UMERC PTO and Controls Working Group Report

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Glossary

AGC: automatic generation control
CEC: Current Energy Converter
DOE: U.S. Department of Energy
HIL: Hardware-in-the-loop
IEC: International Electrotechnical Commission
ME: Marine energy
MEC: Marine Energy Converter
NMEC: National Marine Energy Center
NL: National Laboratory
NREL: National Renewable Energy Laboratory
OTEC: Ocean Thermal Energy Conversion
PNNL: Pacific Northwest National Laboratory
POET: Pacific Ocean Energy Trust
PTO: Power Take-off
SNL: Sandia: Sandia National Laboratories
TC: IEC Technical Committee
TEC: Tidal Energy Converter
TRL: Technology Readiness Level
TS: Technical Specifications
UL: Underwriters Laboratories
UMERC: University Marine Energy Research Community
VSG: Virtual Synchronous Generator
WEC: Wave Energy Converter
Working Group: UMERC PTO and Controls Working Group
WPTO: Water Power Technology Office

Introduction

The marine energy (ME) industry continues to emerge as a vital element of our energy future. To scientists and advocates the promise of these technologies is clear – more than 2,300 TWh/yr of potential resources lie within US waters alone, amounting to approximately 60% of the country's annual energy demand (Kilcher, Fogarty and Lawson, 2021). Capturing even a fraction of this vast, predictable, and low-impact energy source would drive economic growth, energy security, and environmental resilience. To do so, researchers and developers have been steadily working to solve the immense challenges of drawing power from the sea. Depending on the available resource and environmental conditions, different types of marine energy device may be utilized. As such, research has converged on three main forms of devices: wave energy converters (WECs) to capture energy from the motion of surface waves, current energy converters (CECs) and tidal energy converters (TECs) for areas subject to flowing water, and ocean thermal energy conversion (OTEC) devices for areas with extreme temperature differences between deeper waters and the surface. Across each of these technologies, however, foundational research gaps persist. To maximize these devices' efficiency and reliability, and therefore achieve commercial readiness, additional funding and research efforts must be focused on their power take-off (PTO) and control components. Without mastering these critical technologies, domestic devices will struggle to meet the ambitious deployment goals of US states or compete with developers abroad in the global market. As governments worldwide race to develop marine energy standards and supply chains, U.S.-based developers cannot afford to lag behind in these fundamental areas. This report compiles the recommendations of industry and academic leaders from the University Marine Energy Research Community (UMERC) and identifies nine research priorities for further support in the area of PTO and Controls for marine energy technologies. These recommendations are summarized, in part, below in Table 1.

Drawing from expert suggestions from a series of workshops and working groups, this report lays out a coordinated strategy for the development of standardized, scalable, and certifiable PTO technologies that can serve a range of applications—from off-grid autonomous systems to large-scale grid-connected farms. Recommendations span nine critical focus areas including: standardizing PTO design processes and certification frameworks to streamline development and reduce costs, marinizing and weatherizing electrical machines for long-term reliability in ocean and riverine environments, developing power electronics for wide voltage ranges to enhance energy conversion efficiency and grid integration, and advancing survivability mechanisms to protect PTOs from extreme sea states and prolonged fatigue loads. By funding and implementing these strategies, the pathway to commercial marine energy deployment will be accelerated, ensuring the U.S. leads in energy innovation. This report is a technical assessment *and* a call to action for policymakers, industry leaders, and researchers to support scalable, cost-effective, and resilient marine energy solutions to power the American economy.

Table 1: Summary of Report Recommendations

#	Title	Scope	Applicable Tech.	TRL	Budget
1	Standardization of Publicly-Available Design Processes	Establish public, standardized design methodologies for PTOs.	WECs, TECs, CECs, OTEC	4-9	$5-10M
2	Best Practices, Approaches and Certification Pathways for Marinized, Low-Speed Electrical Devices	Develop best practices, technological approaches, and certification guidance for PTO developers.	WECs, TECs, CECs	3-6+	$8-$15M
3	Standardized Wave Energy Power Electronics for Wide Voltage Ranges	Develop standardized, open-source power electronics solutions for wave energy.	WECs	3-7	$5-$6M
4	Testing of Mechanical Components for WECs	Develop standardized testing methodologies for mechanical components under realistic loads.	WECs	4-9	$15-$20M
5	Gearing Improvements and Alternatives	Improve mechanical gearboxes and advance alternative gearing technologies for improved durability.	WECs, CECs, TECs	3-7	$10-$15M
6	Power Electronics Control for ME	Advance power electronics control strategies to ensure stability, reliability, and grid support.	WECs, CECs, TECs	3-7	$5-$10M
7	Extreme Sea PTO Survival Mechanisms	Research, develop, test, and standardize extreme sea survival mechanisms to ensure long-term reliability.	WECs, CECs, TECs	2-5	$5-$10M
8	Marinized Power Electronic Machines: Best Practices, Approaches, and Pathway to Certification	Develop best practices, technological approaches, and pathways to certification for marine power electronic machines.	WECs, TECs, CECs, OTEC	4-7	$25-$50 M
9	Storage-Integrated ME for Grid Integration	Develop and optimize energy storage solutions to prepare ME devices for grid-integration.	WECs, TECs, CECs, OTEC	2-5	$10-$15M

Background

This report is the ultimate result of multiple rounds of discussions between industry, national laboratory, and academic leaders hosted by the Pacific Ocean Energy Trust (POET). In July 2024, POET assembled a subset of these experts to form the UMERC Power Take-Off and Controls Working Group. The mission of the Working Group was to refine the suggestions of a series of workshops and working groups hosted since 2021. A summary of these discussions and their contributions to this report is included below.

2021/2022 Research Landscape Workshops

In a series of online workshops hosted by POET in late 2021, clusters of high-level topic areas were developed in collaboration with approximately 75 industry, lab, and university researchers. Participants identified detailed gaps, challenges, and comments pertinent to the development of a marine energy industry in the US. These notes were then grouped and compiled by experts into a visual format for use as an organized research landscape, since made available on the UMERC website. After several iterations of grouping participant comments, 13 topic areas materialized including Materials and Structures, Design, Hydrodynamics, Manufacturing, Systems, Environment, Resource Characterization, and IO&M (Quinn and Hirsch, 2022). The complete visual aid is included in the Appendix as Supplemental Figure 1, and the entire Research Landscape Workshop Report can be found on the UMERC website.

UMERC WPW Industry Priorities Workshop, May 10, 2023

Drawing from the list of topic areas developed during the 2021/2022 Research Landscape workshops, 18 career professionals from industry and academic institutions were asked to identify priority areas of importance and refine the topic areas. By the end of this exercise, Power Take Off (PTO) and Control emerged as the single most important area for targeted research and development, as detailed in the resulting Industry Priorities Workshop Report, now archived here. This result was, in part, due to the many foundational research questions which revolve around PTO, and the continued potential for improvement in the area of PTO technology (Quinn and Hirsch, 2023b).

Industry Academia Needs Workshop, October 4, 2023

Following the Industry Priorities Workshop, another workshop was assembled during the 2023 UMERC Conference. The objective of this group was to draft a list of tentative research topics to address the previously identified priority areas. Nine project areas were ultimately assembled for PTO and Control research, along with estimated funding requirements and anticipated counts of funding opportunities (Quinn and Hirsch, 2023a). Supplemental Table 2 (Appendix) outlines this list. This list, available from the UMERC repository, while a valuable starting point, proved challenging in its own right. Participants had their own ideas of how to format their suggestions for funding, presenting inconsistent funding estimates. Finally establishing a thorough estimation of

PTO research funding demand thus fell to the subsequent UMERC PTO and Controls Working Group (Working Group).

PTO and Controls Working Group, July 17 2024-Present
To narrow in on core components of the previously assembled project ideas, POET solicited members of marine energy industrial, national laboratory, and academic communities to form the PTO and Controls Working Group. The working group has met monthly since July 2024 to combine similar projects, expand the proposed list, provide more substantive details about potential projects including the type of collaboration, size of projects, duration, and cost. By December 2024 a list of 21 project areas had been finalized, as depicted in Supplemental Table 3 (Appendix). Working group members then ranked these topics in order of priority using a Smartsheet survey, selecting their top ten most urgent priorities from the list. For every first place vote a project received 10 points, second received nine, and so on until tenth received just one point. Any topics not selected by the voter received 0 points. Table 2 displays the final tally for the top ten priorities. For the complete results, please consult Supplemental Table 4 (Appendix).

Table 2: Top 10 PTO and controls research priorities, scored

Ranking	Item	Points Received
#1	A – Standardize PTO design processes/guidelines that are publicly available.	74
#2	C – Marinized electrical machines for low speed applications best practices, approaches and pathway to UL certification.	67
#3	B – Standardized Wave Energy Power Electronics for Wide Voltage Bands for increased efficiency.	58
#4	E – Testing of mechanical components for marine applications and loads focus on wave.	54
#5	G – Gearing (speed increasing mechanism)-magnetic gearing, new solutions, belts.	42
#6	O – Electrical power conversion efficiencies throughout the system - Advanced Metering infrastructure.	42
#7	S – Power electronics control for grid integration (grid-forming, virtual synchronous generation, ancillary services (frequency response, inertia support, etc.)).	42
#8	P – Extreme sea PTO survival mechanism (e.g. shaft disengagement, extreme speeds, extreme torques, extreme loading).	41
#9	D – Marinized power electronic machines at sea applications best practices, approaches and pathway to UL certification.	38
#10	U – Storage-Integrated ME for Grid Integration	35

The working group met again in January 2025 to finalize these results and discuss any potential interdependencies between topics. No interdependencies were identified, and each topic, hereafter referred to as recommendations, was assigned a team of authors with relevant expertise to expand and detail them. Sixth place, Electrical Power Conversion Efficiencies and Advanced Metering Infrastructure, was not completed due to members' timing constraints and capacity. Thus, nine recommendations are made in this report, each describing an essential topic area to propel the American marine energy industry towards global leadership.

The Critical Role of PTO & Controls in Advancing Marine Energy

The realization of marine energy's full potential is hindered by fundamental technological challenges — chief among them, Power Take-Off (PTO) systems and controls. At its core, the PTO system is the heart of most marine energy devices, responsible for converting the power of waves, currents, tides, and thermal exchange into useful electrical energy. Its performance determines Annual Energy Production (AEP), efficiency, Levelized Cost of Energy (LCOE), and long-term viability. Yet, significant knowledge gaps and technical hurdles remain in PTO design, materials, reliability, and integration into grid-scale infrastructure. Without addressing these barriers, marine energy risks falling short of its commercial promise.

Challenges in PTO Systems for Marine Energy Converters

As arrays of marine energy systems — including wave energy converters, tidal turbines, and other flow-based devices — are integrated into the grid, they will ultimately need to cooperate to provide ancillary services and dynamically share electricity loads based on commands from automatic generation control (AGC). Achieving this will likely require the development of advanced power-sharing algorithms, such as droop control, similar to those already applied in wind and solar power converters. However, given the unique power take-off challenges associated with marine energy systems, including the variability of the resource, mechanical-to-electrical conversion complexities, and survivability concerns, these grid integration objectives will become significantly more challenging. In the near term, focusing on core operational reliability and stability will be more critical than immediate participation in AGC. Additionally, to ensure security, resilience, and flexibility, these systems must also be capable of off-grid operation, which will require embedding blackstart capabilities and grid-forming controls directly within the power conversion systems. Compared to wind and solar, marine renewables may actually benefit from stronger initial support for grid-forming functionality due to the inherent intermittency and complexity of the resource. Integrating marine renewables with storage systems — whether through back-to-back converters with a shared DC link, or standalone storage — will be essential to provide reliable grid-forming operation. This mirrors ongoing efforts in wind and solar systems, where significant research has been devoted to developing virtual synchronous generator (VSG) controls that enable inverter-based resources to mimic the inertial and damping properties of traditional synchronous machines. Similar challenges and expectations will arise for marine renewable systems as grid codes increasingly mandate grid-forming and VSG capabilities for all renewable generation technologies seeking to play a role in future resilient power grids.

The Standards Gap

The origins of certification standards for ME devices can be traced to past renewable energy developments. The suite of International Electrotechnical Commission (IEC) Technical Specifications (TS) 62600 for MECs, for example, are fundamentally rooted and mirrored from the IEC 61400 standards for wind energy generation systems. While this helps steer guidelines and recommendations for tidal turbines in particular, thanks in part to their technological similarities to wind turbines, other MEC design families are under-documented. Guidelines for PTO design are particularly illustrative of this point with specifications or standards for PTO systems covered under IEC TS 62600-2 Marine energy systems - Design requirements which suggests safety factors on design relevant quantities for the entire WEC system and hence, also the components used for PTO assemblies. While there are distinct sections for WECs and while there has been progress in refining the language and making it more applicable to WECs, the standards are not fully applicable to PTO design for WECs. For example, most safety factors indicated in the '-2' for different severity groups and DLCs are velocity based, while typically, 'modern' WEC PTO systems are torque controlled. The absence of non-tidal standards forces developers to design for unknown requirements and variables, hindering efficient progress. At the same time, while IEC 61400 are internationally adopted standards, IEC TS 62600 languish as mere technical specifications, leading even TEC researchers to struggle to gain traction in highly-regulated energy markets. Without clear, complete, and binding standards from the IEC, U.S. developers must either stall for time or design their devices for foreign markets and certification schemes (e.g. Det Norske Veritas). To further inform and refine the recommendations (e.g. ultimate limit state and fatigue safety factors, design conditions, severity classes) more in-field and long-term testing of PTO systems in deployed WECs is required. Load and condition monitoring is a must for early deployments to inform and refine the recommendations in the technical specifications to promote safe yet cost effective and economical PTO designs by application of standards.

Priority Recommendations

The remainder of this report is dedicated to the nine most urgent recommendations of this working group. Though they are listed in order, it should be stressed that each focuses on discrete, critical aspects of ME development. Each recommendation includes a description of the topic area (Scope), the design families (WECs, TECs, CECs, or OTEC) anticipated to benefit most directly from the findings (Applicability), specific projects in need of support (Specific Actions), expected impacts of the recommendation (Expected Impact), suggested Technology Readiness Levels (TRLs) for technologies to be studied under these programs, groups to coordinate and involve (Groups Involved), and a total anticipated Budget Required to satisfy industry needs, expressed in terms of small (~$2M), medium (~$5M), and large (~$10M) projects. Applicability presents information about two design factors: project scale and design family. Though there is significant variation between MEC designs, this report differentiates between MECs depending on the resource being harvested: WECs for wave energy, TECs for tidal flow, CECs for ocean or riverine currents, and OTEC for marine temperature differentials. Additionally, development scale is broken into three tiers: Small Scale for isolated, low-power, or off-grid devices; Community Scale for devices or arrays designed to power mid-sized communities; and Utility Scale for large, highly-productive devices or arrays intended for integration with existing power grids. Finally, while these recommendations suggest specific groups, participants, and design families to utilize these recommendations and opportunities, it should be stressed that the marine energy community is likely to find broad, interdisciplinary benefit from this research.

Recommendation 1: Standardization of Publicly-Available Design Processes

Scope

PTO systems are central to the efficiency, reliability, and long-term viability of MECs. However, the lack of standardized design processes and guidelines leads to inefficiencies in development, increased costs, and limited cross-compatibility across different scales and applications. Establishing publicly available, standardized design methodologies will improve the development of PTO systems across all scales, from small-scale, off-grid applications to utility-scale, grid-connected systems. This initiative will support innovation, reduce barriers to entry for new developers, and facilitate interoperability among different PTO solutions.

Applicability

Scale	Wave	Current	Tidal	OTEC
Small Scale/Off-Grid	✓	✓	✓	✓
Community Scale	✓	✓	✓	✓
Utility-Scale	✓	✓	✓	✓

Specific Actions

1. Develop a PTO Design and Certification Framework:
    - Establish a common set of performance metrics and reliability standards across different PTO architectures.
    - Ensure these guidelines encompass a range of applications, including low-power, off-grid, and remote deployments.
    - Collaborate with international standards organizations (e.g., IEC TS 62600, UL, IEEE) to harmonize PTO testing and certification criteria.
2. Create Open-Source Design and Simulation Tools:
    - Develop publicly available PTO modeling tools that allow researchers, startups, and manufacturers to evaluate PTO performance under various marine conditions.

- Enhance existing marine energy simulation platforms (e.g., WEC-Sim, OpenFAST) to include standardized PTO modules for different scales of deployment.

3. Establish a PTO Testing and Validation Protocol:
    - Define accelerated life-testing procedures for PTO durability in real-sea conditions, including extreme weather scenarios.
    - Ensure test beds and laboratory facilities can accommodate PTOs from small, off-grid units to full-scale devices.
    - Identify thresholds or stages where simulation, benchtop testing, tank testing, and full scale testing are appropriate, similar to the Ocean Energy Systems framework (Hodges et al, 2023). A quick attention directing tool to inform PTO developers what they should be doing at each stage of technology maturity in order to progress.
    - Identify problem areas for scaled testing, where the results may be of dubious value. Friction and stiction can be challenging at small scale, but become less so at larger scale with larger masses/forces.
    - Promote data-sharing mechanisms to facilitate knowledge exchange on PTO performance across industry and academia.
    - Simplify and streamline validation protocols based on PTOs' scale to meet their respective standards and certification frameworks. For example, small PTOs designed for ocean monitoring buoys or remote aquaculture should have a lightweight validation process that ensures reliability without requiring the same extensive, multi-year testing regimes as grid-scale deployments.
4. Support Modular PTO Architectures for Flexibility and Scalability:
    - Define modular PTO configurations that allow for plug-and-play compatibility between different marine energy systems, especially for small-scale PTOs.
    - Ensure designs support both mechanical and electro-mechanical PTO architectures, optimizing them for low-power, distributed applications as well as high-energy, utility-scale deployments.
5. Promote Industry-Academia-Government Collaboration:
    - Create a public PTO design repository that includes reference designs, case studies, and best practices.
    - Provide funding incentives for developers who adhere to the standardized PTO guidelines to accelerate adoption.

Expected Impact

- Accelerated commercialization: Reducing design uncertainty will shorten development cycles and encourage investment in PTO technology.
- Improved cost-efficiency: Standardized designs will lower manufacturing costs, making PTO systems more accessible for small-scale and distributed applications.
- Enhanced reliability and survivability: A unified testing framework will lead to more robust PTO designs, reducing failure rates and maintenance costs.
- Stronger industry collaboration: Open-access guidelines will streamline partnerships between research institutions, startups, and established developers, fostering a more innovative and competitive market.

Technology Readiness Levels

- Small-scale PTOs: TRL 4-9, bench-scale prototypes progressing toward operational validation with commercial deployments.
- Community Scale PTOs: TRL 4-8, bench-scale prototypes progressing toward commercial readiness.
- Utility-scale PTOs: TRL 5-8, pilot demonstrations leading to commercial readiness.

Groups Involved

- Academia: Research institutions developing PTO models and simulation tools.
- Industry: Marine energy technology developers, PTO manufacturers, and offshore operators (such as marine system integrators and deployment specialist firms)
- National Laboratories: NLs developing certification standards (eg. NREL), conducting PTO reliability testing (eg. PNNL, NREL, Sandia, NMECs), or simulation tools.
- Government & Standards Bodies: U.S. Department of Energy (DOE) Water Power Technologies Office (WPTO), National Renewable Energy Laboratory (NREL), IEC TC 114, Underwriters Laboratories (UL), and regulatory agencies guiding certification efforts.

$ Budget Required

$5-10M for research, tool development, certification efforts, and pilot demonstrations across small, community, and utility-scale PTO deployment.

Recommendation 2: Best Practices, Approaches and Certification Pathways for Marinized, Low-Speed Electrical Devices

Scope

Low-speed electrical machines are fundamental components of PTO systems in wave and tidal energy converters. Unlike wind energy, where generators operate at high rotational speeds, marine energy systems require low-speed, high-torque machines that function in harsh, corrosive, and unpredictable ocean environments. Developing marinized electrical machines that meet performance, durability, and certification requirements is a major barrier to commercialization. This recommendation outlines best practices, technological approaches, and a certification pathway (e.g., UL certification) for ensuring reliable, efficient, and cost-effective PTO components across different marine energy scales.

Applicability

Scale	Wave	Current	Tidal	OTEC
Small Scale/Off-Grid	✓	✓	✓	
Community Scale	✓	✓	✓	
Utility-Scale	✓	✓	✓	

Specific Actions

1. Develop Standardized Design and Testing Guidelines

- Establish performance benchmarks for efficiency, torque, and power conversion under real-sea conditions.
- Define best practices for insulation, cooling, and corrosion resistance in marine-rated generators and motors.
- Create open-access design guidelines to assist developers in meeting marinization and certification requirements.

2. Optimize Materials and Coatings for Marine Durability
   - Develop saltwater-resistant coatings and encapsulation methods to protect electrical components.
   - Research composite materials and stainless alloys that enhance fatigue resistance and lifespan in marine environments.
   - Implement self-cleaning or biofouling-resistant materials to reduce maintenance needs.
3. Prototype and Test Marinized Electrical Machines
   - Conduct accelerated life-cycle testing to evaluate machine performance under extreme marine loads.
   - Deploy pilot-scale machines in real-sea conditions to assess reliability and power output consistency.
   - Validate PTO designs through lab-based testing at National Marine Energy Centers (NMECS) and/or National Laboratories before field deployment.
4. Establish a UL and IEC Certification Pathway for Marine Power Electronics
   - Work with certification bodies (UL, IEC, IEEE, and classification societies) to define marine-specific standards for low-speed generators.
   - Support in-ocean prototype testing for non-certified machines to de-risk commercialization.
   - Develop standardized test procedures to streamline compliance for marine power electronics.
5. Create Open-Source Modeling and Simulation Tools for PTO Optimization
   - Develop tools to simulate low-speed PTO performance, incorporating wave/tidal loading conditions and environmental variability.
   - Implement grid-integration modeling to test electrical machine behavior under variable ocean power conditions.

Expected Impact

- Increased PTO Reliability: Improved material selection and standardized testing will extend component lifespans and reduce failure rates.
- Lower Cost of PTO Deployment: Standardized marinization practices will cut maintenance costs and enhance manufacturability.
- Accelerated Commercialization: A clear UL certification pathway will reduce regulatory uncertainty and enable faster market adoption.
- Expanded Deployment Opportunities: Enhanced machine durability will allow PTOs to operate in harsher marine environments, supporting off-grid and grid-scale energy systems.

- Improved Grid Integration: Certification and testing frameworks will help developers meet compliance requirements, enabling smoother grid connections.

Technology Readiness Levels

- TRL 3-4: Development of standards, best practices, and material optimization for insulation, corrosion resistance, and cooling solutions. Many initial tests can be conducted before full marinization. Standardization efforts remain at TRL 3-4, requiring further industry collaboration to define testing and certification pathways.
- TRL 4-5: Prototype testing in lab environments, focusing on performance under low-speed, high-torque conditions without marine exposure.
- TRL 5-6: Early real-sea testing of marinized electrical machines, validating durability, efficiency, and power output under operational conditions.
- TRL 6+: Certification efforts (UL, IEC, IEEE) and full-scale deployments to demonstrate long-term grid integration and commercial viability.

Groups Involved

- Industry, national labs and academia with access to relevant lab and bench/open water testing capabilities

Budget Required

$8M–$15M for lab and prototype testing of non-marinized electrical machines' materials, insulation, and corrosion resistance; environmental and accelerated life-cycle testing before open-water deployment; field demonstrations of marinized and weatherized machines in real-world conditions; and certification and standardization (UL, IEC, IEEE) for grid integration.

Recommendation 3: Standardized Wave Energy Power Electronics for Wide Voltage Ranges

Scope

WECs operate in highly dynamic and variable ocean environments, requiring robust power electronics capable of handling wide voltage efficiently. Unlike wind and solar energy, wave power involves more irregular energy inputs with fluctuations in voltage, frequency, and power output. Existing power electronics solutions are often not optimized for marine conditions, leading to efficiency losses, grid integration challenges, and high costs. This recommendation focuses on developing standardized, open-source power electronics solutions for wave energy, ensuring compatibility across multiple WEC designs while improving conversion efficiency, grid compatibility, and long-term reliability.

Applicability

Scale	Wave	Current	Tidal	OTEC
Small Scale/Off-Grid	✓			
Community Scale	✓			
Utility-Scale	✓			

Specific Actions

1. Develop Standardized Power Electronics Architectures for WECs
   - Establish a modular, open-source power electronics platform for wave energy applications.
   - Standardize wide-voltage-range power conversion designs to accommodate variable wave energy inputs.
2. Enhance Power Conversion Efficiency and Stability
   - Research and develop adaptive power electronics control strategies for dynamic wave conditions.

- Improve bidirectional power flow capabilities to enhance energy storage integration and grid reliability.
- Optimize wide-range gap semiconductor materials (e.g., SiC, GaN) for high-efficiency power conversion.

3. Integrate Grid-Forming and Ancillary Service Capabilities
   - Develop grid-compatible power electronics that support frequency response, inertia emulation, and black start capabilities.
   - Ensure compatibility with smart grids, energy storage systems, and offshore power networks.
4. Prototype and Test Standardized Power Electronics in Real-Sea Conditions
   - Conduct hardware-in-the-loop (HIL) testing to validate power electronics under variable marine loads.
   - Deploy pilot-scale power conversion systems in collaboration with WEC developers.
   - Test for compliance with UL, IEC, and IEEE standards to ensure global interoperability.
5. Establish Certification Pathways and Open-Source Documentation
   - Work with certification bodies to define standardized test procedures for marine energy power electronics.
   - Publish open-access design guidelines and simulation tools for use by developers, researchers, and industry partners.

Expected Impact

- Increased Conversion Efficiency: Optimized power electronics architectures will reduce energy losses, improving overall WEC performance.
- Lower Cost of Grid Integration: Standardized designs will simplify regulatory approvals and reduce engineering complexity.
- Scalability and Interoperability: Open-source power electronics will support multiple WEC architectures, increasing industry adoption.
- Improved System Resilience: Grid-forming capabilities will enhance reliability, allowing WECs to provide ancillary services and operate in weak grids.

Technology Readiness Levels

3-7 (Lab-scale prototypes, progressing to field validation in pilot projects)

Groups Involved

- Universities and National Labs with power electronics capabilities.

Budget Required

$5M–$6M for lab and prototype testing of standardized power electronics using off-the-shelf components; hardware-in-the-loop simulations; early-stage real-sea demonstration; and development of certification pathways (UL, IEC, IEEE) and open-source design tools

Recommendation 4: Testing of Mechanical Components for WECs

Scope

Mechanical components for WECs must endure extreme and highly variable marine conditions, including cyclic loading, corrosion, biofouling, and extreme weather events. This recommendation focuses on developing standardized testing methodologies for mechanical components under realistic stochastic marine loads, ensuring long-term performance and cost-effective deployment. Testing protocols must explicitly address the stochastic nature of wave loads by integrating time-varying operational conditions into accelerated lifetime testing frameworks. This effort should prioritize correlation between laboratory-accelerated testing data and real-world performance to improve service life prediction accuracy. By improving mechanical component validation, this effort will reduce failure rates, maintenance costs, and uncertainties in WEC system design. Additionally, this initiative will address the unique requirements of PTOs of varying scales by ensuring testing protocols align with their power and operational constraints.

Applicability

Scale	Wave	Current	Tidal	OTEC
Small Scale/Off-Grid	✓			
Community Scale	✓			
Utility-Scale	✓			

Specific Actions

1. Develop Standardized Testing Protocols for Mechanical Durability
- Establish accelerated life-cycle testing for key mechanical components, including bearings, seals, flexible couplings, shafts, and composite materials.
- Standardize torque, shear, fatigue, and corrosion resistance tests under simulated marine loads.

- Ensure protocols differentiate between small-scale, mid-scale, and large-scale WEC components, optimizing testing rigor for each category.

2. Create a Centralized Marine Testing Infrastructure
    - Expand access to wave basins, offshore test sites, and controlled lab environments to facilitate accelerated life testing. TEAMER has significantly alleviated some of these test infrastructure gaps through facility access support. However, a few critical gaps remain in test infrastructure. There is still a need to:
    - Establish test rig setup (preferably scalable) that can accommodate a range of PTO designs, from small-scale to utility-scale applications.
    - Ensure test facilities support real-world dynamic loading conditions to validate long-term performance.
3. Streamline Testing for PTO Components
    - Simplify certification pathways for marine mechanical components to enable faster commercialization.
    - Develop modular, plug-and-play testing protocols for PTOs, allowing rapid deployment for existing off-grid applications.
    - Ensure cost-effective testing frameworks that avoid overburdening small-scale developers with unnecessary requirements.
4. Enhance Data Collection and Sharing
    - Establish open-access databases for mechanical component test results, enabling knowledge transfer across research institutions and industry.
    - Promote industry partnerships to validate mechanical components across different deployment environments, from shallow waters to deep-sea conditions.

Expected Impact

- Increased Mechanical Reliability: Standardized testing will reduce failure rates, improving component lifespans and lowering operational costs.
- Accelerated Commercial Deployment: Streamlined small-scale PTO testing will allow faster deployment of off-grid and remote energy systems.
- Lowered Costs and Risks: Improved mechanical testing will minimize unplanned maintenance and repair costs, making WEC projects more financially viable.
- Enhanced Industry Collaboration: A shared data ecosystem will accelerate innovation and provide a benchmark for future WEC designs.

Technology Readiness Levels

- Small-scale PTO components: TRL 4-9 (from lab-scale testing to real-sea validation via commercial deployments).
- Utility-scale WEC components: TRL 5-8 (pilot demonstrations progressing toward commercial deployment).

Groups Involved

- Academia: Testing and test development.
- National Labs: Test facilities and testing of components
- Industry: Development of tests needed

Budget Required

$15M-$20M for a mix of small to medium projects for testing of individual components up to whole PTO systems.

Recommendation 5: Gearing Improvements and Alternatives

Scope

Efficient and reliable speed-increasing mechanisms are critical for PTO systems in WECs and other marine energy applications. Conventional mechanical gearboxes, while effective in some applications, suffer from wear, maintenance challenges, and high failure rates in marine environments due to saltwater exposure, biofouling, inconsistent wear, and extreme dynamic loading.

This recommendation focuses on advancing alternative gearing technologies, including magnetic gearing, belt-driven systems, and novel mechanical gear designs, that offer improved durability, efficiency, and reduced maintenance requirements for all scales of marine energy converters. By improving gearing solutions PTO efficiency can be enhanced, mechanical complexity reduced, and system lifespan extended, making wave and current energy more competitive with other renewables.

Applicability

Scale	Wave	Current	Tidal	OTEC
Small Scale/Off-Grid	✓	✓	✓	
Community Scale	✓	✓	✓	
Utility-Scale	✓	✓	✓	

Specific Actions

1. Standardize Testing and Performance Metrics for Marine Gearing Technologies
    - Establish a benchmarking framework to compare mechanical, magnetic, and belt-driven gearing solutions on the following metrics: speed increase, torque density (mass and volumetric), time to failure, required manufacturing tolerances.

- Implement accelerated life-cycle testing for different speed-increasing mechanisms in marine environments.
- Develop open-source design and performance models to facilitate industry adoption.
- Incentivize data-sharing on PTO failures through financial means or by granting early adopters early access to findings.

2. Advance Magnetic Gearing for Marine Applications
   - Develop and test high-torque, low-maintenance magnetic gearboxes for WEC PTO systems.
   - Optimize materials and coatings for corrosion resistance and durability in high-salinity environments.
   - Explore hybrid electromechanical gearing concepts to improve efficiency and load management.
3. Investigate and Prototype Belt-Driven Gearing Systems
   - Evaluate belt-based speed increasers as a lightweight and low-friction alternative to mechanical gearboxes.
   - Develop marine-grade belt materials resistant to biofouling, high humidity, and mechanical fatigue.
   - Test modular belt-driven PTO solutions for small-scale, off-grid WECs.
4. Enhance Reliability of Traditional Mechanical Gearing Solutions
   - Identify low-maintenance mechanical gearbox configurations optimized for WEC PTOs.
   - Develop self-lubricating or sealed lubrication systems to minimize marine fouling and reduce failure rates.
   - Conduct long-term fatigue and failure testing on mechanical gear designs under wave loading conditions.

Expected Impact

- Increased PTO Efficiency: advanced gearing solutions will enable higher energy conversion efficiencies, leading to more cost-effective marine energy generation.
- Reduced Maintenance and Downtime: magnetic and belt-driven systems eliminate mechanical wear, reducing the need for frequent maintenance in harsh ocean conditions.
- Lower Costs for Small-Scale Deployments: lightweight, low-maintenance gearing solutions will reduce capital and operational expenses for off-grid and community-scale WECs.

- Enhanced Grid-Scale Viability: high-performance gearing systems will improve reliability for large-scale WEC farms, ensuring consistent power generation and lowering the Levelized Cost of Energy (LCOE).

Technology Readiness Levels

- Magnetic Gearing: TRL 3-6 (concept development to prototype testing in marine conditions).
- Belt-Driven Gearing: TRL 4-6 (bench-scale prototypes progressing to real-sea validation).
- Optimized Mechanical Gearboxes: TRL 4-7 (pilot demonstration leading to commercial implementation).

Groups Involved

- Academia: Research and development of alternative gearing options
- National Labs: Testing of gearing options
- Industry: Development of gearing needs and testing of options

Budget Required

$10M-$15M for a mix of small to medium projects, including experimental prototypes and real-sea demonstrations.

Recommendation 6: Power Electronics Control for ME

Scope

The integration of ME sources, such as wave, tidal, and ocean current energy, into the power grid requires advanced power electronics control strategies to ensure stability, reliability, and grid support. Power converters must manage fluctuating power outputs, enable seamless grid integration, and enhance system resiliency through grid-forming capabilities. VSG and ancillary services, including frequency response and inertia support, are key enablers for stable operation in powering blue economy applications such as microgrids and islanded systems.

Applicability

Scale	Wave	Current	Tidal	OTEC
Small Scale/Off-Grid	✓	✓	✓	
Community Scale	✓	✓	✓	
Utility-Scale	✓	✓	✓	

Specific Actions

1. Small-Scale, Off-Grid Applications (e.g., remote sensors, standalone systems)
   - Efficient Power Conversion: Use DC-DC and DC-AC converters to stabilize fluctuating energy from marine sources.
   - Energy Storage Integration: Implement battery management systems (BMS) and charge controllers for continuous operation.
   - Autonomous Operation & MPPT: Apply adaptive control strategies to optimize power extraction from variable marine conditions.
   - Compact & Robust Design: Ensure converters are lightweight, corrosion-resistant, and low-maintenance for remote deployment.

2. Community-Scale Systems (e.g., coastal microgrids, islanded grids)
   - Hybrid Energy Management: Develop power electronics interfaces for integrating wave, tidal, current, and storage.
   - Smart Grid Controls: Implement predictive control algorithms for demand-response and load balancing. Implement VSG-based control for inertia emulation and frequency support.
   - Microgrid Synchronization: Use bidirectional inverters and power converters for smooth grid transitions. Improve harmonic mitigation and low-voltage ride-through (LVRT) capabilities.
   - Fault Tolerance & Protection: Design converters with real-time fault detection, isolation, and self-healing capabilities for extreme marine conditions.
3. Utility-Scale Deployments (e.g., WEC farms, tidal/ocean current arrays)
   - High-Efficiency Grid Integration: Use HVDC and medium-voltage AC transmission with grid-forming inverters.
   - Grid Code Compliance: Implement power quality enhancements (e.g., voltage/frequency control, reactive power compensation).
   - Large-Scale Reliability: Apply modular multilevel converters (MMCs) and redundant power paths to enhance system resilience.
   - Advanced Control Strategies: Utilize real-time monitoring, AI-driven optimization, and predictive maintenance for long-term performance. Investigate fast-frequency response (FFR) and droop control techniques to improve grid stability.
4. Experimental Validation & Hardware-in-the-Loop Testing
   - Utilize real-time simulation platforms and HIL testbeds for verifying performance under various grid conditions.
   - Conduct sea-based demonstrations of grid-forming converters.

Expected Impact

- Enhanced standalone system reliability and grid/microgrid stability through robust power electronics control.
- Higher reliability and lower operational costs for ME systems.
- Improved grid resilience in islanded and remote communities.
- Acceleration of commercial deployment by ensuring compliance with grid codes.

Technology Readiness Levels

TRL 3-7 (Lab-scale prototypes, progressing to field validation in pilot projects).

Groups Involved

- Academia: Research on advanced control algorithms and real-time simulation (e.g., national labs, universities).
- National Labs focusing on power electronics and grid integration.
- Industry: Developers of ME systems, inverter manufacturers, and microgrid integrators.

Budget Required

$5M-$10M for a mix of small to medium projects, including experimental prototypes and real-sea demonstrations.

Recommendation 7: Extreme Sea PTO Survival Mechanisms

Scope

Wave and tidal energy systems must withstand highly dynamic and extreme environmental conditions, including large loads, high speeds, and extreme torques. The range of forces a PTO system experiences can vary significantly due to storms, rogue waves, and turbulent flow interactions. Without adequate survival mechanisms, these extreme conditions can lead to mechanical failures, structural fatigue, and excessive downtime, significantly impacting the reliability and cost-effectiveness of marine energy technologies.

To mitigate these challenges, advanced survival mechanisms such as shaft disengagement, torque-limiting devices, and speed regulation technologies must be integrated into PTO systems. While wind energy systems have successfully implemented similar survival strategies, WECs, CECs, and TECs require tailored solutions that account for their unique loading conditions and dynamic operational environments.

This recommendation focuses on the research, development, testing, and standardization of extreme sea survival mechanisms to ensure long-term reliability, cost reduction, and expanded deployment opportunities for wave, current, and tidal PTO systems.

Applicability

Scale	Wave	Current	Tidal	OTEC
Small Scale/Off-Grid	✓	✓	✓	
Community Scale	✓	✓	✓	
Utility-Scale	✓	✓	✓	

Specific Actions

1. Research existing methods for shaft disengagement, speed and torque limiting
   - Investigate shaft disengagement, torque-limiting, and speed-adaptive PTO designs from wind, automotive, and industrial applications that could be adapted for marine energy.
   - Identify high-strength, corrosion-resistant materials that enhance durability under extreme oceanic forces.
   - Explore real-time sensing and control algorithms for adaptive disengagement and overload protection.

2. Modification of existing methods and development of methods to suit specific needs of wave and tidal systems
   - Develop scalable, low-maintenance disengagement mechanisms tailored to wave energy PTOs experiencing irregular, high-impact loads.
   - Adapt torque-limiting clutches and speed-adaptive gear systems for use in wave and tidal PTOs, optimizing for long-term fatigue resistance.
   - Design fail-safe PTO decoupling mechanisms to prevent catastrophic failure in severe storm conditions.

3. Optimize mechanisms and testing protocols
   - Construct and test multiple PTO survival prototypes across different marine environments to assess performance, reliability, and cost-effectiveness.
   - Conduct real-sea validation tests to refine mechanical and electro-mechanical disengagement strategies for both small-scale and large-scale deployments.
   - Develop a modular testing platform that allows for controlled extreme load simulation and iterative design improvements.

4. Development of standards to guide use of mechanisms
   - Establish industry-wide guidelines for extreme load protection in PTOs, ensuring compatibility across different wave and tidal energy systems.
   - Work with regulatory agencies to develop streamlined certification pathways for high-reliability PTO survival designs.
   - Facilitate data-sharing initiatives to provide open-access performance benchmarks for industry adoption.

Expected Impact

- Expand range of device deployment location options: PTO survival mechanisms will allow devices to be deployed in a broader range of high-energy marine environments, expanding commercial feasibility. Consider inter-agency collaboration to expand real-world deployment opportunities (e.g., collaboration with NSF USAP for Antarctic deployment and NOAA/NASA/USCG for Arctic deployment).

- Reduced Structural and Mechanical Fatigue: Smart disengagement and torque-limiting strategies will prevent excessive wear and failure, extending PTO lifespan and reducing maintenance costs.
- Decreased design load window: Improved survival mechanisms will allow developers to optimize structural mass and material use, reducing capital and operational expenses.
- Enhanced Industry Confidence: Standardized survival mechanisms will encourage investment and commercial adoption, positioning wave and tidal energy as a reliable renewable power source.

Technology Readiness Levels

- TRL 2-3: conceptualization and proof-of-concept validation through small-scale prototypes and lab testing.
- TRL 4-5: testing in controlled marine environments and early-stage pilot projects.

Groups Involved

- National Labs: Conducting controlled testing of PTO survival mechanisms under simulated extreme marine conditions (e.g., PNNL, NREL, Sandia).
- Industry and Academia: Developing design requirements and leading in-situ testing in real-sea deployments. Investigating advanced materials, fatigue modeling, and smart control systems for PTO survival applications.

Budget Required

$5M-$10M for multiple small to medium projects focusing on development, testing, and certification: survival mechanism design and testing, material selection and fatigue analysis, and field validation and certification pathways.

Recommendation 8: Marinized Power Electronic Machines: Best Practices, Approaches, and Pathway to Certification

Scope

Marinized power electronic machines play a critical role in offshore renewable energy applications, including wave and tidal energy systems. These machines must operate reliably in harsh marine environments while meeting performance, safety, and durability standards. This topic focuses on best practices, technological approaches, and pathways to achieving UL certification for marine power electronic machines, ensuring compliance with safety, performance, and regulatory requirements.

Applicability

Scale	Wave	Current	Tidal	OTEC
Small Scale/Off-Grid	✓	✓	✓	✓
Community Scale	✓	✓	✓	✓
Utility-Scale	✓	✓	✓	✓

Specific Actions

1. Development of Marinized Power Electronics

- Implement Hybrid marine systems integrating energy storage and large-scale offshore power distribution.
- Design subsea and offshore power electronic systems used in harsh marine environments.
- Design marine-grade inverters, converters, and electrical components for energy transmission.
- Design robust, corrosion-resistant power electronics for long-term offshore operation.

- Implement advanced cooling and encapsulation techniques for marine-grade components.

 2. Best Practices for Reliability and Performance

- Develop standardized testing protocols for accelerated aging and environmental stress testing.
- Enhance fault tolerance and redundancy mechanisms to increase reliability.

3. Pathway to UL Certification

- Identify key UL and IEC standards applicable to marine power electronics such as UL 61800, UL 1741, IEC 60092.
- Develop a roadmap for compliance, including testing, certification, and regulatory approvals.
- Establish partnerships with certification bodies to streamline the certification process.

4. Experimental Validation & Testing Facilities.

- Utilize HIL testing for real-time validation.
- Conduct field trials in offshore environments to assess performance under real-world conditions.

Expected Impact

- Increased reliability and lifespan of power electronics in harsh marine conditions.
- Accelerated commercialization of UL-certified power electronic machines for offshore applications.
- Enhanced grid integration and power quality for marine energy systems.
- Improved investor confidence in offshore renewable energy technologies.

Technology Readiness Levels

TRL 4-7 (Prototype development, lab-scale testing, progressing to real-sea validation).

Groups Involved

- Academia: Research on advanced materials, reliability, and certification methodologies.
- National Laboratories: Testing and validation of power electronics for offshore applications.
- Industry: Marine energy developers, power electronics manufacturers, and certification bodies.

$ Budget Required

$25M-$50M for small to medium projects focusing on testing, validation, and certification pathways.

Recommendation 9: Storage-Integrated ME for Grid Integration

Scope

The integration of energy storage with marine energy converters is essential for ensuring stable grid operation, mitigating power fluctuations, and improving energy dispatchability. ME sources inherently exhibit variability due to changing ocean conditions, making storage a critical component for smoothing power output, enhancing reliability, and enabling seamless grid integration. By effectively coupling storage with ME systems, operators can reduce the impact of short-term fluctuations, provide ancillary services such as frequency regulation and voltage support, and improve the overall resilience of marine-based energy generation.

Applicability

Scale	Wave	Current	Tidal	OTEC
Small Scale/Off-Grid	✓	✓	✓	✓
Community Scale	✓	✓	✓	✓
Utility-Scale	✓	✓	✓	✓

Specific Actions

1. Development of Storage-Integrated Marine Energy Converters
   - Design and optimize energy storage solutions (batteries, flywheels, hydrogen) for marine applications.
     - Develop hybrid control architectures for seamless energy dispatch.
2. Advanced Control Strategies for Grid Integration
   - Implement real-time predictive control algorithms to manage power fluctuations.
   - Optimize energy storage utilization for frequency regulation and peak shaving.
3. Experimental Testing and Validation
   - Conduct laboratory-scale testing and validation of storage-integrated converters.
   - Deploy field-scale pilot projects for performance assessment in real-sea conditions.

4. Deployment Pathways and Grid Compliance

- Identify grid interconnection requirements and develop compliance strategies.
- Establish partnerships with utilities and grid operators for demonstration projects.

Expected Impact

- Increased stability and reliability of ME for grid integration.
- Enhanced power quality and reduced curtailment of wave, tidal, and ocean current energy.
- Expansion of ME market through storage-enabled flexibility.
- Acceleration of commercial adoption with validated real-sea demonstrations.

Technology Readiness Levels

TRL 2-5 (Proof of Concept, Prototype validation, lab testing, progressing to field deployment).

Groups Involved

- Academia: Research on storage technologies, control design, and power electronics.
- National Labs: Grid-integration studies, validation, and standards development.
- Industry: Marine energy developers, storage technology providers, and utility companies.

Budget Required

$10M-$15M for multiple small to medium projects focusing on experimental validation and deployment.

References

Hodges J., Henderson J., Ruedy L., Soede M., Weber J., Ruiz-Minguela P., Jeffrey H., Bannon, E., Holland M., Maciver R., Hume D., Villate J-L, Ramsey T., (2023) *An International Evaluation and Guidance Framework for Ocean Energy Technology*, IEA-OES

Kilcher, L., Fogarty, M. and Lawson, M. (2021). Marine Energy in the United States: An Overview of Opportunities. [online] Available at: https://www.nrel.gov/docs/fy21osti/78773.pdf.

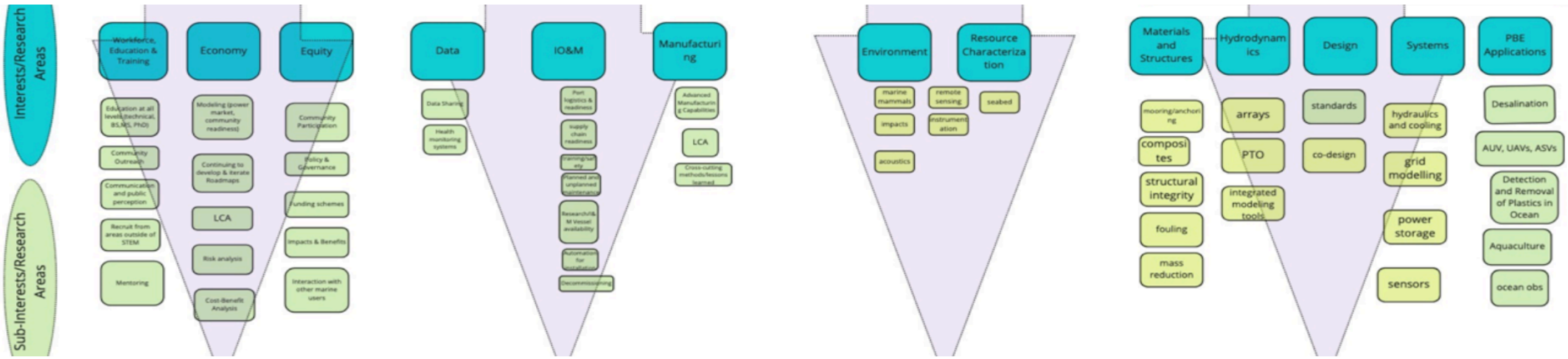
Quinn, S. and Hirsch, S. (2022). UMERC-POET Research Landscape Workshop Report. [online] University Marine Energy Research Community. Available at: https://umerc-us.org/media_center/file/59749b27-c44b-4e69-af4f-286d4d8727d2.

Quinn, S. and Hirsch, S. (2023a). UMERC Industry Academia Workshop Report. [online] University Marine Energy Research Community. Available at: https://umerc-us.org/media_center/file/b6d5041f-eaf5-4c5c-bcdc-305a67263f35.

Quinn, S. and Hirsch, S. (2023b). UMERC Industry Priorities Workshop Report. [online] University Marine Energy Research Community. Available at: https://umerc-us.org/media_center/file/c198d8d8-02f5-42f1-ab4f-9c24eb284b65.

Appendix

Supplemental Figure 1: 2021/2022 Research Landscape Workshops Interests/Research Areas
From: Quinn and Hirsch, 2022



Supplemental Table 2: Proposed projects from the Industry Academia Needs Workshop.
Adapted from (Quinn and Hirsch, 2023a)

#	Topic	Who Should Be Involved	Small Projects <$2M	Medium Projects $2M-$8M (~$5M)	Large Projects >$8M (~$10M)
a	Comparative study and analysis on different PTO technologies and identify their suitable application	Industry partners from different parts of supply chain (generation, transmission, manufacturing, etc) and Academia	3 (each focused on a specific PTO)	1 (to combine the results and do the comparative study)	
b	Build new practical PTO modeling modules (Beyond what is now modeled in WEC-Sim)	National Lab and Academia		1 (Research on new models and validate in experimental testing)	
c	Control for low-level of the WEC for mechanical part and how to harness power (PTO) (General application)	Industry (Calwave) and Academia	3 (different control parts)		
d	Control for Blue economy Applications (energy management for sensors in some applications, traditional control for water desalination) and grid integration (frequency control, voltage control)	Industry and Academia	A lot of small projects for specific applications		1
e	Control Co-design	Industry, national			1 (collaborative

		lab, and academia			projects)
f	Critical components for WEC PTO (generator, transmission, control); Operation & control Algorithms for CECs in array configurations to advance grid-scale studies.	Industry and Academia		3	
g	Identify PTO failure modes during long term testing with simulated loads in a marine environment	University, Developers, National Labs, Federal Funding	40%	20%	40%
h	Marinisation of commercially available components (often from adjacent sectors)…what does it take to get commercially available components 'WEC ready?' "MHK ready?"	University, National Labs, Commercial	70%	30%	
i	Grid-Scale transmission/Integration	Academia, Industry, Government Funding	10%	50%	40%

Supplemental Table 3: Proposed Research Topics from PTO and Controls Working Group

#	W/T/O	Project Topics	Who Should Be Involved?	Small Projects <$2M (~$2M)	Medium Projects <$5M (~$5M)	Large Projects >$5M (~$10M)
A	W	Standardize PTO design processes/guidelines that are publicly available	University led with Developers, Labs, Manufacturers	X		
B	W	Standardized Wave Energy Power Electronics for Wide Voltage Bands for increased efficiency (open source)	Lab/University led - developer and manufacturers or industry/developer led (ABB/Siemens/GE)		X	X
C	W/T	Marinized electrical machines for low speed applications best practices, approaches and pathway to UL certification	Developers, Labs, Universities, P.E			X
D	W/T	Marinized power electronic machines at sea applications best practices, approaches and pathway to UL certification	Developers, Labs, Universities, P.E			X

E	W/T	Testing of mechanical components for marine applications and loads focus on wave	Developers, Labs, Universities, Manufacturers	**X**	**X**	
F	W/T	Bearings -life characterization, cyclical loading, including all seals, lubrication and non-torque loads	University led with Developer and manufacturer partnerships.			
G	W/T	Gearing (speed increasing mechanism)-magnetic gearing, new solutions, belts	Anyone	**X**		
H	W/T	Ropes (ropes/belts) for Power Transfer - wear, fairlead, rope construction for load fatigue, drum/sheave interface, abrasion prevention, monitoring with full scale testing	Developer with university partners, rope manufacturers	**X**	**X**	**X**
I	W/T	Hydraulics - seal life cyclical loading,new materials, design. Increase level of robustness around smaller components of hydraulics (seals and valves, accumulators). Scaled hydraulic testing.	University or National Labs with developer inputs	**X**	**X**	

J	W/T	Springs - new materials for corrosion resistance and fatigue.	University	**X**		
K	W/T	Springs - spring rate control for mechanical systems. Non-linearity spring stiffness.	University	**X**		
L	W/T	Materials for mechanical components	Developers, Labs, manufacturers	**X**	**X**	
M	W	Projects specific to the development of cyclic testing of mechanical systems for the development of historical data, (e.g. for the MTBF for wave energy applications)	Developers, Labs, Universities, Manufacturers			
N	W	Fatigue study of mechanical components for cyclic motion with varying high non-torque loads	Developers, Labs, Universities, Manufacturers		**X**	**X**
O	W/T	Electrical power conversion efficiencies throughout the system - Advanced Metering infrastructure	Labs, Universities	**X**		

P	W	Extreme sea PTO survival mechanism (e.g. shaft disengagement, extreme speeds, extreme torques, extreme loading)	Developers, Labs, Universities, Manufacturers		**X**	
Q	W	Motion rectification (bidirectional motion converted to unidirectional)	Developers, Labs, Universities		**X**	**X**
R	T/O	Short- and long-term system testing of marine current (tidal and ocean current) PTO - in lab or ocean environment - device specific.	Developers, Labs, Universities, Manufacturers		**X**	**X**
S	W/T/O	Power electronics control for grid integration (grid-forming, virtual synchronous generation, ancillary services (frequency response, inertia support, etc.))	University led, developers, labs	**X**		

T	W/T/O	Marine-rated, UL certified power electronics specific for marine energy 1. In-ocean Prototype testing of non-certified power electronics 2. UL certification of invertor	Certification bodies, developers, utilities			**X**
U	W/T/O	Storage-integrated wave, tidal, and ocean current energy converters for grid-integration (research, testing, control design, deployment)	University led - developer, lab, manufacturers input		**X**	

Supplemental Table 4: Topic Area Ranking Results

Rank	Item	Points Received
#1	A – Standardize PTO design processes/guidelines that are publicly available.	74
#2	C – Marinized electrical machines for low speed applications best practices, approaches and pathway to UL certification.	67
#3	B – Standardized Wave Energy Power Electronics for Wide Voltage Bands for increased efficiency.	58
#4	E – Testing of mechanical components for marine applications and loads focus on wave.	54
#5	G – Gearing (speed increasing mechanism)-magnetic gearing, new solutions, belts.	42
#6	O – Electrical power conversion efficiencies throughout the system - Advanced Metering infrastructure.	42
#7	S – Power electronics control for grid integration (grid-forming, virtual synchronous generation, ancillary services (frequency response, inertia support, etc.)).	42
#8	P – Extreme sea PTO survival mechanism (e.g. shaft disengagement, extreme speeds, extreme torques, extreme loading).	41
#9	D – Marinized power electronic machines at sea applications best practices, approaches and pathway to UL certification.	38
#10	U – Storage-integrated wave, tidal, and ocean current energy converters for grid-integration (research, testing, control design, deployment).	35
#11	Q – Motion rectification (bidirectional motion converted to unidirectional).	34
#12	L – Materials for mechanical components.	24
#13	R – Short- and long-term system testing of marine current (tidal and ocean current) PTO - in lab or ocean environment - device specific.	23

#14	F – Bearings -life characterization, cyclical loading, including all seals, lubrication and non-torque loads.	21
#15	I – Hydraulics - seal life cyclical loading,new materials, design. Increase level of robustness around smaller components of hydraulics (seals and valves, accumulators). Scaled hydraulic testing.	21
#16	H – Ropes (ropes/belts) for Power Transfer - wear, fairlead, rope construction for load fatigue, drum/sheave interface, abrasion prevention, monitoring with full scale testing.	18
#17	N – Fatigue study of mechanical components for cyclic motion with varying high non-torque loads.	18
#18	T – Marine-rated, UL certified power electronics specific for marine energy.	18
#19	M – Projects specific to the development of cyclic testing of mechanical systems for the development of historical data, (e.g. for the MTBF for wave energy applications).	15
#20	K – Springs - spring rate control for mechanical systems. Non-linearity spring stiffness.	14
#21	J – Springs - new materials for corrosion resistance and fatigue.	4