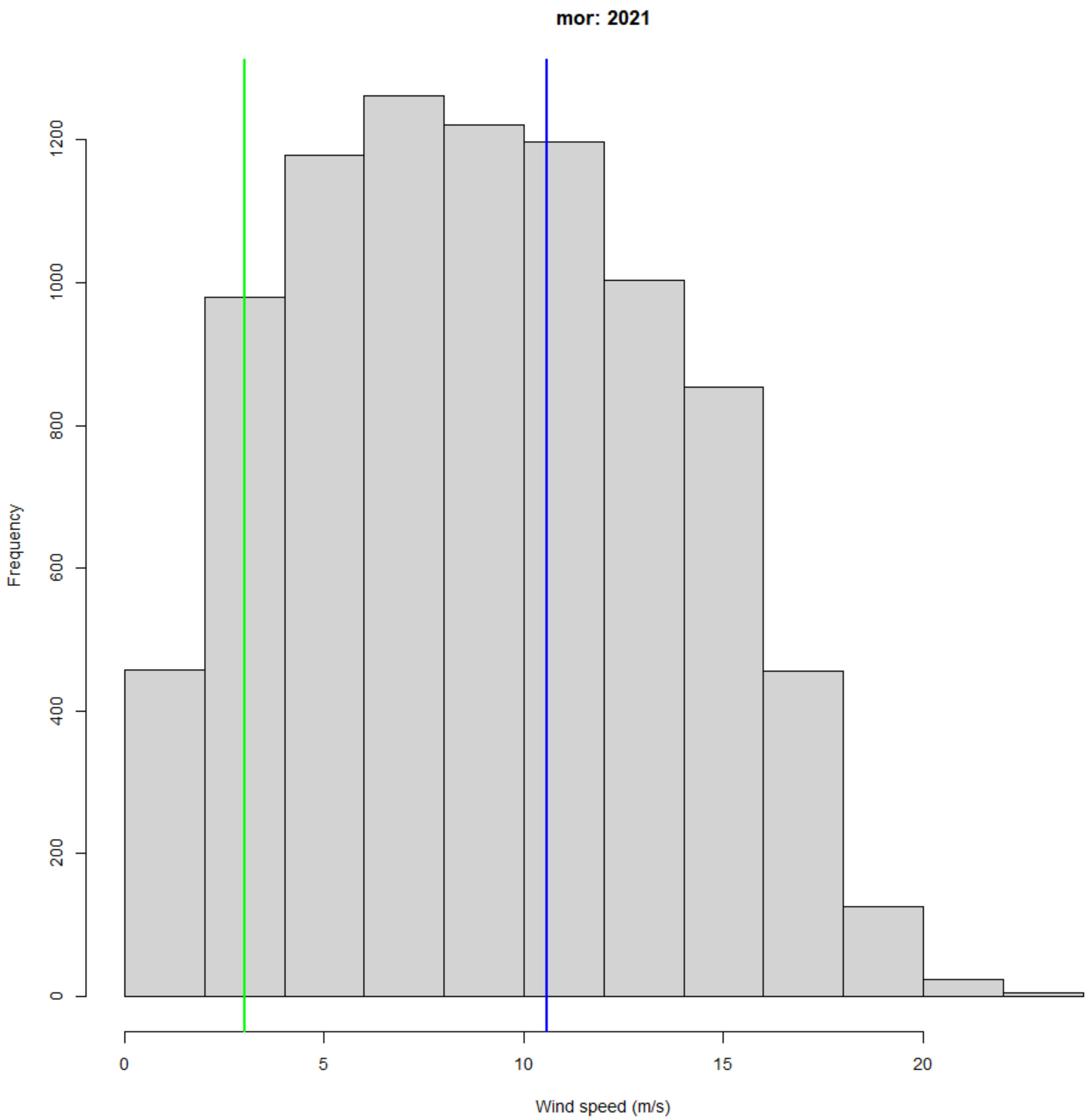
CA 20 (Blue) Morro Bay: 100 m → 9.75 m/s & 150 m → 10.2 m/s yields wind shear = 0.1112

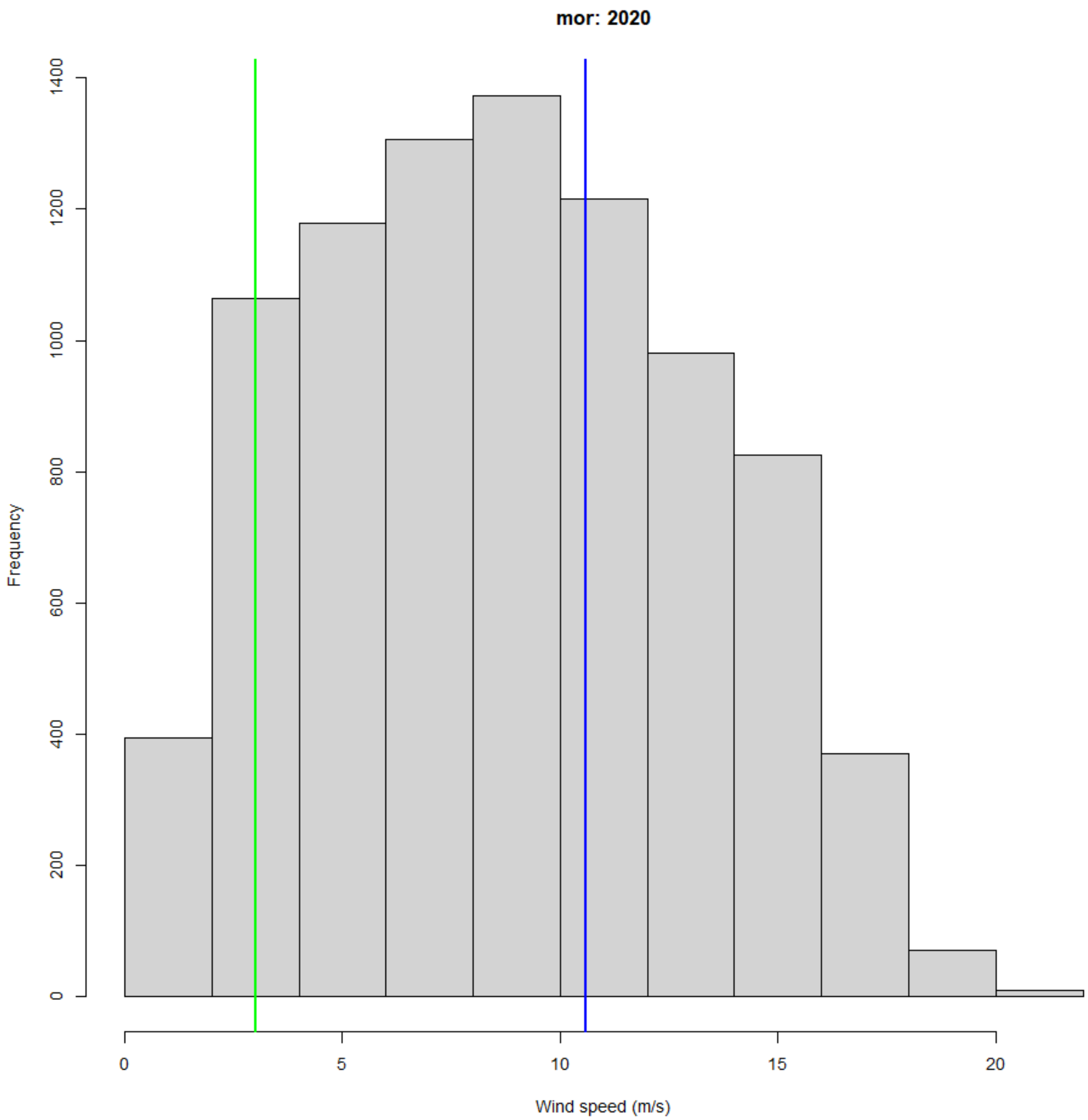
Appendix M: Histograms of annual 150 m Wind Speeds for Morro Bay and Humboldt in 2020 and 2021

Note: green line represents a cut in speed of 3 m/s, blue line represents 10.59 m/s rated wind speed, and red line represents 25 m/s cut out speed for the selected 15 MW IEA wind turbine.




hum: 2020
Frequency
0
200
400
600
800
1000
0
5
10
15
20
25
Wind speed (m/s)


mor: 2021
Frequency
0
200
400
600
800
1000
1200
0
5
10
15
20
Wind speed (m/s)

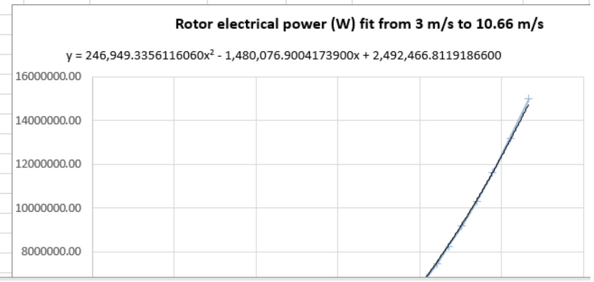


mor: 2020
Frequency
Wind speed (m/s)
0
200
400
600
800
1000
1200
1400
0
5
10
15
20

Appendix N: Breakdown of Hourly Wind Energy Simulations

Screenshot of Excel sheet.

		using updated wind shear values			to be copied to final document	gross annual capacity factors				one wind turbine MW rating	15
Hours of the year	Wind Speeds using Assumed Wind Shear from NREL 2020	model fit for 3 to 10.66 m/s	actual MW using piecewise function	resulting gross capacity factor	Net capacity factor *	method one	method two	new wind shear	Humboldt nrel net CF	*hourly net capacity factor is calculated as such: take the ratio of the net CF divided by the gross CF, then take that number and multiply it by each hourly gross CF	
t1	0.645643016	1.63980754	0	0.0000	0.000000	**0.663**	**0.659**	0.6624	0.494- 0.502	humboltd assumed losses	
t2	0.896171089	1.364395282	0	0.0000	0.000000					wake (median)	0.061
t3	1.139043765	1.126991626	0	0.0000	0.000000				0.5445	env.	0.016
t4	1.898433928	0.572656702	0	0.0000	0.000000					technical	0.012
t5	2.199970968	0.43154384	0	0.0000	0.000000		check	0.5445		electrical	0.039
t6	1.808087292	0.623680321	0	0.0000	0.000000			ratio of Net/gross	0.822	availability	0.05
t7	1.179070963	1.09066214	0	0.0000	0.000000					total losses	0.178
t8	1.388978851	0.91310133	0	0.0000	0.000000		Losses	0.117910402			
t9	1.846492133	0.601498417	0	0.0000	0.000000						
t10	2.605195631	0.312633012	0	0.0000	0.000000						
t11	3.282930335	0.295006417	0.295006417	0.0197	0.016166						
t12	3.669698716	0.38662033	0.38662033	0.0258	0.021187						
t13	4.180147202	0.620628973	0.620628973	0.0414	0.034010						
t14	5.073851399	1.340232359	1.340232359	0.0893	0.073445						
t15	6.311391312	2.988018266	2.988018266	0.1992	0.163743						
t16	8.628200972	8.106419555	8.106419555	0.5404	0.444232						
t17	9.716394467	11.42552806	11.42552806	0.7617	0.626119						
t18	11.14849861	16.68492275	15	1.0000	0.822000						
t19	12.88962353	24.44358679	15	1.0000	0.822000						
t20	14.41421203	32.46686662	15	1.0000	0.822000						
t21	15.71165546	40.19896264	15	1.0000	0.822000						
t22	16.86984721	47.803538	15	1.0000	0.822000						



1. The first two columns are the developed 150 m wind speeds for each hour.
2. The third column houses all the simulated wing generation in MW that fit the quadratic curve from Figure 6.

J3 | fx | =(I3^2*246949.335611606-1480076.90041739*I3+2492466.81191866)/(10^6)

	A	I	J	K	L	M	N	O	P
1			using updated wind shear values			to be copied to final document	gross annual capacity factors		
2	Hours of the year	Wind Speeds using Assumed Wind Shear from NREL 2020	model fit for 3 to 10.66 m/s	actual MW using piecewise function	resulting gross capacity factor	Net capacity factor *	method one	method two	new wind shear
3	t1	0.645643016	1.63980754	0	0.0000	0.000000	**0.663**	**0.659**	0.6624

3. The fourth column is the result of the piecewise function to calculate actual generation. Anything less than the cut in speed yields 0 MW of generation, between the cut in speed and the rated power speed the function adopts the values in the third column, anything between the rated power and 25 m/s is 15 MW, and any wind speed over 25 m/s yields 0 MW of generation.

IF | fx | =IFS(I3<3,0,AND(I3>=3,I3<=10.66),J3,AND(I3>10.66, I3<25),15,I3>=25,0)

	A	I	J	K	L	M	N	O	P
1			using updated wind shear values			to be copied to final document	gross annual capacity factors		
2	Hours of the year	Wind Speeds using Assumed Wind Shear from NREL 2020	model fit for 3 to 10.66 m/s	actual MW using piecewise function	resulting gross capacity factor	Net capacity factor *	method one	method two	new wind shear
3	t1	0.645643016	1.63980754	I3>=25,0)	0.0000	0.000000	**0.663**	**0.659**	0.6624

4. The fifth column is the calculation for the hourly capacity factor

=K3/$T$1

J	K	L	M	N	O	P	Q	R	S	T
using updated wind shear values			to be copied to final document	gross annual capacity factors				one wind turbine MW rating		15
model fit for 3 to 10.66 m/s	actual MW using piecewise function	resulting gross capacity factor	Net capacity factor *	method one	method two	new wind shear	Humboldt nrel net CF	*hourly net capacity factor is calculated as such: take the ratio of the net CF divided by the gross CF, then take that number and multiply it by each hourly gross CF		
1.63980754	0	=K3/$T$1	0.000000	0.663	0.659	0.6624	0.494- 0.502		humboltd assumed losses	

5. The sixth column is the result of applying assumed losses to the gross capacity factor

=P3*T4+P3*T5+P3*T6+P3*T7+P3*T8

K	L	M	N	O	P	Q	R	S	T
nd shear values		to be copied to final document	gross annual capacity factors				one wind turbine MW rating		15
actual MW using piecewise function	resulting gross capacity factor	Net capacity factor *	method one	method two	new wind shear	Humboldt nrel net CF	*hourly net capacity factor is calculated as such: take the ratio of the net CF divided by the gross CF, then take that number and multiply it by each hourly gross CF		
0	0.0000	0.000000	0.663	0.659	0.6624	0.494- 0.502		humboltd assumed losses	
0	0.0000	0.000000						wake (median)	0.061
0	0.0000	0.000000				0.5445		env.	0.016
0	0.0000	0.000000						technical	0.012
0	0.0000	0.000000		check	0.5445			electrical	0.039
0	0.0000	0.000000			ratio of Net/gross	0.822		availability	0.05
0	0.0000	0.000000						total losses	0.178
0	0.0000	0.000000		Losses	*T8				

=Q5/P3

K	L	M	N	O	P	Q
d shear values		to be copied to final document	gross annual capacity factors			
actual MW using piecewise function	resulting gross capacity factor	Net capacity factor *	method one	method two	new wind shear	Humboldt nrel net CF
0	0.0000	0.000000	0.663	0.659	0.6624	0.494- 0.502
0	0.0000	0.000000				
0	0.0000	0.000000				0.5445
0	0.0000	0.000000				
0	0.0000	0.000000		check	0.5445	
0	0.0000	0.000000			ratio of Net/gross	=Q5/P3
0	0.0000	0.000000				
0	0.0000	0.000000		Losses	0.117910402	

=L3*$Q$8

K	L	M	N	O	P	Q
d shear values		to be copied to final document	gross annual capacity factors			
actual MW using piecewise function	resulting gross capacity factor	Net capacity factor *	method one	method two	new wind shear	Humboldt nrel net CF
0	0.0000	=L3*$Q$8	0.663	0.659	0.6624	0.494- 0.502
0	0.0000	0.000000				
0	0.0000	0.000000				0.5445
0	0.0000	0.000000				
0	0.0000	0.000000		check	0.5445	
0	0.0000	0.000000			ratio of Net/gross	0.822
0	0.0000	0.000000				
0	0.0000	0.000000		Losses	0.117910402	

6. The assumed losses for each site are shown below

Wind Modeling Assumptions

Humboldt Losses	
wake (median)	0.061
env.	0.016
technical	0.012
electrical	0.039
availability	0.05
total losses	0.178

Morro Bay Losses	
wake (median)	0.067
env.	0.016
technical	0.012
electrical	0.039
availability	0.05
total losses	0.184

a. NREL 2022 provided many different values for wake losses, therefore the median value was chosen for each site.

Appendix O: Results of Humboldt Hybrid Scenarios

Wind Farm Characteristics		Objective values (Maximized annual revenues) for each market				Differences in revenues from using storage				% Increase in revenues from using storage				Differences in revenues from using storage on a per pump-turbine basis (revs. divided by # of pump turbines)			
Capacity (MW)	storage to wind ratio	DAM 2021* high wind generation	DAM 2020	RTM 2021 *high wind generation	RTM 2020	DAM 2021	DAM 2020	RTM 2021	RTM 2020	DAM 2021	DAM 2020	RTM 2021	RTM 2020				
3045	0.16%	$762,911,738	$400,531,372	$669,293,785	$353,859,094	$167,734	$158,538	$136,375	$162,060	0.02%	0.04%	0.02%	0.05%				
15	33.33%	$3,911,163	$2,117,835	$3,420,940	$1,894,795	$153,804	$145,555	$124,598	$152,445	4.09%	7.38%	3.78%	8.75%				
3045	7.88%	$770,505,093	$407,761,655	$675,446,727	$361,281,625	$7,761,089	$7,388,821	$6,289,317	$7,584,590	1.02%	1.85%	0.94%	2.14%	$161,689	$153,934	$131,027	$158,012
3045	15.76%	$777,944,517	$414,825,545	$681,480,397	$368,634,096	$15,200,512	$14,452,711	$12,322,987	$14,937,061	1.99%	3.61%	1.84%	4.22%	$158,339	$150,549	$128,364	$155,594
3045	23.65%	$785,226,057	$421,690,461	$687,380,153	$375,865,800	$22,482,053	$21,317,628	$18,222,743	$22,168,766	2.95%	5.32%	2.72%	6.27%	$156,125	$148,039	$126,547	$153,950
3045	31.53%	$792,352,580	$428,402,124	$693,145,481	$383,017,052	$29,608,576	$28,029,290	$23,988,070	$29,320,018	3.88%	7.00%	3.58%	8.29%	$154,211	$145,986	$124,938	$152,708
1515	15.84%	$387,092,371	$206,425,307	$339,091,100	$183,444,965	$7,599,049	$7,225,030	$6,160,566	$7,467,623	2.00%	3.63%	1.85%	4.24%	$158,314	$150,521	$128,345	$155,575
1515	31.68%	$394,294,259	$213,211,368	$344,921,738	$190,635,154	$14,800,937	$14,011,091	$11,991,203	$14,657,812	3.90%	7.03%	3.60%	8.33%	$154,176	$145,949	$124,908	$152,686
1515	47.52%	$401,218,292	$219,665,800	$350,528,048	$197,604,017	$21,724,969	$20,465,523	$17,597,514	$21,626,675	5.72%	10.27%	5.29%	12.29%	$150,868	$142,122	$122,205	$150,185
1515	63.37%	$407,939,006	$225,778,594	$356,028,659	$204,321,568	$28,445,683	$26,578,317	$23,098,125	$28,344,225	7.50%	13.34%	6.94%	16.11%	$148,155	$138,429	$120,303	$147,626

Appendix P: Results of Morro Bay Hybrid Scenarios

Wind Farm Characteristics		Objective values (Maximized annual revenues) for each market				Differences in revenues from using storage				Differences in revenues from using storage as a percent increase				Differences in revenues from using storage on a per pump-turbine basis (revs. divided by # of pump turbines)			
Capacity (MW)	storage to wind ratio	DAM 2021	DAM 2020	RTM 2021	RTM 2020	DAM 2021	DAM 2020	RTM 2021	RTM 2020	DAM 2021	DAM 2020	RTM 2021	RTM 2020	DAM 2021	DAM 2020	RTM 2021	RTM 2020
5550	0.09%	$1,114,413,159	$673,103,212	$958,864,666	$581,949,927	$167,429	$157,598	$138,418	$162,891	0.02%	0.02%	0.01%	0.03%				
15	33.33%	$3,165,826	$1,959,723	$2,719,826	$1,726,481	$154,351	$140,951	$128,674	$154,083	5.13%	7.75%	4.97%	9.80%				
5550	4.32%	$1,122,191,369	$680,372,695	$965,310,893	$589,516,610.45	$7,945,639	$7,427,080	$6,584,645	$7,729,574	0.71%	1.10%	0.69%	1.33%	$165,534	$154,731	$137,180	$161,033
5550	8.65%	$1,129,933,787	$687,492,212	$971,753,801	$597,086,435	$15,688,057	$14,546,597	$13,027,553	$15,299,399	1.41%	2.16%	1.36%	2.63%	$163,417	$151,527	$135,704	$159,369
5550	12.97%	$1,137,501,476	$694,389,815	$978,101,437	$604,559,723	$23,255,745	$21,444,200	$19,375,190	$22,772,687	2.09%	3.19%	2.02%	3.91%	$161,498	$148,918	$134,550	$158,144
5550	17.30%	$1,144,929,986	$701,143,803	$984,326,389	$611,941,418	$30,684,255	$28,198,188	$25,600,141	$30,154,382	2.75%	4.19%	2.67%	5.18%	$159,814	$146,866	$133,334	$157,054
1845	13.01%	$378,162,637	$230,856,111	$325,169,689	$200,995,335	$7,751,218	$7,147,163	$6,457,991	$7,590,456	2.09%	3.19%	2.03%	3.92%	$161,484	$148,899	$134,541	$158,134
1845	26.02%	$385,455,734	$237,475,457	$331,246,972	$208,318,470	$15,044,315	$13,766,509	$12,535,274	$14,913,590	4.06%	6.15%	3.93%	7.71%	$156,712	$143,401	$130,576	$155,350
1845	39.02%	$392,386,489	$243,782,442	$337,036,697	$215,460,595	$21,975,071	$20,073,494	$18,324,998	$22,055,715	5.93%	8.97%	5.75%	11.40%	$152,605	$139,399	$127,257	$153,165
1845	52.03%	$399,046,866	$249,916,216	$342,581,458	$222,436,010	$28,635,448	$26,207,268	$23,869,759	$29,031,130	7.73%	11.71%	7.49%	15.01%	$149,143	$136,496	$124,322	$151,204