Innovating Distributed Embedded Energy Prize (InDEEP): A Lessons Learned Report

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1 National Laboratory of the Rockies
2 Sandia National Laboratories

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NATIONAL LABORATORY OF THE ROCKIES

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List of Acronyms and Abbreviations

DEEC	distributed embedded energy converter
DEEC-Tec	distributed embedded energy conversion technology
DOE	U.S. Department of Energy
InDEEP	Innovating Distributed Embedded Energy Prize
NLR	National Laboratory of the Rockies
TPL	technology performance level
TRIZ	Theory of Inventive Problem Solving
WaveSPARC	Systematic Process and Analysis for Reaching Commercialization (for wave energy converter technologies)
WEC	wave energy converter
WPTO	Water Power Technologies Office

Executive Summary

The U.S. Department of Energy's Water Power Technologies Office (WPTO) launched the Innovating Distributed Embedded Energy Prize (InDEEP) in March 2023 to accelerate innovation in distributed embedded energy conversion technologies (DEEC-Tec). DEEC-Tec integrates numerous small energy converters into materials or systems to harvest ambient energy. Administered by the National Laboratory of the Rockies with technical support from Sandia National Laboratories, InDEEP focused on the development of distributed embedded energy converters (DEECs) and their integration into scalable DEEC-Tec metamaterials[1] for future marine renewable energy applications.

Over three competitive phases spanning two years, InDEEP awarded approximately $2.3 million to teams from academia, startups, and innovation sectors such as soft robotics, microelectronics, and advanced materials, most of whom had not previously worked in marine energy. Phase I emphasized conceptual design, Phase II required fabrication and benchtop testing of individual DEECs, and Phase III focused on integrating those DEECs into functional DEEC-Tec metamaterial prototypes. Although the prize did not call for full ocean wave energy converter (WEC) development, all teams were required to describe how their DEEC-Tec innovations might be applied to future WEC systems.

To attract and support a broad talent pool, the prize combined proven and novel strategies, including a public engagement leaderboard, structured teaming support, access to non-judging technical mentors, and a library of technical trainings. Key insights from the competition revealed that DEEC-Tec metamaterials must be intentionally designed to achieve advantageous emergent behaviors (such as coordinated deformation, frequency tuning, and structural adaptability) that exceed the capabilities of individual DEECs or their simplistic amalgamation. Additional lessons included the critical need for rigorous and standardized performance testing, both to ensure equitable evaluation and to guide—and gain traction for—future DEEC-Tec development pathways.

Teams that lacked defined test plans often struggled to demonstrate progress or benchmark their designs. Likewise, integrating power electronics proved essential for producing usable DEECs and DEEC-Tec metamaterials and for demonstrating system-level viability. Foundational materials science emerged as a somewhat unexpected but welcomed domain of application for promoting DEEC-Tec's possible potential, with breakthroughs in soft materials, dielectric elastomers, and ionic composites arising from the prize—technology developments that could enable new deformation modes for marine energy power conversion systems, increased durability, and low-cost energy capture.

InDEEP also catalyzed the formation of a multidisciplinary DEEC-Tec community, enabling WPTO to access hard-won insights from adjacent fields and apply them directly to marine energy challenges. This was accomplished, primarily, by intentionally lowering entry barriers and offering structured support. Indeed, by such mechanisms, the prize was able to expand the

[1] A DEEC-Tec metamaterial is a material system composed of many DEECs working synergistically to enable adaptable and distributed energy conversion.

pool of innovators engaged in marine energy and helped seed a new class of distributed, embeddable, modular, and resilient energy conversion solutions.

The potential applications of DEEC-Tec span near-term, mid-term, and long-term horizons—from autonomous power systems for ocean sensing, aquaculture, and marine robotics in the blue economy to eventual integration into distributed grid-scale ocean wave energy architectures. InDEEP demonstrated that by investing in early-stage subsystem development and supporting a broad, interdisciplinary community, WPTO can accelerate innovation in marine energy and lay the groundwork for future breakthroughs.

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1 Introduction

The Innovating Distributed Embedded Energy Prize (InDEEP) was launched by the U.S. Department of Energy's (DOE's) Water Power Technologies Office (WPTO) to accelerate the development of distributed embedded energy conversion technologies (DEEC-Tec) for ocean wave energy conversion [1] [2] [3]. DEEC-Tec integrates numerous small energy converters into materials or systems to harvest external sources of energy [4]. By leveraging a prize-based model, WPTO aimed to support early-stage or unconventional concepts that often fall outside the scope of standard notices of funding opportunity. Figure 1 was the primary advertising graphic for the InDEEP competition.

Figure 1. Launching advertisement. InDEEP was implemented to accelerate interdisciplinary innovation in DEEC-Tec.

Illustration by Josh Bauer, NLR

Administered by the National Laboratory of the Rockies (NLR), with technical support from Sandia National Laboratories, InDEEP offered competing teams up to $2.3 million in total awards. Rather than supporting complete wave energy converter (WEC) system designs, the prize aimed to cultivate foundational DEEC components (relatively small energy transducers) and DEEC-Tec metamaterials, which are systems composed of many interconnected DEECs [2]. These modular elements could serve as the building blocks for future full-scale WEC technologies [5] [2] [3] [6].

InDEEP was structured around several core objectives:

- Expand participation beyond the traditional marine energy community
- Promote interdisciplinary collaboration and mentorship
- Support proof-of-concept development for DEECs and DEEC-Tec metamaterials
- Lower entry barriers through phased, milestone-based funding

- Advance WPTO's broader marine energy innovation goals.

To reduce the burden of entry, WPTO replaced traditional proposal formats with concise concept summaries, one-slide overviews, and brief progress reports. Funding was distributed incrementally—$15,000 in Phase I, $80,000 in Phase II, and $200,000 in Phase III—enabling participation from small businesses, academic teams, and first-time federal applicants.

Recruitment combined wide-reaching digital outreach (via platforms hosted by American-Made Challenges and the DOE Office of Energy Efficiency and Renewable Energy) with targeted scouting by the open innovation firm yet2, which identified more than 35 promising technical categories of DEEC-Tec relevance (see Figure 2) [7]. A visual listing of the promising technical categories identified by yet2 applicable to DEEC-Tec is also given in Appendix A, Figure A-1. Nonetheless, InDEEP participant feedback revealed that personal, direct engagements such as one-on-one emails, conference conversations, and individual follow-ups, were far more effective than generalized announcements. This finding emphasized the importance of relationship-driven recruitment strategies. See Appendix A, Figure A-2 for a visual overview of those recruitment strategy results.

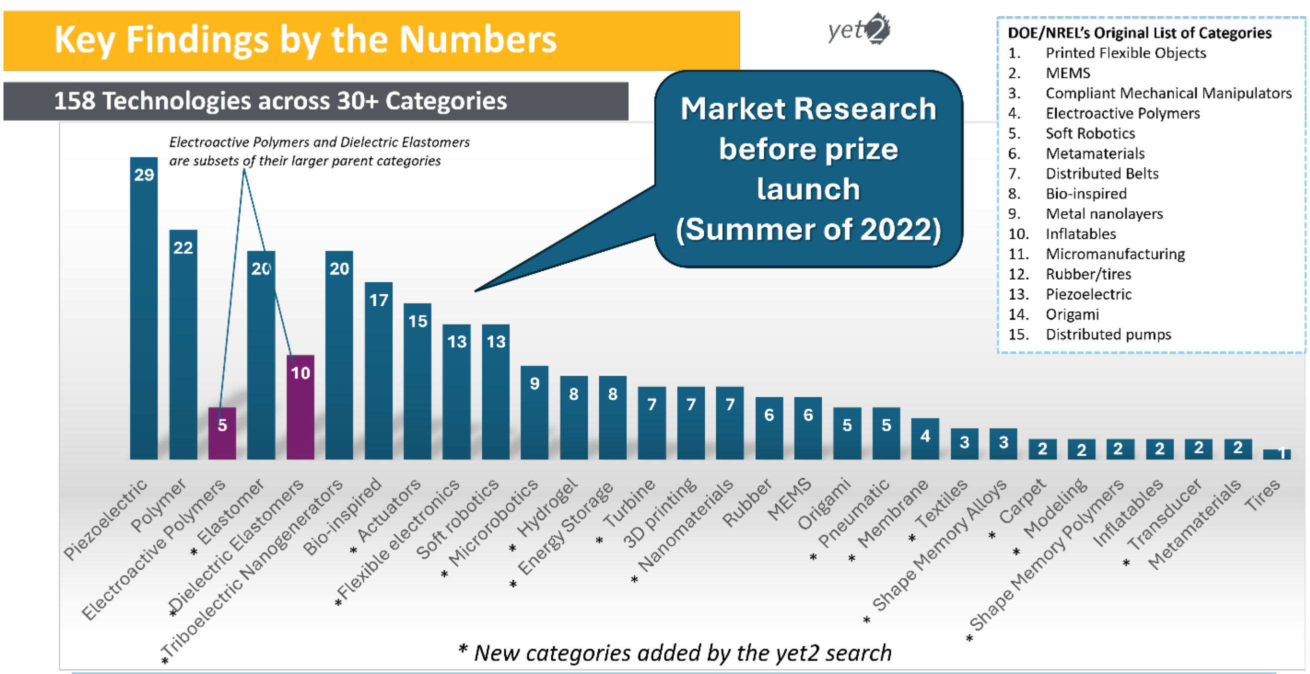

Figure 2. yet2 supported the InDEEP competition through global market scouting, identifying 158 possible participants and profiling 35 promising technology categories for the advancement of DEEC-Tec.

Figure from yet2

Throughout the competition, teams were encouraged to follow the DOE's WaveSPARC framework, which connects techno-economic performance metrics to iterative design decisions. [8] [9] [10] [11] [12] [13] [14].

The prize unfolded in three structured phases:

- **Phase I – Concept Development:** Teams proposed novel DEEC and DEEC-Tec metamaterial concepts, often using simple computer-aided design models and storyboards to illustrate their purpose and operation.
- **Phase II – Individual DEEC Demonstration:** Teams built, tested, and evaluated working prototypes of individual DEECs—energy transducers that convert one form of energy into another using some form of energy conversion mechanism.
- **Phase III – DEEC-Tec Metamaterial Demonstration:** Teams integrated multiple DEECs into integrated functional frameworks—DEEC-Tec metamaterials—aimed at creating advantageous emergent properties such as distributed deformations, tunable frequency response, embodied computing,[2] etc.

A visual overview of InDEEP's phases is given in Figure 3.

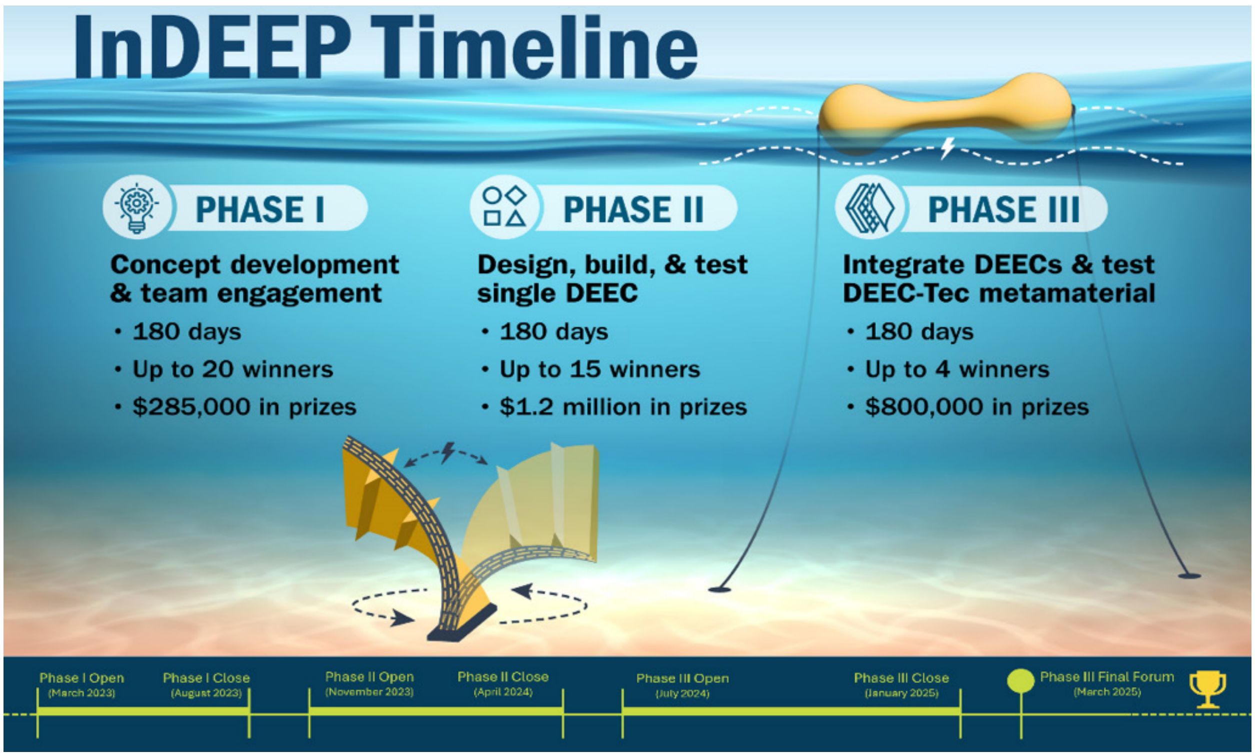

Figure 3. InDEEP unfolded in three phases, guiding teams from conceptual design through individual DEEC prototypes to full-scale integration and testing of DEEC-Tec metamaterials. Note, the prize did not call for full DEEC-Tec-based WEC design and development.

Illustration by Tara Smith, NLR

The prize culminated in a Final Forum held in March 2025 at NLR's two Colorado campuses (Flatirons Campus and South Table Mountain Campus) [15]. This event featured in-person presentations, poster sessions, an innovation seminar, and an international collaboration

[2] Embodied computing integrates sensing, actuation, and computation directly into physical materials, enabling structures to autonomously respond to their environment.

presentation from Wave Energy Scotland[3] [16]. InDEEP ultimately demonstrated that small-scale, modular innovation—when supported by structured funding, guidance, and community-building—can unlock new directions for marine energy research and development.

This report details the InDEEP competition—how it was designed, supported, and executed—along with its key technical results and strategic takeaways. The report's organization and structure summaries are outlined below:

- **Section 2** describes the prize's support architecture, including training webinars, mentorship activities, and recruitment strategies designed to make participation accessible across skill levels.
- **Section 3** reviews administrative lessons learned from the prize's design and execution, with an emphasis on prize flexibility, engagement strategies, and event coordination.
- **Section 4** presents key technical findings from across all three phases, highlighting how DEEC-Tec understanding evolved, what challenges arose, and where opportunities remain.
- **Section 5** offers recommendations for advancing DEEC-Tec innovation within the marine energy sector, structured around near-, mid-, and long-term priorities.
- **Section 6** concludes with reflections on InDEEP's broader contributions—both technical and cultural—and outlines how the prize helped shape a foundation for future DEEC-Tec development.
- **Appendix A** gives supplemental details of InDEEP's recruitment strategy, emphasizing yet2's tech scouting and the effectiveness of personalized outreach over widely broadcasted generic announcements.
- **Appendix B** details the webinars and mentorship provided during InDEEP, covering wave energy, DEEC-Tec, structured innovation, technology performance level (TPL), and demonstration guidance.
- **Appendix C** describes the energy conversion types used in Phase II, individual DEEC prototypes, highlighting classification, performance validation, and key innovation strategies.
- **Appendix D** outlines Phase III DEEC-Tec metamaterial types, prize outcomes, and community-building efforts.
- **Appendix E** presents participant feedback emphasizing how InDEEP fostered innovation, structure, and collaboration, accelerating both technical and professional growth.
- **Appendix F** describes and showcases the Phase III poster session, where finalist teams showcased their projects, thereby enabling interaction, feedback, and peer recognition.
- **Appendix G** outlines InDEEP's digital engagement platforms, especially HeroX, and how they supported outreach, competition tracking, community-building, and recognition.
- **Appendix H** describes the American-Made program website, InDEEP's official hub for competition guidance, timelines, submissions, and innovation support.

[3] Wave Energy Scotland is a Scottish government initiative supporting the development and commercialization of wave energy technologies.

- **Appendix I** showcases InDEEP's presence on Challenge.gov.
- **Appendix J** lists InDEEP awardees from Phases I and II, detailing prize amounts, winning teams, and links to official announcements.
- **Appendix K** summarizes feedback from the Phase III Final Forum, highlighting participant insights, suggestions for future improvements, and prize winners.
- **Appendix L** outlines how InDEEP used iterative design tools like TPL assessments and the Theory of Inventive Problem Solving (TRIZ) to support innovation and technology refinement.

2 Support Architecture

To support broad and effective participation, InDEEP was built on a comprehensive, multi-modal support framework that guided teams from initial concept development through to functional prototyping. This structure was designed to be accessible to participants regardless of their prior experience with DEEC-Tec or federal innovation programs. Core resources included a series of live webinars covering key topics such as wave energy fundamentals, DEEC-Tec architecture, innovation methodologies, and performance evaluation tools like the TPL system (see Table B-2 and Appendix L for more information). Recordings of these sessions were made available for on-demand review, allowing teams to engage at their own pace. Detailed descriptions of these offerings can be found in Appendix B.

Participants also benefited from regular open office hours with domain experts (see Table B-1 for a listing of those experts), which allowed for real-time troubleshooting and technical guidance. In addition, the official InDEEP rulebook [17] functioned as a curated technical reference, providing access to datasheets, academic literature, and design guidelines. Teams frequently credited this combination of structured learning and expert mentorship as essential in navigating the interdisciplinary challenges of DEEC-Tec research and development.

Recruitment employed a two-pronged strategy: (1) broad digital outreach created initial awareness through DOE channels, and (2) personalized engagement—via direct emails, conference conversations, and then targeted follow-ups by the open innovation firm yet2. The personalized engagement proved significantly more effective in converting interest into applications. Indeed, survey data confirmed that most InDEEP finalists discovered the prize through personal referrals and trusted networks, emphasizing the value of relationship-driven outreach (see Figure A-2 for a visual overview of how teams discovered and learned about InDEEP).

As the prize advanced into the technical phases, several design and fabrication trends emerged:

Phase II: For individual DEEC developments, many teams pursued variable-capacitance and piezoelectric DEECs, ostensibly due to their relative simplicity, known (or trending) interest in the DEEC-Tec domain, and their availability of off-the-shelf components (especially true for piezoelectrics) [18] [19] [20]. However, these approaches typically delivered low power output relative to their induction-based DEEC counterparts. In that regard, less common but ultimately more promising mechanisms included induction, ionic, hydraulic, and hybrid systems. Nonetheless, these appeared to require more sophisticated fabrication and electronics but did offer greater inherent ability for energy conversion and electricity generation (see Appendix C for more information regarding individual DEECs).

Phase III: In assembling individual DEECs into DEEC-Tec metamaterials, most teams used straightforward structural formats such as adhesive layers and patchwork fabrics/layouts—likely selected for their simplicity and ease of fabrication. More advanced architectures, including origami-based folds, woven composites, and elastomeric lattices, appeared less frequently but appeared to exhibit greater promise for producing synergistic and more advantageous behaviors (see Appendix D for greater insights into DEEC-Tec metamaterial submissions).

The milestone-based funding model helped sustain engagement across all three phases:

- **Phase I** awarded $15,000 to each selected concept-stage team.
- **Phase II** awarded $80,000 to teams that demonstrated working individual DEEC prototypes.
- **Phase III** awarded $200,000 each to four top-performing teams (FluxMagic, Artimus Robotics, Pittsburgh Coastal Energy, and Water Bros Development) for their advanced DEEC-Tec metamaterial demonstrations.

While overall feedback from participants was positive, several operational improvements were identified:

- Give earlier access to teaming and collaboration tools (e.g., matchmaking platforms or shared workspaces).
- Enable faster disbursement of milestone funds.
- Provide a more clearly defined set of deliverable templates and expectations.

Moreover, participants expressed confusion about the "Leaderboard," a tool originally intended to incentivize engagement (e.g., InDEEP webinar attendance) with their specific concerns being centered upon the Leaderboard's scoring system not being clearly communicated, limiting its effectiveness [21]. A revised "Engagement Tracker" (in place of a Leaderboard) with automated team point tracking and aggregation is recommended for future prizes.

Despite these issues, InDEEP successfully filled a strategic gap in DOE's innovation portfolio by validating a subsystem-first approach with an aim toward future application in ocean wave energy developments. By focusing on modular DEECs and their DEEC-Tec metamaterial counterparts—rather than complete WEC system designs—the prize more effectively encouraged collaboration among experts from diverse fields not typically involved in WEC design, such as microelectromechanical systems (MEMS), fluid power, soft robotics, and materials science. These cross-domain interactions, often rare in traditional marine energy funding structures, were instrumental to the innovation and momentum generated by InDEEP.

Looking ahead, the following enhancements are recommended for similar future initiatives:

- More rigorous tracking of outreach and recruitment data
- Earlier integration of TPL checkpoints to guide technical maturity
- Strategic support for underrepresented but high-potential DEEC-Tec concepts
- Expanded post-prize mentoring to support commercialization and technology transfer.

Ultimately, InDEEP demonstrated that targeted support—paired with thoughtful program design—can help novel, small-scale energy technologies evolve into, first, an ecosystem of modular DEEC-Tec-based ocean wave energy solutions for low-power needs (e.g. power at sea, small scale electricity production for harbor services, and other niche low-power demanding efforts) and then, potentially, evolving into utility electric-grid-scale DEEC-Tec innovations and solutions.

3 Prize Results: Lessons Learned About Prize Design and Administration

The design of InDEEP (including its phased structure, participant support systems, Power Connector engagement, and culminating Final Forum) was intentionally crafted to align with the core objectives outlined in Section 1. By using a staged, milestone-based approach paired with targeted guidance, InDEEP lowered barriers to entry and fostered meaningful participation from a diverse range of solvers—many of whom, as already mentioned, were new to the marine energy sector altogether. Thus, this pay-for-performance model simplified the application process while providing incremental funding and technical support, increasing the success rate of participants across experience levels.

In alignment with its goal to attract innovators beyond the traditional wave energy community, InDEEP actively encouraged interdisciplinary participation. In this regard, the Power Connector, yet2, played a key role by conducting technology and market scans, developing detailed profiles of 35 promising DEEC-related innovations (see Figure 2 and Figure A-1 for a visual overview), and distributing surveys to better understand the needs and interests of potential applicants. These activities helped shape the prize's outreach strategy.

While yet2's efforts effectively identified new ideas, the data showed that sustained engagement from nontraditional sectors was limited—revealing an opportunity for improvement in future programs. Across all phases, however, integrated support through webinars, mentorship, engagement tools, and event programming created a cohesive and positive participant experience. The following subsections summarize key lessons learned to inform the design of future prize initiatives.

3.1 Adaptability Is Essential for Long-Term Support

One important lesson was the need to remain adaptable over the course of a multi-year prize. By committing early to a fixed set of support activities in the official rules document, the prize team limited its ability to adjust offerings in response to evolving participant needs or resource availability. Future prizes would benefit from maintaining flexibility in early-stage planning documents, allowing organizers to refine support mechanisms as the prize competition unfolds. This agility can improve both program delivery and participant outcomes.

3.2 Define Testing and Integration Requirements Early

In later phases, some teams would not likely meet NLR's testing and safety requirements if asked to demonstrate their concepts at NLR, which would have restricted their ability to demonstrate hardware on-site. Such constraints (e.g., facility-specific environmental, health, and safety protocols) were not communicated early enough to enable every team to showcase real-time, in-person demonstrations of their designs at NLR. As a result, InDEEP opted to rely solely on virtual demonstrations.

Additionally, while the open-ended nature of the design space was meant to encourage creativity, some participants expressed uncertainty over the lack of clear integration guidance. Future prize programs may benefit from introducing real-world constraints earlier, such as lab testing requirements or clearer baseline performance standards. Doing so can help teams align their designs with viable demonstration pathways without stifling innovation.

3.3 Developing Standard Operating Procedures for Final Events

The InDEEP Final Forum underscored the need for formalized standard operating procedures for organizing WPTO-sponsored events, particularly those held at national labs. Although the team had extensive experience with off-site venues, on-campus coordination at NLR presented unexpected challenges (especially in the post-COVID environment, where institutional policies had shifted). Creating standard operating procedures for both on-site and off-site prize events would streamline logistics, reduce last-minute planning burdens, and lower costs by avoiding duplicated effort. Such procedures would also help ensure consistent and professional experience for participants and stakeholders alike.

4 Technology Results: Lessons Learned About DEEC-Tec

Across all three phases of InDEEP, participants surfaced key technical insights that illustrate both the promise and the challenges of DEEC-Tec in marine energy applications. These lessons reflect how the field matured during the competition, thereby highlighting evolving design strategies, material considerations, integration challenges, and emerging areas for innovation.

1. **Emergent behaviors must be intentionally designed.** One of the most critical insights from Phase III was that emergent behaviors in DEEC-Tec metamaterials (such as coordinated deformation or tunable dynamic frequency response) do not occur by default. These properties must be deliberately engineered through the spatial, mechanical, and/or electrical interaction of the individual DEECs making up their corresponding DEEC-Tec metamaterial. Teams that merely combined individual DEECs without intentionally designing for emergent, system-level benefits—such as enhanced energy conversion through synergistic behaviors—often struggled to demonstrate the added value of their DEEC-Tec metamaterial designs.
2. **Comprehensive performance metrics are essential.** Many teams focused primarily on output voltage when evaluating their DEECs and/or DEEC-Tec metamaterials. However, voltage alone does not capture the full performance picture. Effective assessment requires additional metrics such as input mechanical energy, electrical current, electrical power output, efficiency, frequency response, and mechanical durability, to name a few. These should ideally be measured using standardized methods, such as long-duration cycling, load cell integration, etc.
3. **Piezoelectric materials present significant limitations.** While piezoelectric materials offered ease of use and solid-state simplicity, they consistently underperformed in key areas. Their challenges include low energy yield, susceptibility to charge leakage, packaging difficulties, and high cost. These issues limit their scalability and make it difficult and costly to integrate them into larger DEEC-Tec metamaterial systems.
4. **Power electronics must be integrated from the start.** Several promising DEEC designs fell short due to a lack of power conditioning components. For DEEC-Tec systems to be viable, mechanical-to-electrical conversion must be paired with appropriate electronics to condition, store, and deliver usable energy. It is preferable to integrate power electronics in the design stage to support emergent properties of a DEEC-Tec metamaterial rather than deferring until later development stages.
5. **Variable-capacitance-based DEECs are promising but scaling them to higher electrical power output remains a challenge.** Variable-capacitance DEECs aligned well with DEEC-Tec's modular ethos and appeared frequently across all phases [18] [20]. However, they exhibited low power output and suffered from durability issues related to dielectric materials. Some teams experimented with hybridizing these systems using electromagnetic or ionic mechanisms to boost overall DEEC performance, but high-power scalability would likely remain a hurdle to overcome.
6. **Hybrid energy conversion can enhance functionality.** Combining multiple energy conversion types (e.g., piezoelectric with capacitive, hydraulic with ionic, pneumatic with

induction) showed potential to improve electrical power output performance, responsiveness, and resilience. These hybrid DEECs may also offer redundancy at the DEEC component level. However, their complexity increases integration challenges and, likely, development costs, making them more difficult to scale without coordinated, cross-disciplinary, and thoughtful design approaches.

7. **How DEECs are arranged matters as much as what they do.** How DEECs are arranged spatially—through folding patterns, woven composites, or layered assemblies—has a major impact on energy harvesting and other performance metrics. Designs that actively shaped and transformed incoming energy (e.g., the energy from ocean wave motion) through origami-inspired folds or patchwork configurations, for example, often appeared to achieve better coupling between DEEC-Tec metamaterial mechanical deformation and energy conversion at the individual DEEC level, thus emphasizing the importance of thoughtful structural design of DEECs and corresponding DEEC-Tec metamaterials [22].
8. **WaveSPARC philosophy drove a shift to performance-first innovation.** The use of the WaveSPARC framework helped shift participant focus to measurable outcomes [12] [13] [14]. Rather than designing for broad conceptual goals, teams adopted a bottom-up approach—building testable, modular subsystems (individual DEECs) that could be iteratively refined and scaled into larger DEEC-Tec metamaterial architectures.
9. **Materials science played a central role in advancing DEEC-Tec innovation.** Teams that incorporated advanced materials—such as custom dielectrics, ionic gels, and shape-tunable elastomers—greatly broadened the range of possible designs. These materials enabled new ways to capture and convert energy, revealing creative pathways that traditional mechanical approaches had not yet explored.
10. **DEEC-Tec community of practice is emerging.** By the final phase of the competition, participants had begun to coalesce around a shared vocabulary, design considerations, and set of trade-offs (e.g., balancing individual DEEC responsiveness with corresponding DEEC-Tec metamaterial durability). This convergence signals the early formation of a community of practice with the potential to shape future research and collaboration in this still-nascent field of research and development of DEEC-Tec, especially as it pertains to marine energy applications.
11. **Power density remains a key limitation for several DEEC types.** Throughout all phases, achieving sufficient power density proved challenging—particularly for piezoelectric, variable-capacitance, and ionic DEECs, which typically lagged by one to three orders of magnitude compared with induction-based DEECs [19] [20]. Although using advanced materials (such as high-permittivity dielectrics) and higher operating voltages could theoretically improve performance, these methods remain technically demanding when targeting higher electrical power output densities. Consequently, lower–power-density DEECs and their associated DEEC-Tec metamaterials may be more appropriate for low-power applications—such as passive ocean sensing—rather than for utility-grid-scale energy generation.
12. **Cross-domain integration represents a key frontier for DEEC-Tec advancement.** Future progress will depend on innovation at multiple scales—both within individual DEEC mechanisms and conversion types, and across larger DEEC-Tec metamaterial

systems that incorporate them. A particularly promising direction emerging from InDEEP involves designing DEEC-Tec architectures that intentionally convert low-frequency ocean motion into higher-frequency mechanical or electrical inputs for individual DEECs. This approach would better align ocean wave energy frequencies with the optimal operating frequency ranges of different DEEC types and DEEC-Tec conversion technologies, marking an important next step for the field.

5 Recommendations for the Marine Energy Sector

InDEEP provided a valuable platform to explore not only novel DEEC-Tec technologies but also how structured innovation frameworks can support interdisciplinary, early-stage development through a prize competition. Insights gained from both the prize administration and technical outcomes point to a promising—though still emerging—pathway for DEEC-Tec as a contributor to the future of marine energy research and development. Rather than outlining a fixed roadmap, the following recommendations offer a flexible framework for advancing DEEC-Tec concepts across near-term, midterm, and long-term time horizons. These priorities emphasize the importance of system-level thinking, performance-driven evaluation, iterative development, and community engagement, particularly as DEEC-Tec technologies transition from conceptual prototypes to deployable systems.

A key lesson from InDEEP is that DEEC-Tec innovation must be evaluated holistically. Thus, progress depends not only on improving individual energy conversion mechanisms (the individual DEECs) but also on addressing underlying materials, sub-system integration strategies, control systems, and real-world deployment challenges (to name a few). Testing in increasingly realistic environments, refining evaluation metrics, and building cross-sector partnerships will be essential to future DEEC-Tec success.

5.1 Near-Term Priorities: Early DEEC-Tec Development Pathways and Applications

Building upon InDEEP's outcomes, the DEEC-Tec annual operating procedure research (see [3], [2], and [23]), general marine-energy stakeholder feedback, and WPTO's Powering the Blue Economy™ framework, the near-term (0–3 years) should concentrate on low-power, modular DEEC-Tec systems that can be laboratory tested quickly, generate compelling data, identify challenges, build collaborations, and win early buy-in from operators and funders [24]. These early use cases would provide accessible environments for prototyping, allow for cost-effective evaluations, and help validate fundamental design assumptions.

Key areas of focus for the near-term include (in no specific order):

- **DEEC-Tec metrics for design and readiness evaluation:** Develop and refine DEEC-Tec-specific evaluation metrics—such as power density, durability, system integration, and emergent properties scores—to guide iterative design and assess prototype maturity. These metrics should support consistent development practices tailored to the DEEC-Tec domain, enabling team-level self-assessment and strengthening shared understanding of DEEC-Tec concepts and readiness across the developer community.
- **Embedded electronics:** Reduce the need for external support hardware by integrating all essential DEEC-Tec electronics—e.g., power conditioning circuits, controllers, and sensor firmware—directly into each individual DEEC transducer and/or throughout a DEEC-Tec metamaterial.
- **Rapid prototyping & micro-pilot demonstrations:** Quickly advance DEEC-Tec subsystems, whether individual DEECs or DEEC-Tec metamaterials, through rapid prototyping and micro-pilot demonstrations, such as benchtop characterizations and/or wave-tank experiments. Prioritize original designs that uncover high-impact marine energy applications uniquely suited to DEEC-Tec technologies.

- **Durable, marine-grade packaging:** Develop adaptable, saltwater-tolerant encapsulants with anti-biofouling properties explicitly for DEEC-Tec systems—perhaps engineer such packaging and encapsulants to be intrinsic parts of individual DEECs and DEEC-Tec metamaterials—and validate through accelerated environmental and mechanical testing.
- **DEEC-Tec community development & collaboration infrastructure:** Support the continued growth of a connected, collaborative DEEC-Tec community by establishing shared platforms and events. This would include launching an open simulation and benchmarking toolkit, developing "DEEC-Tec Readiness Scorecards" for concept visibility, and hosting annual workshops that bring together researchers, funders, and regulators to exchange insights and align expectations of DEEC-Tec's possibilities.

This near-term roadmap aims to more greatly enable DEEC-Tec subsystem research, development, and deployment efforts to address key technical risks and build momentum toward larger-scale DEEC-Tec-based marine energy systems. Likewise, at this near-term stage, evaluations in laboratories (or, even, small-scale simulated marine environments) can help uncover valuable emergent behaviors in DEEC-Tec metamaterials and guide more effective co-design between DEEC-Tec subsystems (e.g., individual DEECs) and those full-system DEEC-Tec structures (e.g., DEEC-Tec metamaterials or composite DEEC-Tec structures made from multiple types of DEEC-Tec metamaterials). Moreover, when combined with standardized DEEC-Tec performance metrics and reliability protocols (e.g., DEEC-Tec Readiness Scorecards), this near-term approach could strengthen data-driven DEEC-Tec credibility for funders, certifiers, and other stakeholders—while also helping to unify the burgeoning DEEC-Tec community.

5.2 Midterm Priorities: Integration With Know WEC Designs

As DEEC-Tec systems mature into the midterm (4–6 years), DEEC-Tec technologies could serve to augment traditional wave energy converter (WEC) platforms or other general maritime structures—enhancing functionality without requiring full-system redesigns of the parent WEC or maritime structures. Thus, integration with existing marine concepts and structures offers a pragmatic path for real marine environment validation.

Key areas of focus for the midterm include (in no specific order):

- **DEEC-Tec modules for traditional WEC designs or maritime structures:** Develop standardized DEEC-Tec modules that are compatible with existing WEC designs or maritime structures, capable of enhancing (or giving) energy production and high-value features—such as embodied computing, structural health monitoring, and active antibiofouling—without requiring a complete redesign of the WEC's core power take-off system or altering the parent structure's primary function.
- **Smart mooring for ocean wave energy harvesting:** The mooring lines could offer a promising dual benefit: they can generate electrical power while simultaneously reducing peak mechanical loads on the structure it is attached to. This combination could appeal to both marine operations and WEC design engineers—by lowering maintenance demands and by reducing risk. In addition, these systems could demonstrate added value through improved energy yield, structural damping, robustness, and built-in distributed mooring load sensing.

- **Embedded hybrid control system:** Integrating DEEC-Tec with traditional WECs—via a dedicated DEEC-Tec-powered control system—could enable embodied computing for in situ active control of an entire WEC's PTO system. This would optimize energy conversion without relying solely on a WEC's PTO or external shore-power connected sources. By decoupling critical control functions from the main powertrain, this approach could enhance system reliability, support independent hotel loads, and provide valuable monitoring and resilience during extreme sea states or shore power outages—allowing the WEC to enter into, for example, a safe or survivable mode under DEEC-Tec powered control.
- **DEEC-Tec-powered sensor meshes and skins:** Self-powered DEEC-Tec sensor layers—applied as meshes or skins to structures—could enable continuous, battery-free monitoring of corrosion, fatigue, and cracking in offshore maritime structures. These systems could reduce maintenance demands, deliver real-time structural health data, and offer a scalable solution for predictive maintenance; being particularly valuable in remote, high-risk marine environments where safety and reliability are critical.

By focusing on "bolt-on" DEEC-Tec enhancements for existing marine energy systems and maritime structures, these mid-term research avenues offer a compelling, low-risk path forward. They aim to improve performance, reduce structural fatigue, and deliver valuable data—while demonstrating how DEEC-Tec can integrate seamlessly with current systems, thereby gaining support from developers, insurers, regulators, and coastal stakeholders without requiring completely new DEEC-Tec-based WEC designs and full system replacements.

5.3 Long-Term Priorities: Stand-Alone DEEC-Tec Systems

In the longer term (7–12 years), DEEC-Tec may evolve into a platform for stand-alone, scalable ocean wave energy conversion systems—even becoming suitable for grid connection consideration. However, achieving this vision will require breakthroughs in energy conversion efficiency, control integration, system durability, and manufacturing technologies.

Key areas of focus for the long-term include (in no specific order):

- **Scalable, low-cost manufacturing of DEEC-Tec components:** Highly scalable and low-cost manufacturing that can enable cost-effective, high-volume production of DEEC-Tec systems will be essential for bringing DEEC-Tec from lab to market. In this way, high-volume, inexpensive production methods would increase the likelihood of widespread DEEC-Tec adoption and could strengthen its value proposition compared to other renewable energy technologies.
- **Fully self-optimizing DEEC-Tec-based structures via embodied computing:** Fully integrated embodied computing with energy conversion—also known as AI-on-Structure—would enable self-optimizing marine energy systems that adapt in real time, without relying on bulky onboard hardware or remote control. This transformative approach may also attract interest from major funders such as DARPA, the Office of Naval Research (ONR), and autonomy researchers for its potential to redefine how ocean energy systems operate in dynamic environments and respond to mission demands automatically and with minimal energy usage for self-optimization per mode of desired operation.

- **Utility grid scale ready DEEC-Tec-based WECs:** Demonstrate that DEEC-Tec-based wave energy converters can safely and reliably connect to utility-scale power grids, meeting performance, safety, and power quality standards. Achieving grid compliance will be critical for securing the confidence of regulators, grid operators, certification bodies, and investors—and for positioning DEEC-Tec as a scalable renewable energy solution for powering coastal communities.
- **Hybrid DEEC-Tec platforms for multiuse infrastructure:** Integrate DEEC-Tec-based wave energy systems into coastal protection structures and aquaculture platforms to enable dual-purpose infrastructure that both harvests energy and enhances coastal resilience. This approach could support a global push toward multi-use marine assets and installations that could attract funding from energy sectors, disaster-risk reduction sectors, and infrastructure hardening sectors. It could especially be compelling for deployments at ports, near coastal cities, and for national security driven initiatives.

In this long-term vision, DEEC-Tec could evolve into a highly scalable platform for next-generation marine energy systems that could enable cost-effective growth through modular deployment and mass manufacturing. Its integration into marine vehicles, breakwaters, utility-grid systems, etc. would demonstrate broad utility, while the incorporation of AI via embodied computing could attract state-of-the-art research and funding beyond the traditional marine energy space. Clear milestones—such as utility-grid compliance and autonomous trials—would further build stakeholder confidence and help unlock new opportunities for DEEC-Tec's application into the marine energy domain.

5.4 Strategic Integration and Future Direction

The DEEC-Tec development pathway—progressing from low-power, modular subsystems to integrated hybrid systems and ultimately to stand-alone, grid-ready or fully autonomous platforms—reflects a deliberate strategy of staged innovation, de-risking, and cross-sector engagement. This phased approach, as emphasized throughout the InDEEP Prize and informed by stakeholder feedback and frameworks like WaveSPARC, enables both early market entry and long-term scalability.

To sustain momentum and guide future efforts, the DEEC-Tec community should:

- **Advance performance-first design principles**, applying frameworks such as WaveSPARC to connect techno-economic goals with system-level decision-making [12] [14];
- **Use fit-for-purpose evaluation metrics**, including readiness scorecards and standard benchmarks, to track maturity, reliability, and integration potential;
- **Remain adaptable** to evolving deployment scenarios, energy needs, and multiuse infrastructure opportunities across the blue economy or national security interests;
- **Leverage staged validation**, ensuring each DEEC-Tec subsystem or metamaterial evolve within real-world marine energy contexts.

Although the exact path forward will depend on emerging technologies and shifting market forces, InDEEP demonstrated the value of a broad, interdisciplinary foundation—spanning materials science, embedded systems, compliant structures, and control systems. Continued collaboration between public agencies, private innovators, national laboratories, and academic researchers will be essential to position DEEC-Tec as a transformative approach to next-generation marine energy conversion. This long-term strategic direction not only supports innovation across near-, mid-, and long-term horizons—it also lays the groundwork for future funding, coordination, and commercialization strategies that are flexible, scalable, and aligned with national energy, security, and resilience priorities.

6 Final Remarks

InDEEP served as a meaningful catalyst for advancing DEEC-Tec, moving the field from early conceptual exploration to the development of functional subsystem prototypes and proof-of-concepts. Through its structured, milestone-based approach, InDEEP emphasized subsystem innovation, interdisciplinary collaboration, and the intentional design of individual DEECs and corresponding DEEC-Tec metamaterial energy conversion systems. Over the course of the competition, participants explored a wide range of energy conversion mechanisms (individual DEECs), DEEC-Tec metamaterial architectures, and integration strategies that had not previously been prioritized in the marine energy sector. These contributions helped expand the design space for ocean wave energy conversion and revealed corresponding new opportunities for modular, scalable solutions.

By applying TPL metrics and WaveSPARC's performance-first framework, the prize encouraged teams to ground their designs in measurable outcomes [12] [13] [14]. This emphasis on bottom-up development fostered creativity in energy conversion methods, enabled novel hybrid configurations, and highlighted the importance of designing for adaptability and resilience. InDEEP also allowed participants to investigate a largely untapped set of engineering challenges—including how to intentionally design for emergent behavior, define complete energy pathways, and establish robust testing practices. These insights provide a foundation for future DEEC-Tec research and development. Beyond its technical achievements, the prize highlighted the power of a thoughtfully designed support structure. Flexible prize mechanics, sector scans, and tailored participant resources (such as mentorship, webinars, and reviewer feedback) lowered the barrier to entry and helped cultivate a diverse community of innovators. Indeed, this community has begun to coalesce around a shared vision for what DEEC-Tec can become.

Rather than delivering a complete solution, InDEEP helped seed a new research culture—one built around the modular integration of distributed embedded energy converters (individual DEECs) into coordinated DEEC-Tec metamaterial systems. This culture embraced open-ended innovation, cross-disciplinary thinking, and performance-based iteration as core values for advancing DEEC-Tec into the realm of ocean wave energy conversion and, more generally, marine energy systems at large. Ultimately, InDEEP demonstrated that well-structured prize competitions can drive both technical progress and community formation. The prize's outcomes offer a strong foundation for future DOE initiatives, private sector collaboration, and academic research focused on advancing DEEC-Tec as a viable and versatile solution for marine energy systems.

Glossary

DEEC-Tec	Distributed Embedded Energy Conversion Technology; a technology that integrates numerous small energy converters into materials or systems to harvest ambient energy.
DEEC	A single relatively small energy converter (also known as energy transducer), typically only a few centimeters in size, converts external sources of energy into electricity or another useful energy form (e.g., pressure-volume work).
DEEC-Tec metamaterial	A material system composed of many DEECs working synergistically to enable adaptable and distributed energy conversion.
InDEEP	Innovating Distributed Embedded Energy Prize; a DOE-sponsored prize competition to spur the development of DEEC-Tec systems for wave energy conversion.
TPL	Technology Performance Level; a scale used to assess the performance characteristics of technology; a scoring framework that lets early-stage marine-energy technologies be rated for maturity and commercial promise.
TRIZ	Theory of Inventive Problem Solving; a methodology for innovation that uses patterns of invention derived from global patent analysis.
TRL	Technology Readiness Level; A standardized scale for assessing the maturity of a technology from concept to deployment.
WaveSPARC	It is the U.S. Department of Energy's Systematic Process and Analysis for Reaching Commercialization; a performance-first methodology that couples techno-economic metrics with structured design iteration to guide ocean wave energy technologies toward market readiness. It emphasizes early, measurable energy-output benchmarks to accelerate progress toward cost-effective, commercial wave energy solutions.
WEC	An ocean wave energy converter; a device that captures and converts the energy of ocean waves into usable power.

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Appendix A. Support Architecture: Supplemental Information

The prize administration team implemented a multifaceted recruitment strategy, combining market scouting, targeted outreach, and digital amplification to attract participants from within and beyond the marine energy sector. A key partner in this effort was yet2, a global open innovation and technology scouting firm. yet2 conducted technology landscaping across more than 30 categories—including soft robotics, piezoelectrics, and dielectric elastomers—to identify novel technologies with potential relevance to DEEC-Tec. Figure A-1 gives a visual overview of those identified promising technologies with potential for InDEEP and DEEC-Tec applications.

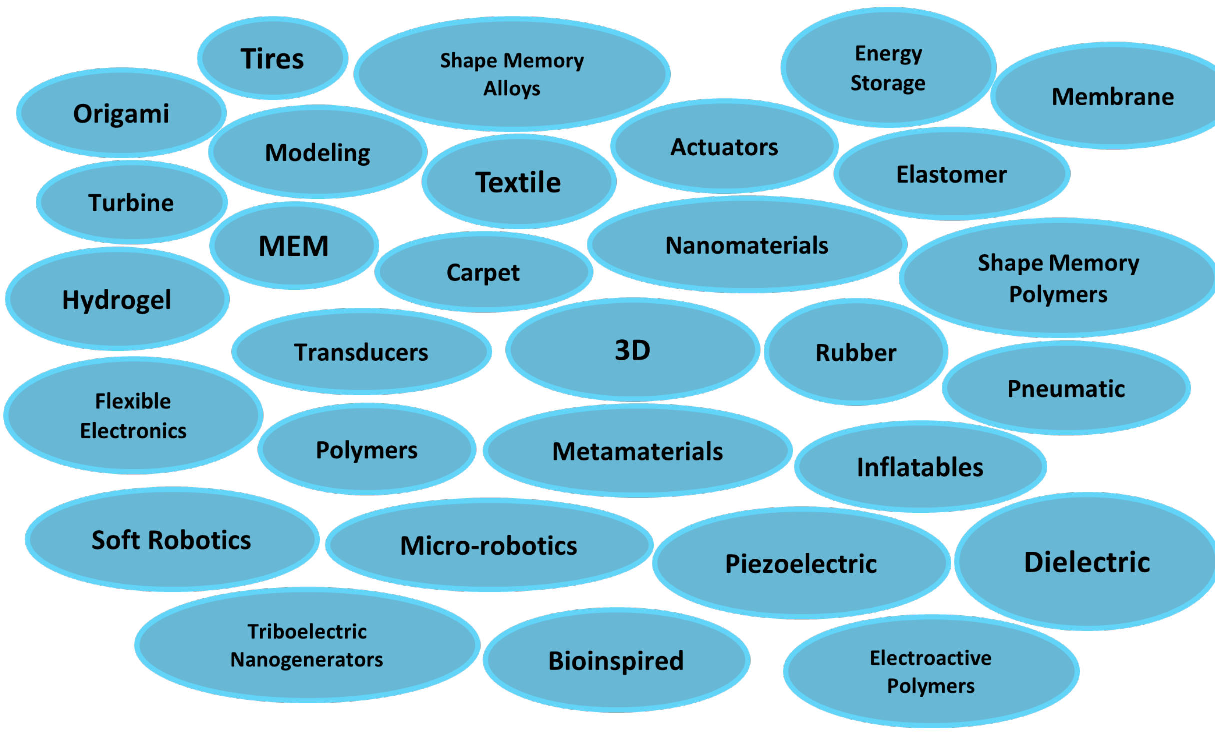


Figure A-1. yet2's identified promising technology domains with prize potential for DEEC-Tec.

Illustration by Blake Boren, NLR

In parallel, the prize team used established recruitment pathways, including social media announcements and newsletters through WPTO, NLR, and American-Made Challenges. Prize information was also shared via AmericanMadeChallenges.org and Challenge.gov—two centralized federal prize platforms [25]. However, based on competitor survey data, these channels did not significantly contribute to actual participant registrations. Most competitors cited hearing about the prize through direct communication from DOE, NLR, or Sandia National Laboratories, suggesting that personal and program-level outreach were more impactful than general listing platforms. This insight highlights a key lesson learned: while broad outreach channels can enhance visibility, conversion from awareness to participation is more likely when supported by trusted networks, clear value propositions, and timely, direct engagement. A general visual overview of how teams heard about the InDEEP challenge is shown in Figure A-2.

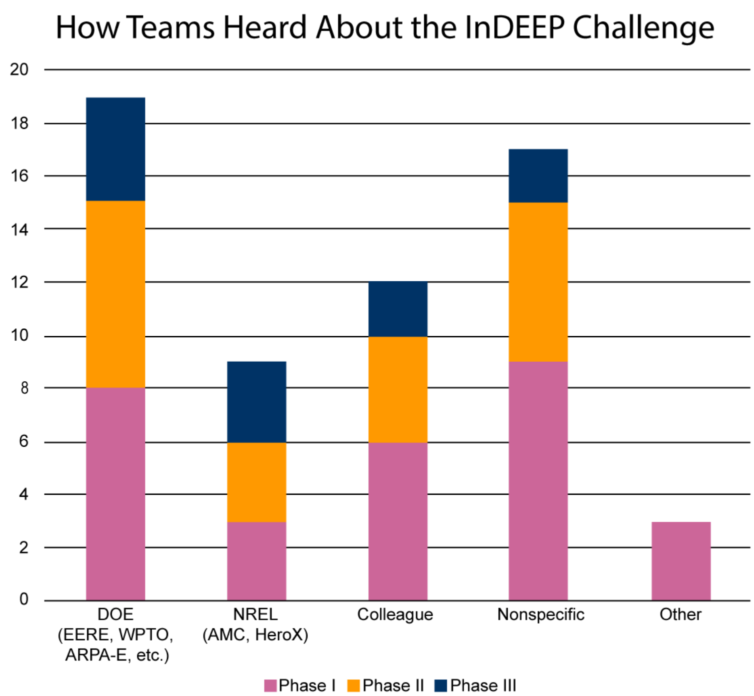


Figure A-2. Team responses by phase; in Phase I, the prize team used power connectors to boost recruitment. In Phase II, they relied on traditional outreach methods. No recruitment was done in Phase III, as it was closed to new competitors.

Figure by Blake Boren, NLR

Appendix B. Webinar and Mentorship Descriptions

The webinar topics covered the core thematic areas of the InDEEP competition. Each topic was tailored to a corresponding prize phase and designed to build upon earlier content while still adhering to its respective core thematic area—guiding teams toward successful prize submissions. Specific descriptions of the webinars—the core thematic areas—are given here:

Kickoff Webinars

Each prize phase began with a Kickoff Webinar that introduced competitors to the competition's structure, expectations, timelines, and support tools [9]. These sessions also included live Q&A, helping participants clarify questions about the rules, deliverables, and judging criteria [26] [27].

Ocean Wave Energy Webinars

These webinars provided foundational knowledge on ocean wave dynamics and marine energy system development [10], [11], [12]. Topics included wave motion principles, hydrodynamic forces, energy capture challenges, and historical technology evolution (e.g., Pelamis, Salter Duck) [28] [29] [30]. The sessions helped participants contextualize their DEEC-Tec designs within broader marine energy needs. While primarily targeting grid-scale concepts, they also touched on emerging opportunities within the blue economy—signaling a potential diversification of DEEC-Tec use cases.

DEEC-Tec Webinars

Focused on introducing the modular and scalable nature of DEEC-Tec, these sessions outlined the layered system architecture of DEECs and DEEC-Tec metamaterials [13], [14], [15]. While full WEC integration was outside the prize scope, the webinars helped teams understand how subsystems could eventually feed into broader marine energy solutions [31] [32] [33]. Topics included early DEEC concepts like variable capacitance devices and key design considerations such as compliance, redundancy, and adaptability [18] [19].

Structured Innovation Webinars

These sessions introduced TRIZ-based innovation strategies, including ideation tools and techniques for navigating technical contradictions. Participants were guided through defining functional needs, generating concept alternatives, and refining designs [34] [35] [36]. Although the TRIZ framework was covered earlier in the rules and technical training, these webinars expanded on its application to DEEC-Tec systems and encouraged structured experimentation. Additional information regarding TRIZ and other structured innovation techniques can be found in [16], [5], [17], [18], [19], [37], [38], [39], [40], and [41].

Technology Performance Level Webinars

The TPL webinars trained participants to use the TPL assessment framework—a tool developed by NLR to evaluate early-stage marine energy technologies across dimensions such as performance, durability, material risk, and manufacturability [20], [21]. While the web tool primarily targets grid-connected WECs, competitors were encouraged to use the framework as a reflective tool to align their concepts with long-term techno-economic goals [42] [43] [44]. Submission-specific guidance included documenting test plans, assessing recyclability, and evaluating design failure modes. Future competitions may benefit from defining the TPL framework earlier in program materials and contextualizing it with respect to the prize for greater clarity and utility. Additional information regarding TPL can be found in [6] and [7].

Demonstration Preparation Webinar

This session guided teams on how to effectively present their DEEC prototypes in virtual demonstrations [22]. It provided practical directions on structure (e.g., 30-minute presentation, 30-minute Q&A), storytelling, camera setup, and how to convey data validity through real-time explanation of methods, observations, and safety considerations [23] [45]. The session also reminded competitors to use feedback mechanisms and leaderboard data to improve submissions.

Access to Subject Matter Experts

InDEEP provided dedicated access to marine energy subject matter experts throughout all three phases. Ronan Costello (WaveVenture) and Kim Nielsen (Ramboll) hosted virtual mentoring sessions to support technical understanding and application of DEEC-Tec in wave energy environments; an overview of their mentorship is given in Table B-1.

Table B-1. Overview of InDEEP Mentorship

Phase	Competitors Attended	Support Provided
I	Ronan Costello – 19 Kim Nielsen – 3	Onboarding, teaming, scoping, orientation, rules clarification
II	Ronan Costello – 7 Kim Nielsen – 4	Wave energy mentoring, eligibility guidance, TPL and testing support, submission preparation
III	Ronan Costello – 5 Kim Nielsen – 3	System integration, performance refinement, submission preparation

As part of the Final Forum, competitors attended a half-day seminar on structured innovation techniques hosted by Dave Verduyn of the Innovation Tutorials Academy [46]. This session reinforced the structured innovation techniques introduced earlier in the prize and provided additional frameworks for concept generation, design refinement, and problem-solving. Methods covered by the seminar are given in Table B-2.

Table B-2. Structured Innovation Methods

Method	Description
"BrainWriting" 6-3-5	A structured group ideation format promoting parallel thinking
Attribute Dependency	A tool for exploring new product configurations by changing relationships between features
40 Inventive Principles (TRIZ)	A set of heuristics for solving technical contradictions
"PainStorming"	A method focused on identifying and solving user pain points
Separation Principles	Techniques for resolving conflicting system requirements
Trimming	A tool for eliminating unnecessary components to simplify designs

Appendix C. Phase II Information: Individual DEECs

At its core, an individual DEEC takes in one form of energy (usually mechanical) and converts it into another (typically electrical) [1] [2]. This conversion relies on specific conversion phenomena that each DEEC is designed to utilize [2]. These underlying fundamental mechanisms are what make each DEEC unique and understanding them is essential for evaluating their performance and potential. To better compare and analyze the different approaches, submitted DEECs were broadly categorized by the general type of energy conversion phenomena they employed. The main categories of these conversion phenomena, identified during the competition, are summarized in Table C-1.

Table C-1. DEEC Conversion Type

Energy Conversion Type	Description of Physical Phenomena
Variable-Capacitance	Mechanical energy is converted into electricity by physically changing capacitor electrode spacing, area, or capacitor's dielectric constant (effective dielectric values that could be varied and/or altered dynamically) [47] [48] [19]. Such actions change electrical capacitance, creating voltage variations that transform mechanical work into electrical energy [49] [50] [20].
Piezoelectric	Mechanical stress applied to certain crystals, ceramics, or polymers generates electricity [51] [52]. The mechanical strain shifts atomic structures within these materials, creating electrical voltage, allowing electricity generation from repeated or varying mechanical stressing of the piezo material [53].
Ionic	Mechanical forces drive ion transport around and/or through specially designed materials or membranes, causing charge separation [54]. This ion movement generates voltage differences and/or electric currents (often direct current), converting mechanical energy into electricity [55] [56].
Induction	Electricity is generated by moving conductive materials through magnetic fields, by changing magnetic fields around stationary conductors, or both [57] [58]. According to Faraday's law, this relative movement creates voltage potential from mechanical motions that can drive electrical current [59] [60]. For example, a rotating magnetic field in the presence of a conductor and electrical load, all things being equal, would generate an alternating electrical current.
Hydraulic	Mechanical energy is converted by applying pressure to move incompressible fluids through confined pathways, creating fluid flow and kinetic energy [61] [62] [63]. Hydraulic devices like motors or turbines use this fluid motion to power generators that can produce electrical energy [64] [65].
Pneumatic	Mechanical forces compress or direct pressurized gases (usually air) through valves or nozzles, producing flow and kinetic energy. Pneumatic turbines or motors capture this energy, driving generators to create electricity [66] [67].
Multiple Types; Hybrid	Some DEECs were explicitly designed to *simultaneously* utilize multiple types of energy conversion phenomena—such as variable capacitance with piezoelectric effects, ion transport with magnetic induction, or with hydraulic or pneumatic interactions with magnetostriction—to work

Energy Conversion Type	Description of Physical Phenomena
	together in converting external sources of energy into electrical power [68] [69] [70].

Figure C-1 presents a high-level, approximate overview of the different types of underlying DEEC conversion phenomena identified in all prize submissions regardless of prize phase. It visually compares the relative number of entries based on their DEECs' primary energy conversion type(s) employed, helping to illustrate common trends and the overall diversity of approaches.

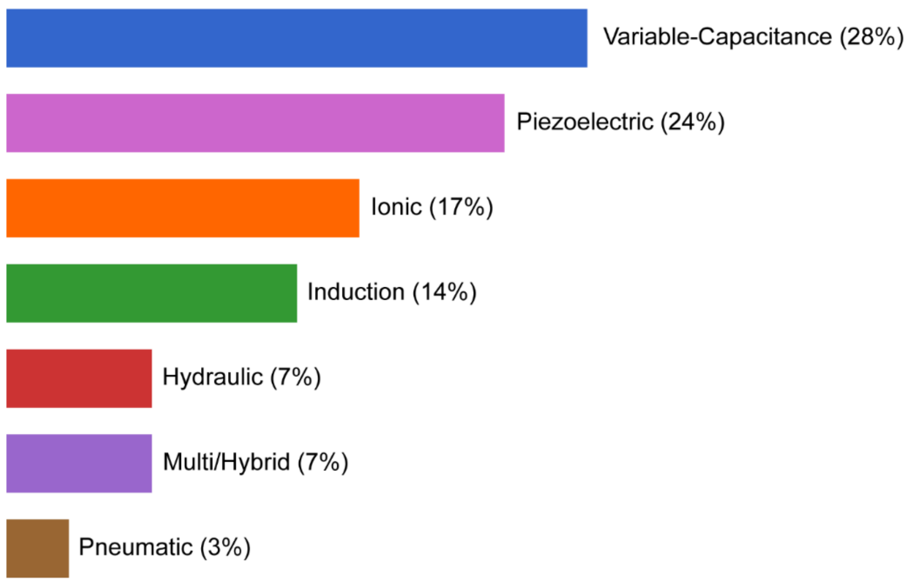


Figure C-1. Distribution of DEEC conversion types submitted across all three prize phases; each submission is counted once per phase. See Table C-1 for conversion-type definitions. Although entries span multiple mechanisms, variable-capacitance and piezoelectric DEECs dominate, suggesting future prizes may wish to incentivize exploration of less-represented modalities and examine the factors driving current preferences.

Figure by Blake Boren, NLR

Phase II advanced selected teams toward functional, tested DEEC prototypes. Fifteen teams progressed from Phase II, with live virtual demonstrations serving as a central component of the evaluation. These demonstrations validated DEEC operation and introduced quantitative performance metrics, including voltage output, power characteristics, and cycling durability. Innovation methods—such as TRIZ and Systematic Inventive Thinking—featured prominently in many successful submissions, illustrating how structured ideation supported prototype refinement. Technologies included single-mode and hybrid DEECs (e.g., combining piezoelectric and electrostatic elements), with several teams incorporating early DEEC-Tec metamaterial integration concepts. Non-selected teams often deviated from the prize's DEEC-centric focus or encountered significant technical hurdles. Lessons from this phase highlighted the value of structured mentoring, the importance of clear technical guidance, and the need to reinforce DEEC-Tec framing over a complete WEC system development.

Appendix D. Phase III Information: DEEC-Tec Metamaterials

Prize outcomes are also categorized based on the general type of DEEC-Tec metamaterial designed and implemented by the teams. DEEC-Tec metamaterials are essentially formed by combining individual DEECs together in ways that allow them to work together synergistically so that the overall performance of the resulting DEEC-Tec metamaterial ideally exceeds the sum of its individual DEEC parts [2]. The generalized architectures of DEEC-Tec metamaterials identified during the prize are given in Table D-1.

Table D-1. General Types of DEEC-Tec Architectures

DEEC-Tec Metamaterial Type	Description of Physical Phenomena
Adhesion to Substrate	A DEEC-Tec metamaterial made by attaching small DEECs to a (often flexible) surface/substrate, where each DEEC unit generates electricity as its corresponding substrate material deforms and/or moves relative to the substrate.
Embedding in Elastomer	A soft, flexible DEEC-Tec metamaterial created by embedding numerous small DEECs within a stretchable elastomer [6]. When the stretchable elastomer material bends, stretches, or twists due to motion, the embedded DEECs convert portions of that mechanical energy into electricity.
Lattice	A DEEC-Tec metamaterial made from many relatively small DEEC units arranged in a 2D or 3D lattice. The open structure could potentially flex, compress, and twist, with each DEEC located at a node or edge. As the lattice deforms, the DEECs interact and generate electricity through their respective mechanical response.
Flow Chambers	A DEEC-Tec metamaterial made of interconnected flow chambers, where each chamber either generates electricity directly (chamber is a DEEC itself, e.g., ionic flow and transport) or links multiple DEECs through fluid movement. Instead of relying solely on solid deformation, it uses fluid dynamics (pressure changes and internal flow) to activate energy conversion.
Origami	A DEEC-Tec metamaterial made of DEECs that arrange and enable origami folds and patterns. As the structure folds, bends, or flexes in response to motion, the geometry activates energy conversion via the DEECs making up its origami structure [22].
Patchwork	A DEEC-Tec metamaterial made of individual DEEC patches, each with possibly unique energy-converting properties, joined into a fabric-like system. Like a patchwork quilt, together the individual DEECs form a unified system or surface that harvests and converts energy in a distributed patchwork manner.
Woven	A DEEC-Tec metamaterial made by weaving threads that act as individual DEECs (or a series of individual DEECs) into a fabric-like structure. Each strand could, potentially, use a different energy conversion type, and together create a woven system that could bend, stretch, and/or deform while generating electricity with coordinated performance.

Figure D-1 provides a high-level, approximate breakdown of the different general types of DEEC-Tec metamaterials submitted to the prize. It illustrates the relative number of entries that followed each DEEC-Tec metamaterial design approach, offering a visual summary of the overall distribution across the various categories.

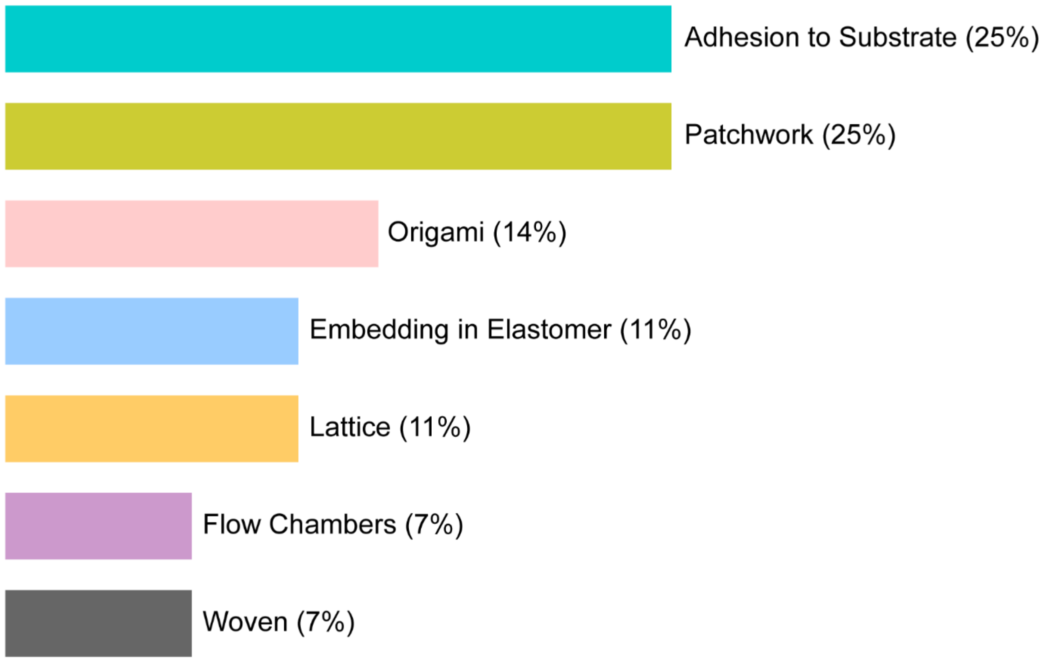


Figure D-1. Distribution of DEEC-Tec metamaterial architectures submitted across all three prize phases; each submission (or referenced concept) is counted once per phase. See Table D-2 for DEEC-Tec metamaterial descriptions. Although DEEC-Tec metamaterial designs spanned several categories, "adhesion-to-substrate" and "patchwork" approaches dominate, suggesting future work should encourage exploration of less-represented metamaterial strategies and/or examine why certain DEEC-Tec architectures are currently preferred.

Figure by Blake Boren, NLR

The final phase, Phase III, culminated in the successful demonstration of working DEEC-Tec metamaterials. Of the 11 finalists, four teams were awarded top prizes: FluxMagic, Artimus Robotics, Pittsburgh Coastal Energy, and Water Bros Development. Their submissions demonstrated creative integration of individual DEECs into scalable, modular architectures with potential applicability across marine energy systems. Review criteria prioritized not only technical merit and prototype validation but also scalability, manufacturability, and alignment with sector needs such as autonomous ocean sensors and blue economy applications. Seven other teams earned honorable mentions for conceptual advances, creative architecture, and strong technical execution. The Phase III in-person Final Forum brought all finalists together for the first time, supporting peer exchange, mentorship, and community-building—hallmarks of the prize's broader impact.

Appendix E. Participant Comments

Throughout InDEEP, participants reported that the competition significantly influenced the advancement of their technologies, offering both structure and motivation to refine their various concepts. In this way, the prize not only provided technical resources and validation opportunities, but also fostered creativity, collaboration, and real-world readiness. The following quotes highlight how competitors experienced meaningful innovation and personal/team growth as a direct result of their participation.

> "For me [the best part is] seeing who else is working on this technology. It's still a nascent field, and I think our approach and some of the other teams' approach, they're all achieving the same objective but they're very different in how they go about it. Being able to interface with some of those folks and learn what they've done and where they came from and how they intend to take it forward has given us insights into that community that exists that we otherwise probably wouldn't have been involved in." – Anonymous Competitor

> "Doing research is something different, you are not challenging someone. Here, we are competing with similar field researchers. In the very first phase there were like 50 teams, and now in the Final Forum there are 11 teams. It means that the idea we worked on has potential. We know that if we work hard we can get something better out of [our tech] that will help us to improve our environment." – Anonymous Competitor

> "Being in a room here with lots of people who are enthusiastic about the same kind of fields, even with disparate technologies, has been really interesting and good." – Anonymous Competitor

> "Meeting all the other competitors as part of the Final Forum has been brilliant. It's our first time we've really met with any of them and there's been some really good chats and it's been good interacting with them. So that's probably been, at the very final stage, probably my favorite moment." – Anonymous Competitor

> "This has really helped define the process of how to get [our tech] out into the market." – Anonymous Competitor

> "InDEEP has definitely given us more perspective on what we need to do to mature the technology to get it ready to go to a marine environment. There were developments happening already in the lab…but this helps to focus the attention on changing the parameters and approving the parameters that matter." – Anonymous Competitor

> "First and foremost, [the best part was] meeting new people. Not only from different institutions and universities, but I think the best part was bringing together different team members, like 'Dr. X' and 'Dr. Y,' as a team. The relationship within the team was a close-knit and valuable experience for me." – Anonymous Competitor

"Being in the marine energy space, it attracts a certain type of researcher, because it's a harsh environment. So, seeing other people that are bold enough to take a shot at putting a device in the ocean and then making electricity…those are fun people to be around." – Anonymous Competitor

"InDEEP is bringing out some technologies that haven't been aggressively considered before for marine energy. So it's another possible solution. It's an innovative or disruptive way to approach the problem. I'll be curious to see if any of those get traction where other technologies may have faltered." – Anonymous Competitor

"Getting to actually know people that are also trying to solve similar problems allows us to borrow techniques and collaborate where we can." – Anonymous Competitor

"I really like the collaborative nature that these events tend to bring about in a space that tends to be overly competitive where maybe it doesn't need to be." – Anonymous Competitor

"One of the good things about participating was that…you know it's a competition and you don't get to share a lot…but everyone being in this wave energy generating field, I actually felt that it was a whole single team." – Anonymous Competitor

"Working with the tech so you can actually have a demo rather than just running some tests, thinking about how you're putting it together to be able to show it to somebody, was something we wouldn't have done without the prize, and that's been useful." – Anonymous Competitor

"The prize money from Phase 2 has really allowed us to start to integrate our technology into real world situations, like underwater, which are some unique challenges. It's given us an opportunity to really push the boundaries of the application space for our technology." – Anonymous Competitor

"For me, it's been an opportunity to get very creative with our technology. It's been really fun to look at our technology under a different lens and figure out the technical issues and hurdles that can also be applicable to robotic systems that we're working on. It's been a great opportunity for creativity." – Anonymous Competitor

Appendix F. Final Event: Poster Session

The final event poster session featured teams that advanced to Phase III of the InDEEP competition, providing them with a platform to present their projects through written descriptions, visuals, and brief team bios. This interactive poster session format allowed reviewers, peers, mentors, and prize administrators to engage directly with InDEEP participants, ask questions, and explore each project's ideas and approach. The session fostered open dialogue, networking, and recognition of the teams' efforts and achievements. Phase III team posters (scaled down) are displayed in this section, in no particular order.

F.1 Condensed Wave Matter

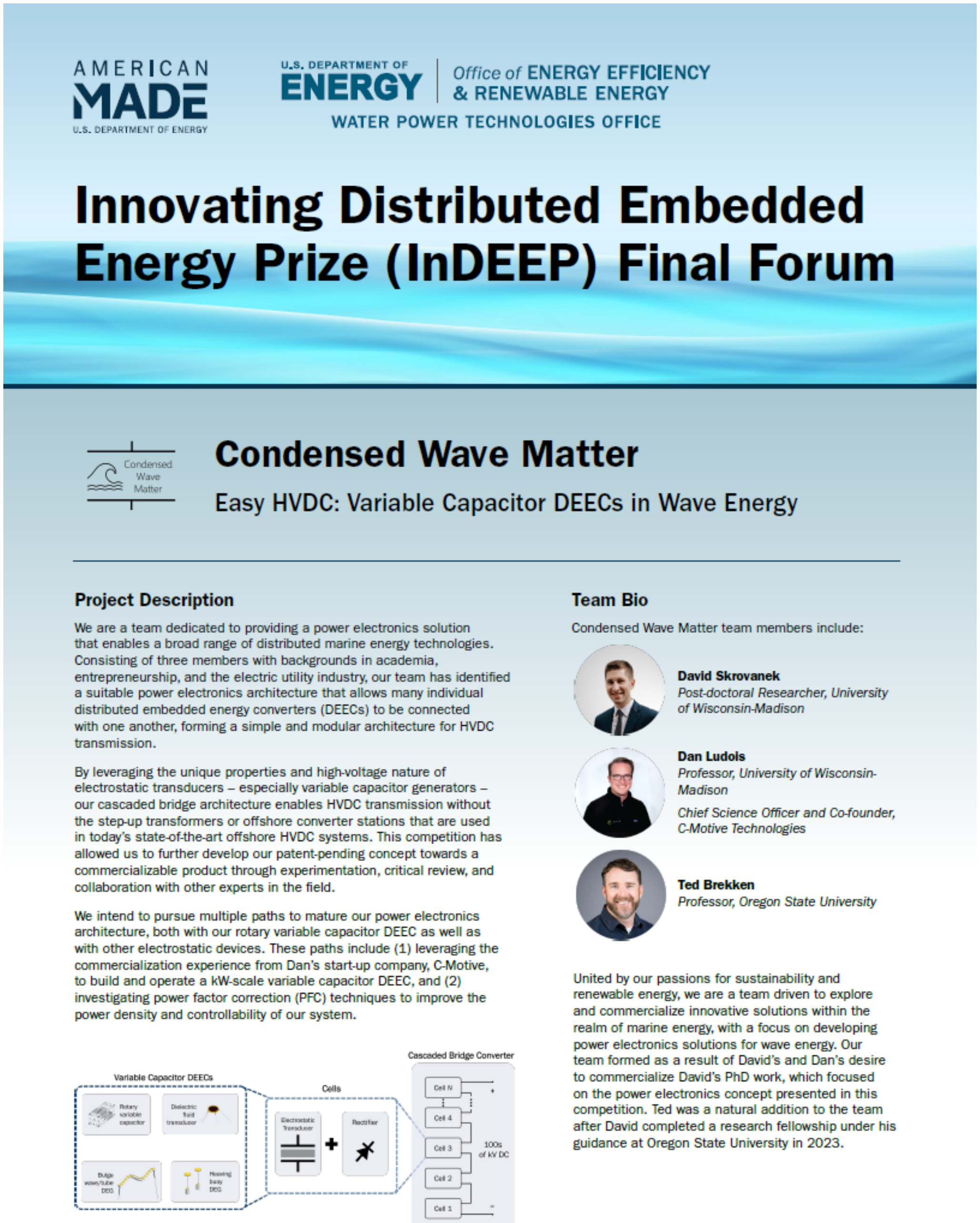


Figure F-1. Phase III Poster Session; Condensed Wave Matter Poster

F.2 EBB-FLOW

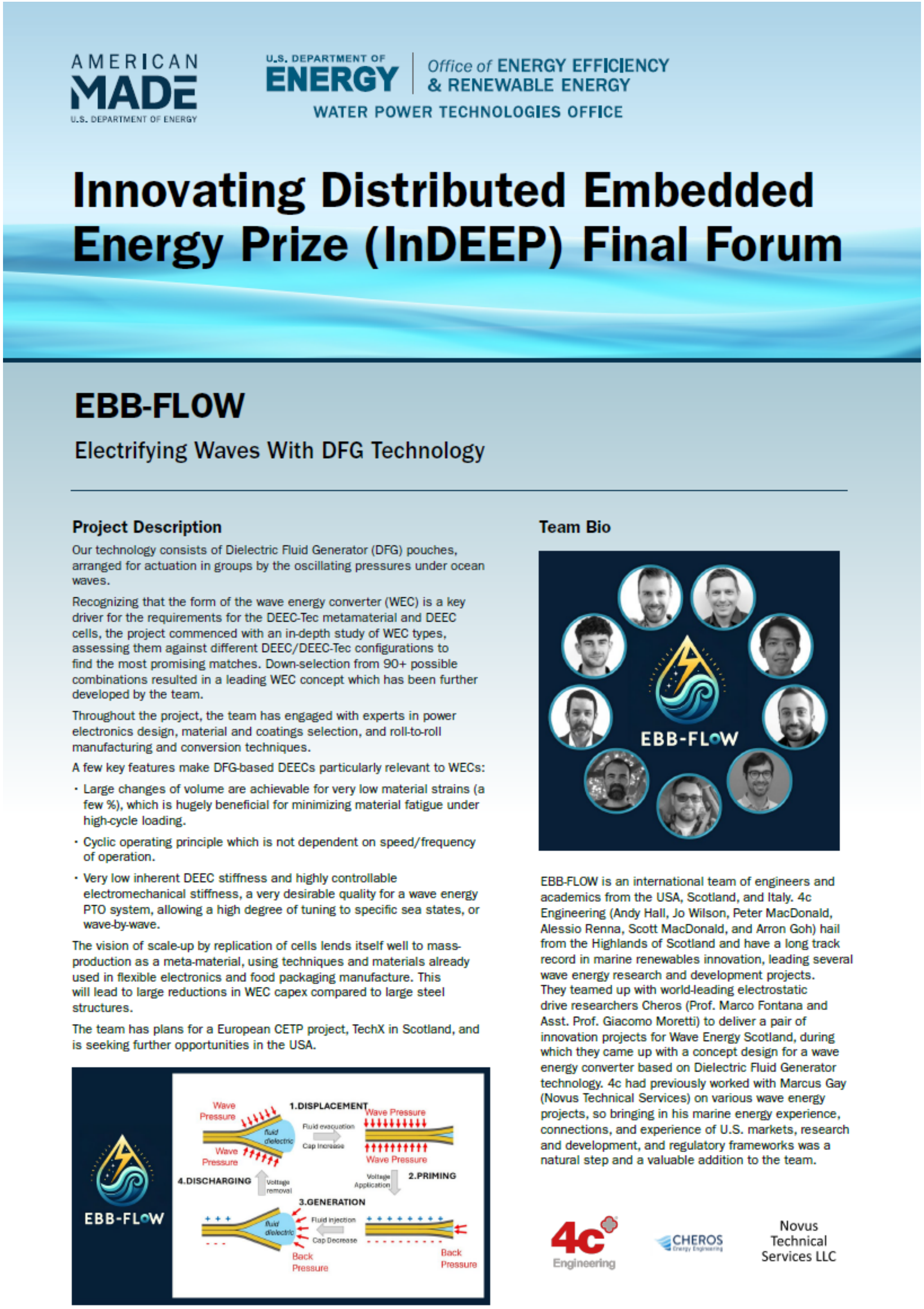


Figure F-2. Phase III Poster Session; Ebb-Flow Poster

F.3 PECWEC

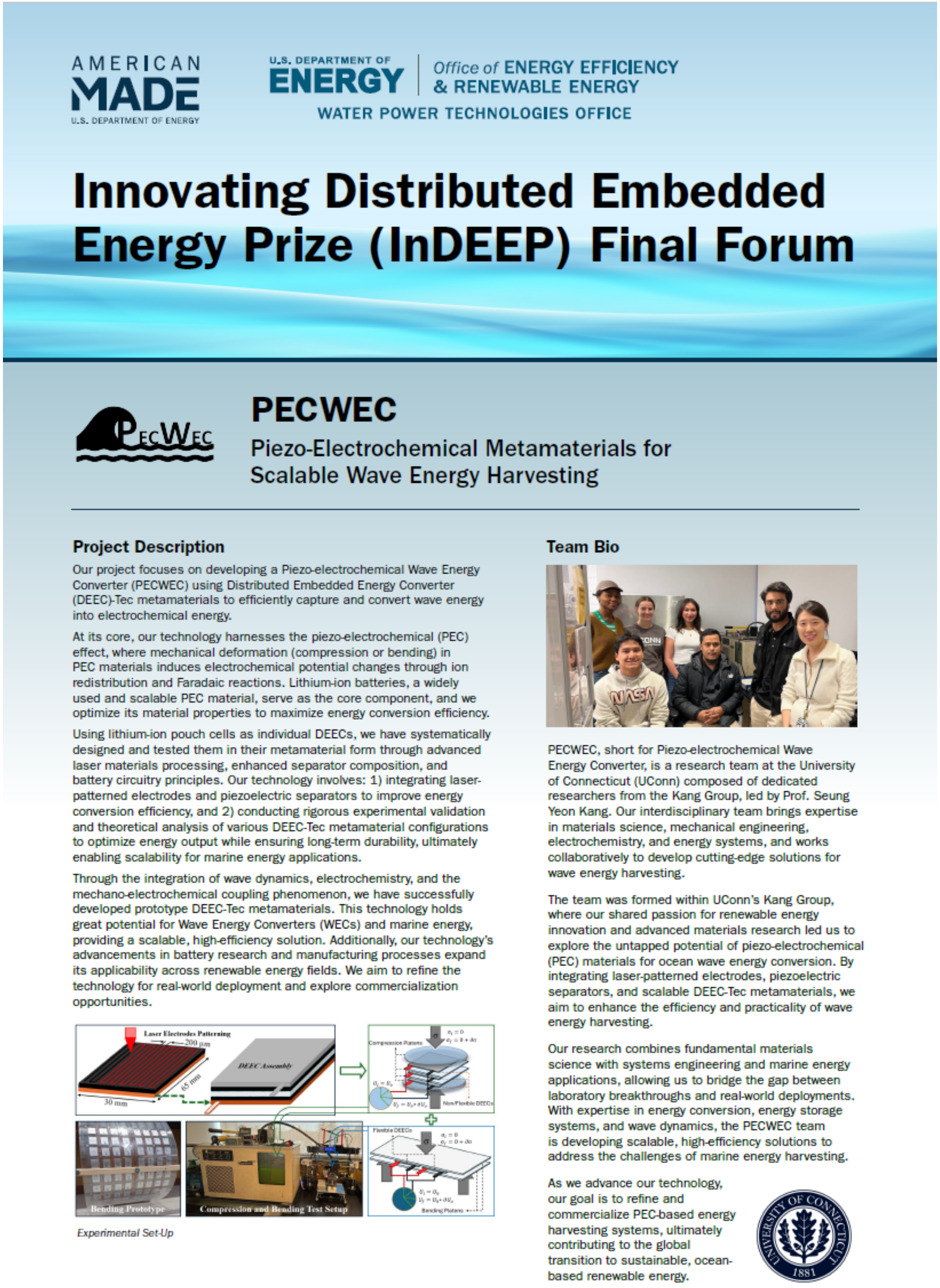
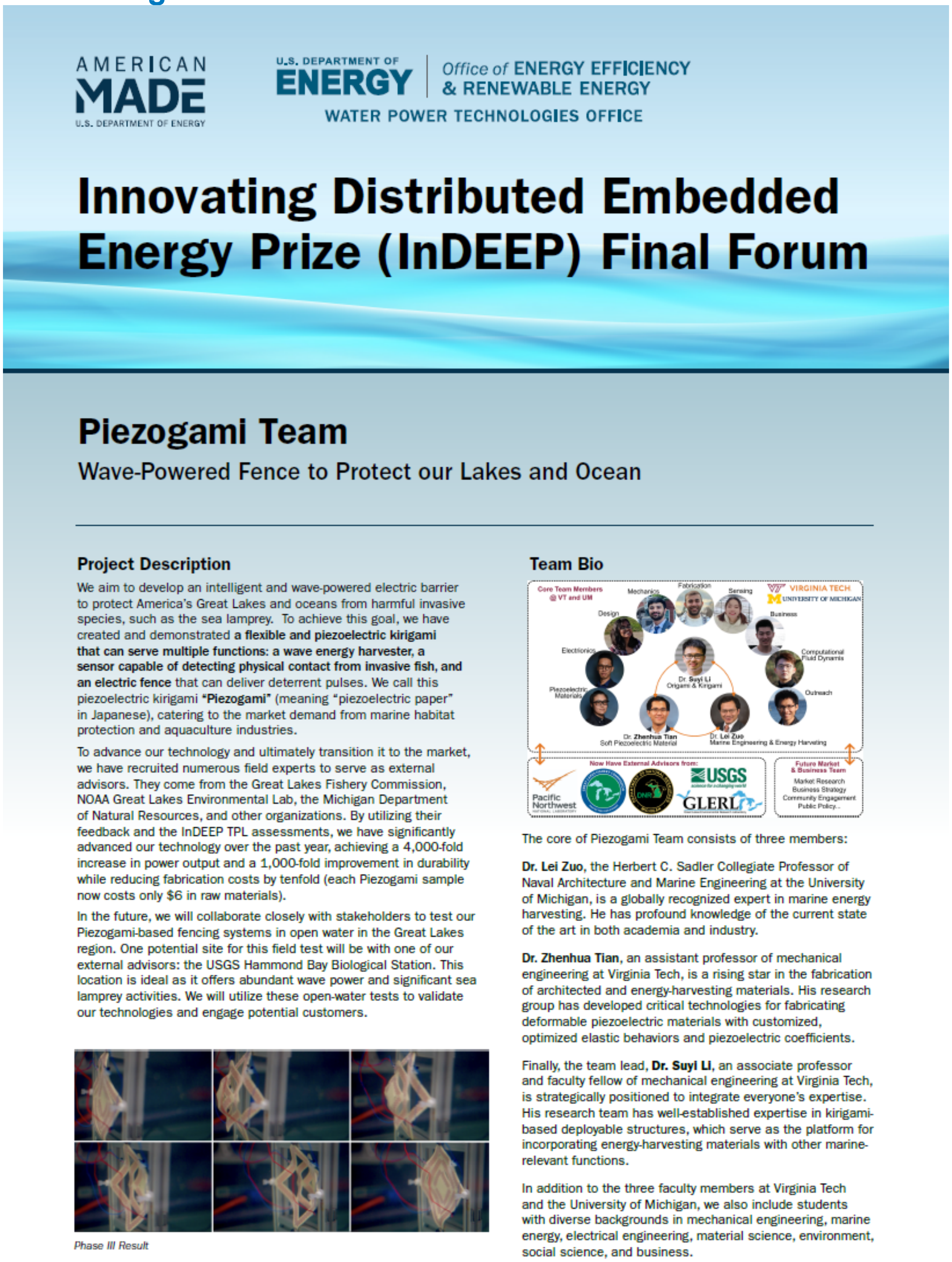


Figure F-3.Phase III Poster Session; PECWEC Poster

F.4 Piezogami Team



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WATER POWER TECHNOLOGIES OFFICE

Innovating Distributed Embedded Energy Prize (InDEEP) Final Forum

Piezogami Team

Wave-Powered Fence to Protect our Lakes and Ocean

Project Description

We aim to develop an intelligent and wave-powered electric barrier to protect America's Great Lakes and oceans from harmful invasive species, such as the sea lamprey. To achieve this goal, we have created and demonstrated **a flexible and piezoelectric kirigami that can serve multiple functions: a wave energy harvester, a sensor capable of detecting physical contact from invasive fish, and an electric fence** that can deliver deterrent pulses. We call this piezoelectric kirigami **"Piezogami"** (meaning "piezoelectric paper" in Japanese), catering to the market demand from marine habitat protection and aquaculture industries.

To advance our technology and ultimately transition it to the market, we have recruited numerous field experts to serve as external advisors. They come from the Great Lakes Fishery Commission, NOAA Great Lakes Environmental Lab, the Michigan Department of Natural Resources, and other organizations. By utilizing their feedback and the InDEEP TPL assessments, we have significantly advanced our technology over the past year, achieving a 4,000-fold increase in power output and a 1,000-fold improvement in durability while reducing fabrication costs by tenfold (each Piezogami sample now costs only $6 in raw materials).

In the future, we will collaborate closely with stakeholders to test our Piezogami-based fencing systems in open water in the Great Lakes region. One potential site for this field test will be with one of our external advisors: the USGS Hammond Bay Biological Station. This location is ideal as it offers abundant wave power and significant sea lamprey activities. We will utilize these open-water tests to validate our technologies and engage potential customers.

Phase III Result

Team Bio

The core of Piezogami Team consists of three members:

Dr. Lei Zuo, the Herbert C. Sadler Collegiate Professor of Naval Architecture and Marine Engineering at the University of Michigan, is a globally recognized expert in marine energy harvesting. He has profound knowledge of the current state of the art in both academia and industry.

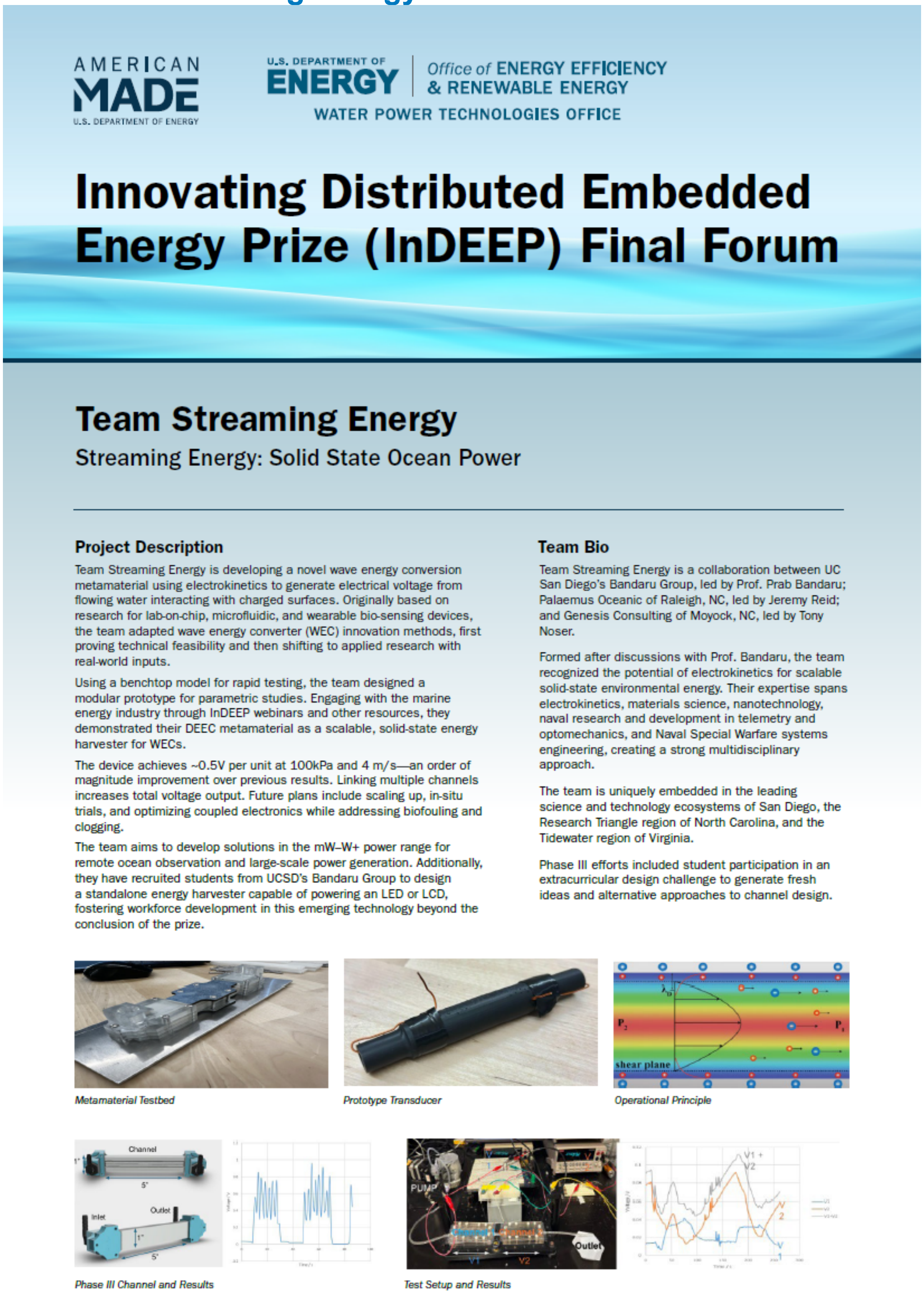
Dr. Zhenhua Tian, an assistant professor of mechanical engineering at Virginia Tech, is a rising star in the fabrication of architected and energy-harvesting materials. His research group has developed critical technologies for fabricating deformable piezoelectric materials with customized, optimized elastic behaviors and piezoelectric coefficients.

Finally, the team lead, **Dr. Suyi Li**, an associate professor and faculty fellow of mechanical engineering at Virginia Tech, is strategically positioned to integrate everyone's expertise. His research team has well-established expertise in kirigami-based deployable structures, which serve as the platform for incorporating energy-harvesting materials with other marine-relevant functions.

In addition to the three faculty members at Virginia Tech and the University of Michigan, we also include students with diverse backgrounds in mechanical engineering, marine energy, electrical engineering, material science, environment, social science, and business.

Figure F-4. Phase III Poster Session; Piezogami Team Poster

F.5 Team Streaming Energy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WATER POWER TECHNOLOGIES OFFICE

Innovating Distributed Embedded Energy Prize (InDEEP) Final Forum

Team Streaming Energy

Streaming Energy: Solid State Ocean Power

Project Description

Team Streaming Energy is developing a novel wave energy conversion metamaterial using electrokinetics to generate electrical voltage from flowing water interacting with charged surfaces. Originally based on research for lab-on-chip, microfluidic, and wearable bio-sensing devices, the team adapted wave energy converter (WEC) innovation methods, first proving technical feasibility and then shifting to applied research with real-world inputs.

Using a benchtop model for rapid testing, the team designed a modular prototype for parametric studies. Engaging with the marine energy industry through InDEEP webinars and other resources, they demonstrated their DEEC metamaterial as a scalable, solid-state energy harvester for WECs.

The device achieves ~0.5V per unit at 100kPa and 4 m/s—an order of magnitude improvement over previous results. Linking multiple channels increases total voltage output. Future plans include scaling up, in-situ trials, and optimizing coupled electronics while addressing biofouling and clogging.

The team aims to develop solutions in the mW–W+ power range for remote ocean observation and large-scale power generation. Additionally, they have recruited students from UCSD's Bandaru Group to design a standalone energy harvester capable of powering an LED or LCD, fostering workforce development in this emerging technology beyond the conclusion of the prize.

Team Bio

Team Streaming Energy is a collaboration between UC San Diego's Bandaru Group, led by Prof. Prab Bandaru; Palaemus Oceanic of Raleigh, NC, led by Jeremy Reid; and Genesis Consulting of Moyock, NC, led by Tony Noser.

Formed after discussions with Prof. Bandaru, the team recognized the potential of electrokinetics for scalable solid-state environmental energy. Their expertise spans electrokinetics, materials science, nanotechnology, naval research and development in telemetry and optomechanics, and Naval Special Warfare systems engineering, creating a strong multidisciplinary approach.

The team is uniquely embedded in the leading science and technology ecosystems of San Diego, the Research Triangle region of North Carolina, and the Tidewater region of Virginia.

Phase III efforts included student participation in an extracurricular design challenge to generate fresh ideas and alternative approaches to channel design.

Metamaterial Testbed

Prototype Transducer

Operational Principle

Phase III Channel and Results

Test Setup and Results

Figure F-5. Phase III Poster Session; Team Streaming Energy Poster

F.6 Water Bros Development

Figure F-6. Phase III Poster Session; Water Bros Poster

F.7 WaveHarvest

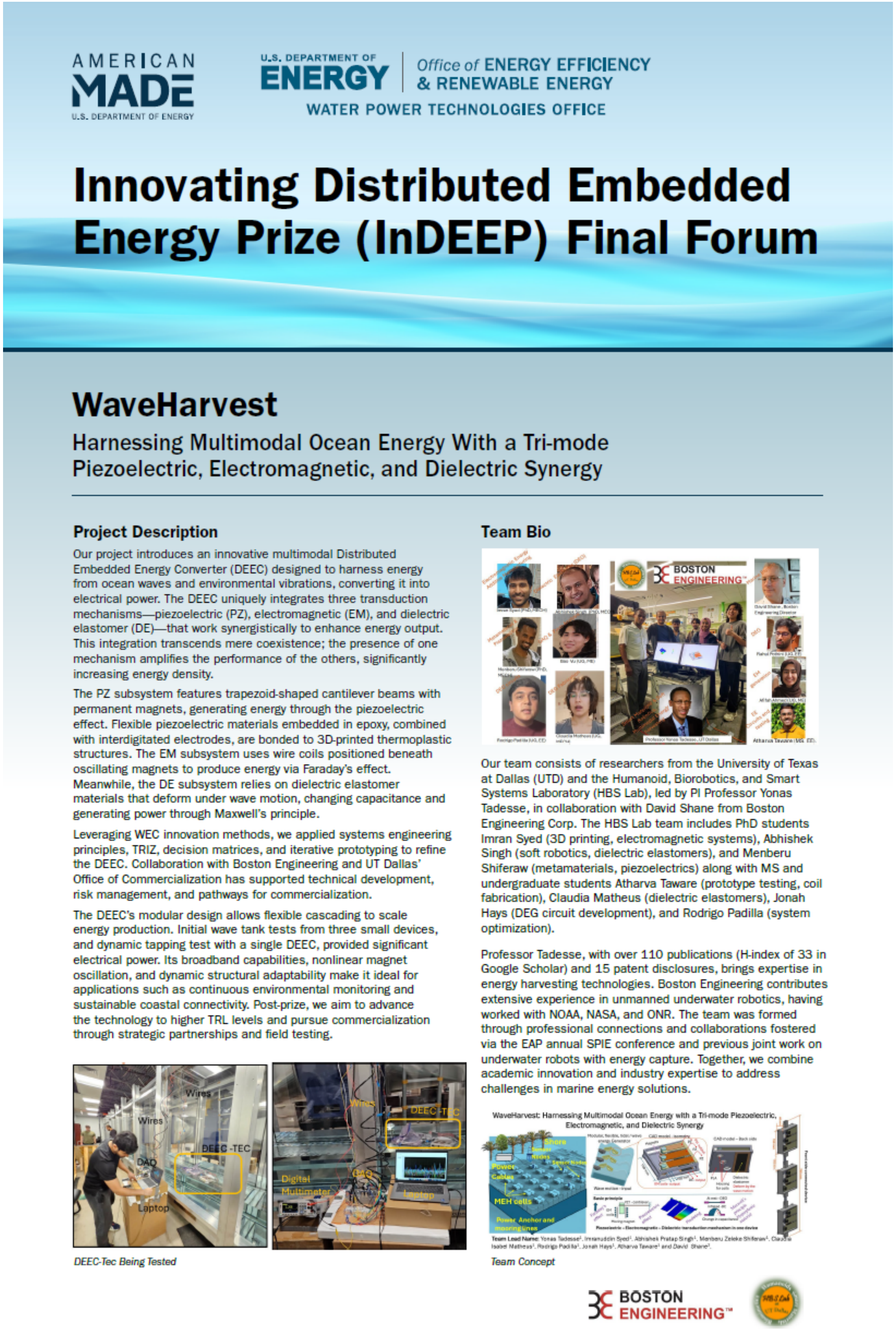

Figure F-7. Phase III Poster Session; WaveHarvest Poster

F.8 Pittsburgh Coastal Energy

Figure F-8. Phase III Poster Session; Pittsburg Coastal Energy Poster

F.9 Soft Energy

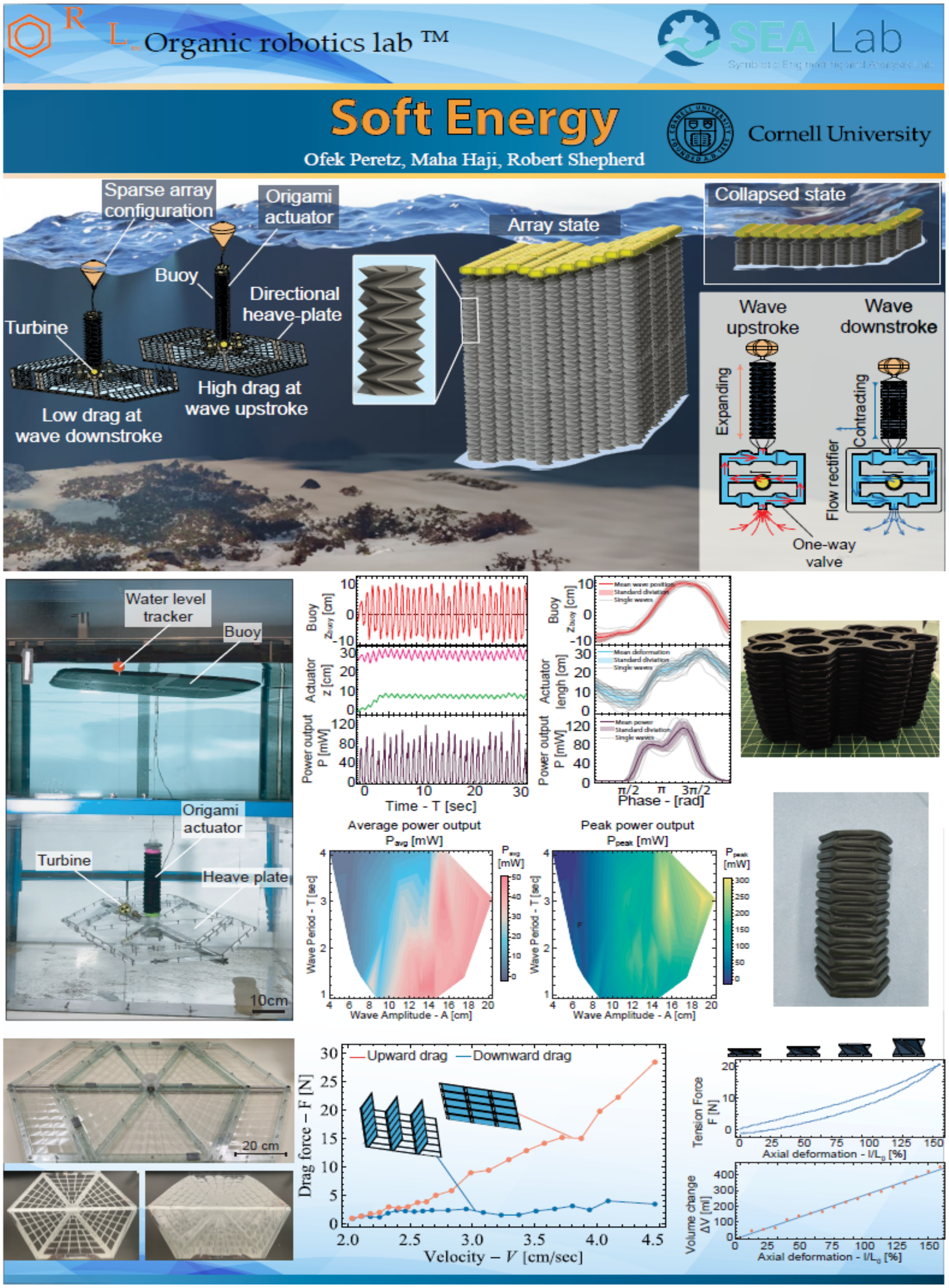

Figure F-9. Phase III Poster Session; Soft Energy

Appendix G. Engagement Platforms

Engagement platforms are digital tools that facilitate easier connections and collaboration among organizers, competitors, reviewers, mentors, and the public. In InDEEP, these platforms supported every stage of the prize, from design and registration to submissions, communication, community-building, and data-driven evaluation. The sections below highlight the key platforms used and their role in supporting InDEEP's success.

G.1 HeroX

HeroX is a global crowdsourcing platform that connects problem solvers with prize-based innovation challenges. It offers easy-to-use tools for designing, managing, and evaluating competitions and has supported organizations like NASA and the DOE. For InDEEP, HeroX (https://www.herox.com/indeep) helped showcase the prize's international reach; drawing 370 followers from six continents (Figure G-1).

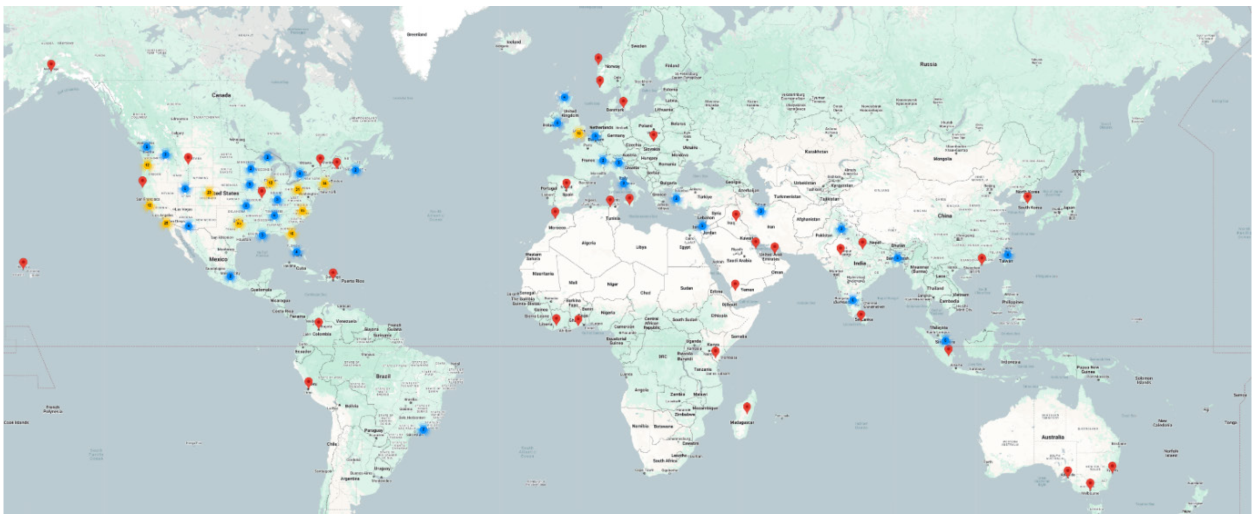

Figure G-1. HeroX map of 370 InDEEP followers (as of 10 April 2025).

HeroX supported the creation of a dedicated Winners Page on the InDEEP site to showcase competition results. This page highlights the winning teams from each phase; Phase I winners are shown in Figure G-2, and Phase II winners are shown in Figure G-3. The Winners page provided a central, public space to celebrate and promote the achievements of InDEEP's top competitors.

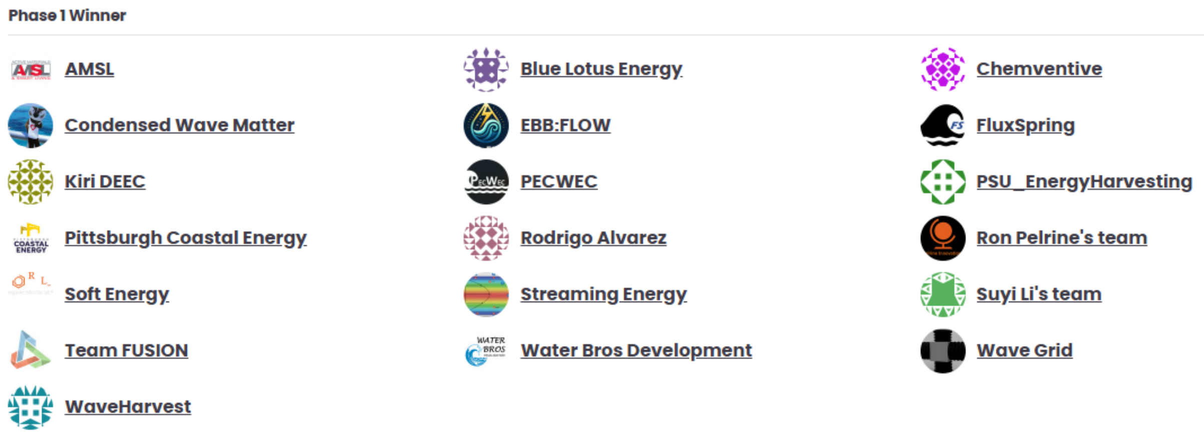

Figure G-2. InDEEP Phase I winners [71].

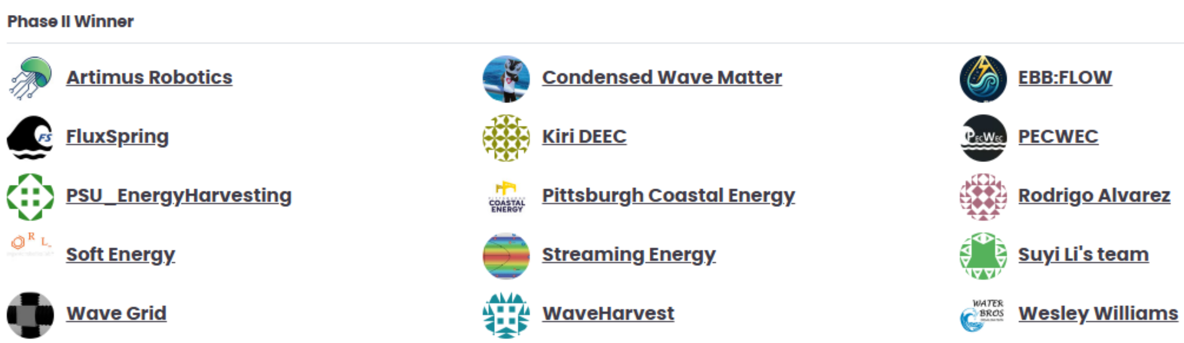

Figure G-3. InDEEP Phase II winners [71].

The HeroX platform included Leaderboards that let InDEEP teams see how they ranked during each phase. These boards showed real-time or periodic standings based on specific engagement activities, helping motivate teams and track progress. For example, in Phase II, the Leaderboard awarded up to 15 bonus points for completing tasks listed in the prize rules. Tables G-1 to G-3 display the Leaderboards for Phases I, II, and III, respectively. Overall, this feature promoted transparency and helped sustain team engagement throughout the competition.

Table G-1. Phase I Leaderboard

Instance	Leader	Status
1	Pittsburgh Coastal Energy	11 Points
2	CannGraphene, LLC	10 Points
3	Wave Grid	10 Points
4	Water Bros Development	9 Points
5	SOAR	8 Points
6	Ron Pelrine's Team	7 Points
7	AMSL	5 Points
8	Soft Energy	3 Points
9	Team Streaming Energy	3 Points
10	BIOINTERPHASE	2 Points
11	WET	1 Point
12	Camswails6	1 Point
13	Buckeyes	1 Point
14	Talos Industry Corporation	0 Points
15	SecondSees, Inc.	0 Points
16	Blue Lotus Energy	0 Points
17	Hassan Masoud	0 Points

Table G-2. Phase II Leaderboard

Instance	Leader	Status
1	Pittsburgh Coastal Energy	14 Points
2	Chemventive	8 Points
3	Water Bros Development	7 Points
4	EBB:Flow	7 Points
5	Wave Grid	6 Points
6	Kiri DEEC	6 Points
7	Maiden Wave Energy	5 Points
8	Soft Energy	4 Points
9	Electric Aquanauts	3 Points
10	AMSL	3 Points
11	Electroactive Polymers	3 Points
12	FluxMEMS	3 Points
13	Condensed Wave Matter	2 Points
14	HydrokinetX	2 Points
15	Team FUSION	0 Points
16	Suyi Li's Team	0 Points

Table G-3. Phase III Leaderboard

Instance	Leader	Status
1	Pittsburgh Coastal Energy	13 Points
2	EBB:Flow	7 Points
3	Streaming Energy	6 Points
4	Artimus Robotics	6 Points
5	Wave Grid	5 Points
6	Water Bros Development	5 Points
7	FluxMEMS	5 Points
8	Kiri DEEC	4 Points
9	PECWEC	4 Points
10	Condensed Wave Matter	3 Points
11	Piezogami Team	2 Points
12	Soft Energy	2 Points
13	Wave Harvest	1 Point
14	Elysium Robotics	1 Point

Appendix H. American-Made Program Webpage

The American-Made program website is the DOE's central platform for advancing energy innovation through prize competitions, technical assistance, and a national support network. Administered by NLR, it offers funding, lab support, and connections to sector partners across sectors like solar, wind, and storage. As the official hub for the InDEEP competition, https://americanmadechallenges.org/challenges/indeep, the site provided participants with detailed guidelines, timelines, and submission portals to support teams through each phase, from concept to prototype [72].

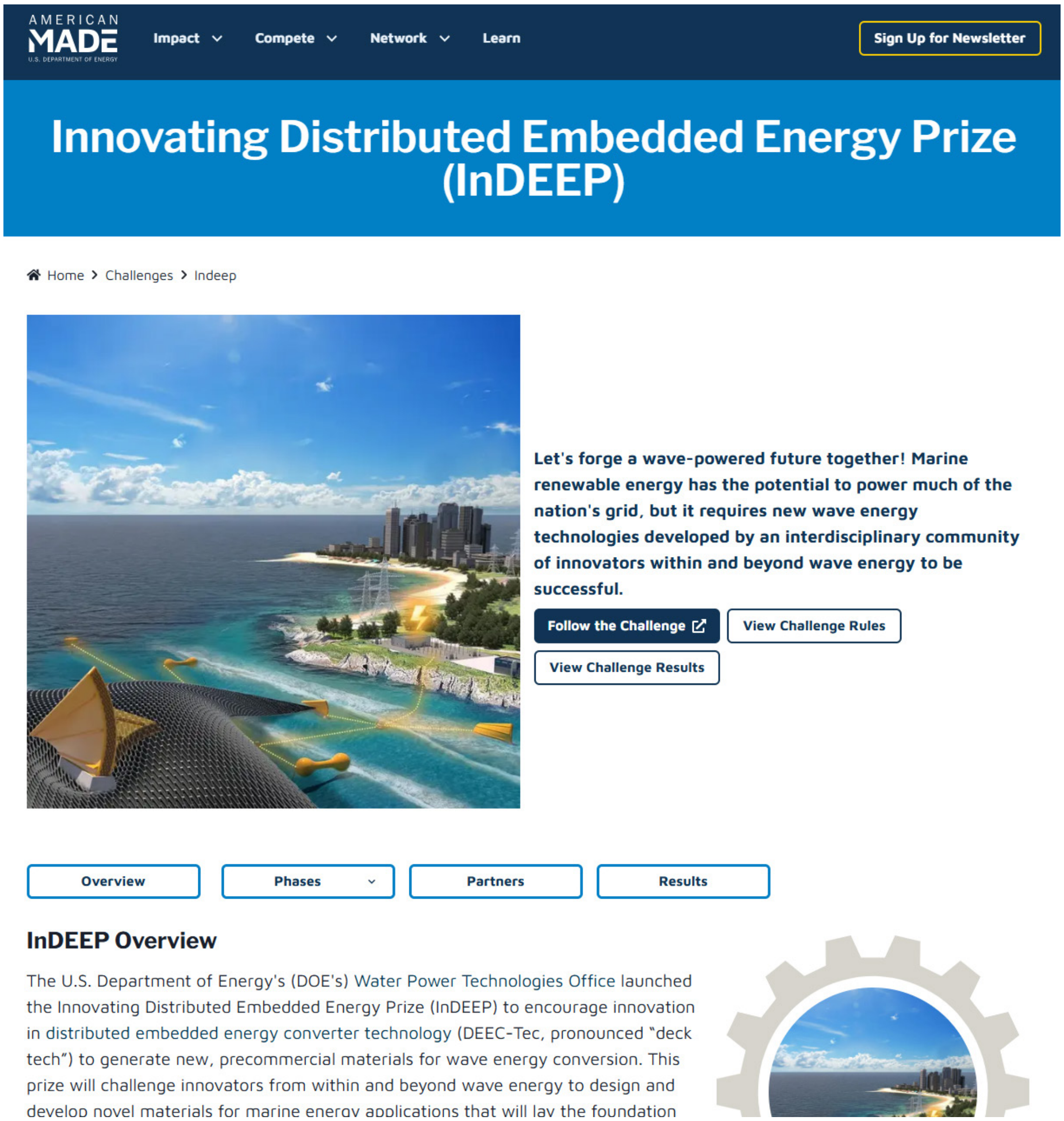

Figure H-1. American-Made InDEEP webpage (https://americanmadechallenges.org/challenges/indeep) [72].

Appendix I. Challenge.gov webpage

InDEEP had a Challenge.gov web presence. Phase III of the prize was closed so the Challenge.gov page did not contain the Phase III information.

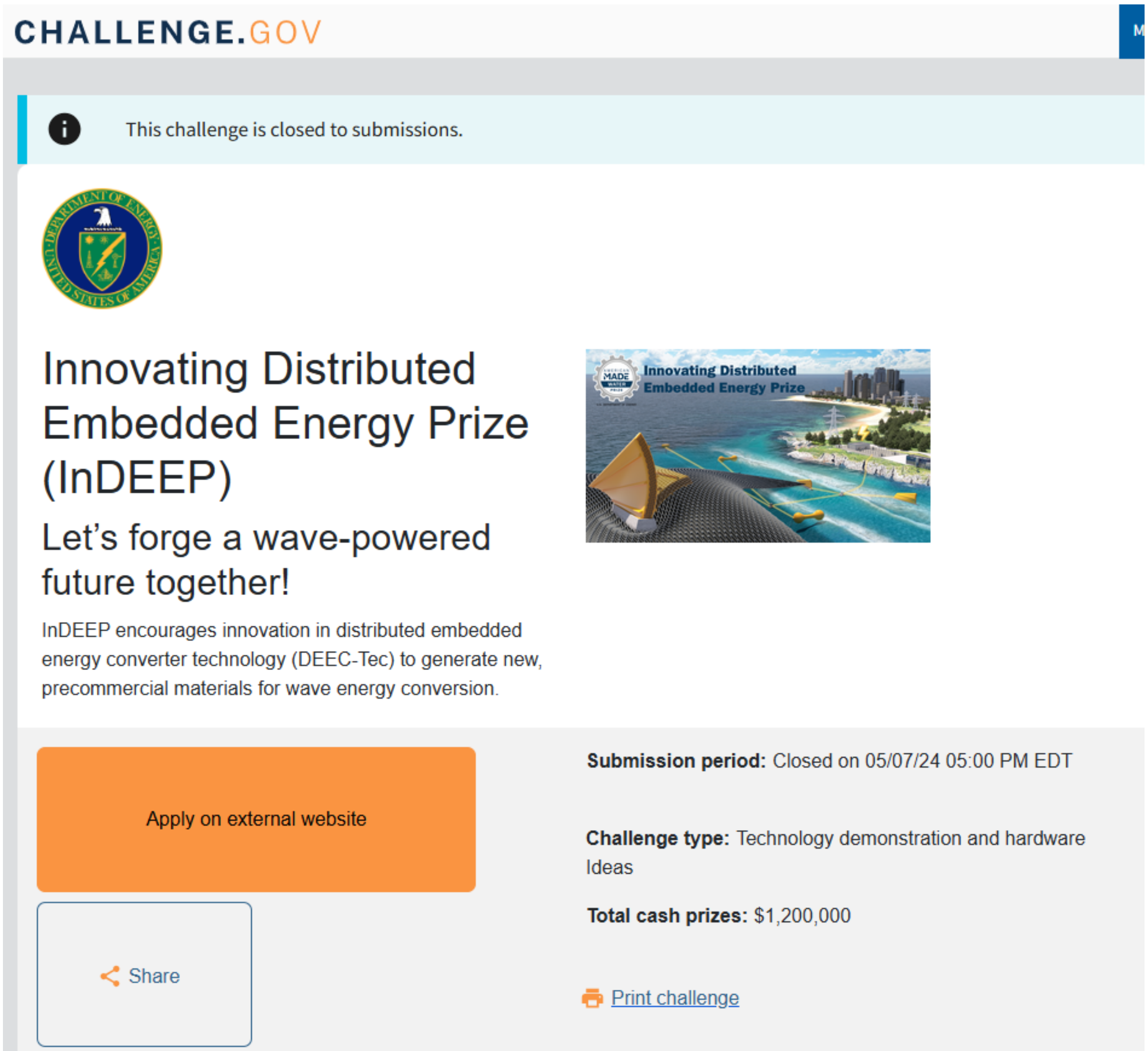

Figure I-1. Challenge.gov InDEEP webpage (https://www.challenge.gov/?challenge=indeep).

Appendix J. InDEEP Awardee Information

InDEEP awarded $15,000 each to 19 teams in Phase I (November 2023) for their innovative concepts. In Phase II (July 2024), 15 teams received $80,000 each—totaling $1.2 million—for demonstrating the performance potential of their DEEC-Tec solutions. Winning teams represented universities, startups, and innovators from across the United States, including returning awardees such as Pittsburgh Coastal Energy, PECWEC, PSU EnergyHarvesting, Streaming Energy, and Soft Energy. These awards reflect national efforts to advance DEEC-Tec development and its role in marine renewable energy.

J.1 InDEEP Phase I Award Press Release November 7, 2023

The Office of Energy Efficiency and Renewable Energy (EERE) announced the awardees: https://www.energy.gov/eere/water/articles/doe-announces-winners-first-round-prize-focused-novel-wave-energy-technologies

The following teams were each awarded $15,000 for their innovative DEEC-Tec concepts:

1. Active Materials and Smart Living from Las Vegas, Nevada
2. Blackfish Engineering from Braintree, Massachusetts
3. Blue Lotus Energy from Adair, Oklahoma
4. Chemventive from Chadds Ford, Pennsylvania
5. Condensed Wave Matter from Madison, Wisconsin
6. Elysium Robotics from Austin, Texas
7. FluxMagic from Portland, Oregon
8. Michigan Technological University and Arizona State University from Houghton, Michigan
9. PECWEC from Storrs/Mansfield, Connecticut
10. Piezogami Team from Blacksburg, Virginia
11. Pittsburgh Coastal Energy from Pittsburgh, Pennsylvania
12. PSU EnergyHarvesting from State College, Pennsylvania
13. RQR Wave Team from Longmont, Colorado
14. Soft Energy from Ithaca, New York
15. Streaming Energy from La Jolla, California
16. Team FUSION from Newport, Michigan
17. Water Bros Development from Charlotte, North Carolina
18. WaveHarvest from Dallas, Texas
19. Wave Grid from Galveston, Texas

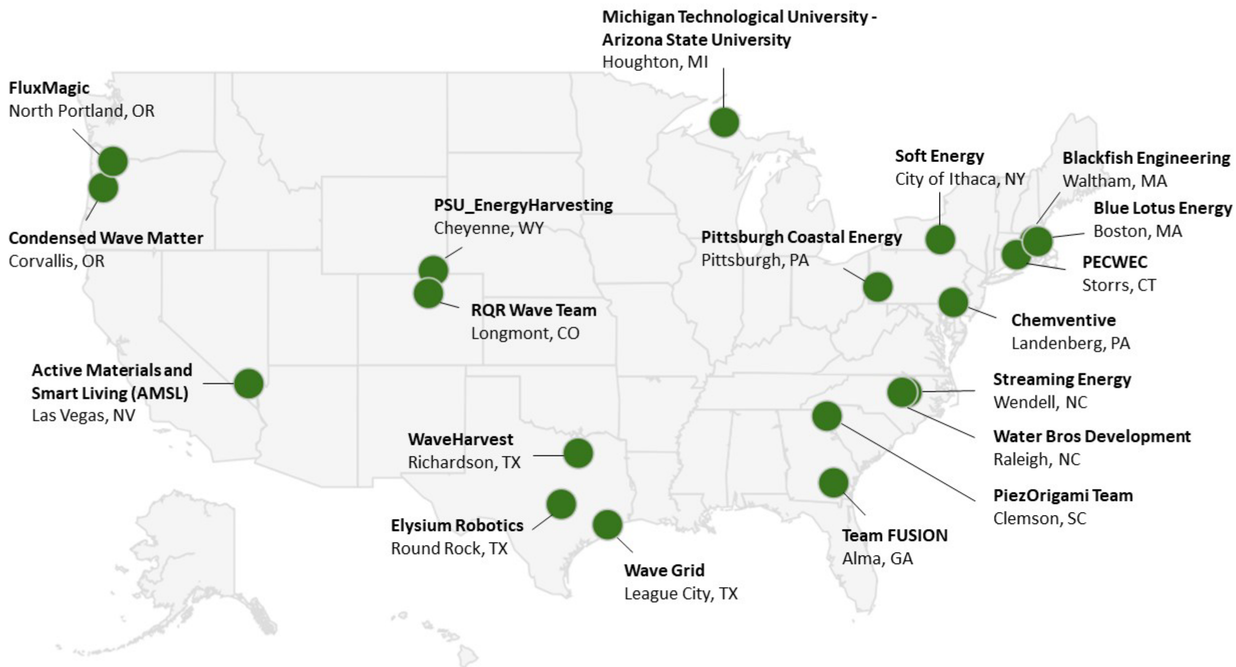

Figure J-1. Map of InDEEP Phase I winning teams.

J.2 InDEEP Phase II award press release July 29, 2024

The Office of Energy Efficiency and Renewable Energy (EERE) announced the awardees: https://www.energy.gov/eere/water/articles/marine-energy-technology-innovators-receive-12-million-second-phase-prize

Each team was awarded $80,000, for a combined $1.2 million in cash prizes, for showcasing the performance capabilities and characteristics of their DEEC-Tec concepts.
The winners of Phase II are:

1. Artimus Robotics from Boulder, Colorado
2. Condensed Wave Matter from Madison, Wisconsin
3. EBB:Flow from Braintree, Massachusetts
4. Elysium Robotics from Austin, Texas
5. FluxMEMS from Portland, Oregon
6. Kiri DEEC from Houghton, Michigan
7. PECWEC from Storrs, Connecticut
8. The Piezogami Team from Blacksburg, Virginia
9. Pittsburgh Coastal Energy from Pittsburgh, Pennsylvania
10. PSU EnergyHarvesting from State College, Pennsylvania
11. Soft Energy from Ithaca, New York
12. Streaming Energy from La Jolla, California
13. WaterBros Development from Charlotte, North Carolina
14. Wave Grid from Galveston, Texas
15. WaveHarvest from Dallas, Texas

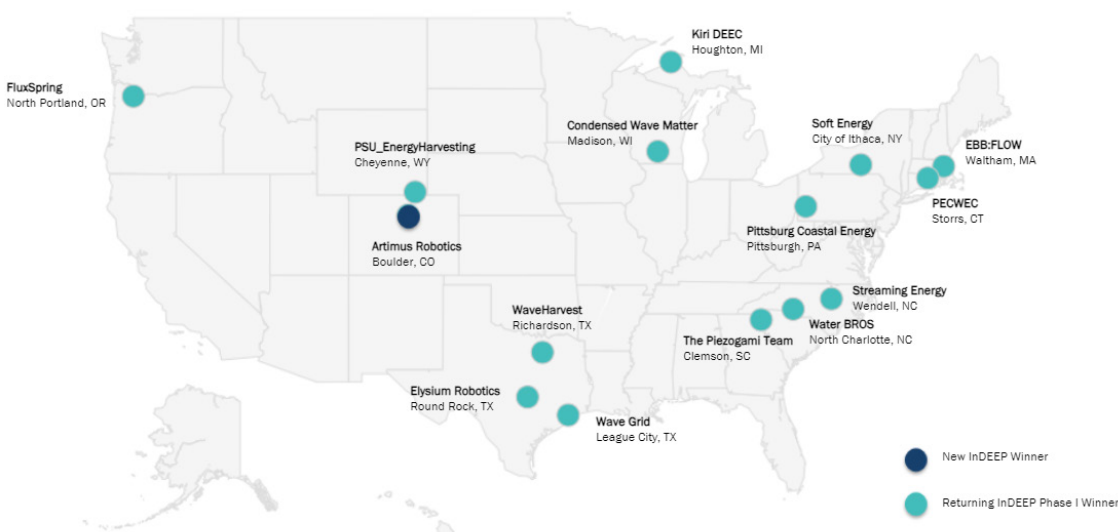

Figure J-2. Map of InDEEP Phase II winning teams.

Appendix K. Phase III Final Forum In-Person Event

The InDEEP Final Forum provided a critical opportunity to gather participant feedback and celebrate the achievements of Phase III's winning teams. This feedback offers valuable insights into what worked well and where future competitions can improve. The forum also underscored the importance of in-person collaboration and the ongoing effort to advance DEEC-Tec innovations in marine renewable energy. What follows is a summary of key takeaways.

Summary of Final Forum Feedback

Participants described the Final Forum as informative, welcoming, and especially valuable for in-person networking—something they felt was missing from virtual interactions. Many emphasized the opportunity to connect with other teams and mentors, particularly those with ties to future funding opportunities such as the Small Business Technology Transfer (STTR) program, the Small Business Innovation Research (SBIR) program, and any other small and medium-sized enterprises. As a result, several participants suggested that future competitions include earlier or mid-competition gatherings, structured networking events, or even incubator-style support to foster collaboration. However, a few noted that the competitive nature of the prize discouraged some from fully engaging in networking. To better support testing and partnerships, participants also recommended offering foundational trainings, team matchmaking, and access to key resources earlier in the competition timeline.

Feedback also pointed to areas for improvement. The leaderboard was seen as confusing or only marginally useful for technical development; participants suggested rebranding it as an "Engagement Tracker" and aligning it more closely with judged criteria. Requests included earlier prize payments, clearer communication about payment timing, competition-specific TEAMER calls (see: https://teamer-us.org/), and guidance on managing work at risk. Webinars could be improved by avoiding repetitive introductions, perhaps linking them to earlier recordings instead. Competitors wanted more up-front funding, clearer rules, deeper dives into deliverables, timely feedback after each phase, and templates (such as for posters) to reduce effort. Finally, the timeline and prize purse were noted as challenges—Phase I felt rushed, Phase II too short for teams without existing infrastructure, and the Phase III award insufficient for the work required. Participants expressed a desire for collaborative, practical workshops over lectures and follow-up materials like slide decks.

Winners of Phase III

In Phase III (2025), InDEEP awarded $200,000 each to four teams: Pittsburgh Coastal Energy, FluxMagic, Artimus Robotics, and Water Bros Development. These teams were successful in showcasing the performance potential of their innovative DEEC-Tec metamaterial solutions. These awards, totaling $800,000, reflect national efforts to advance DEEC-Tec and its role in shaping the future of marine renewable energy.

Figure K-1. Phase III competitor locations.

Appendix L. Iterative Innovation and Assessment

InDEEP used structured design and evaluation methodologies to support teams in developing, assessing, and refining their technologies. At the core of this approach were Technology Performance Level (TPL) assessments, which offered a more holistic evaluation of both technical and economic potential compared to traditional Technology Readiness Level (TRL) assessments. In addition, innovation frameworks such as TRIZ provided teams with creative strategies for addressing design challenges. [11]. These tools, emphasized throughout the prize, built on prior DOE-funded efforts such as the WaveSPARC project and supported iterative improvement across all phases [12] [13] [14] [14].