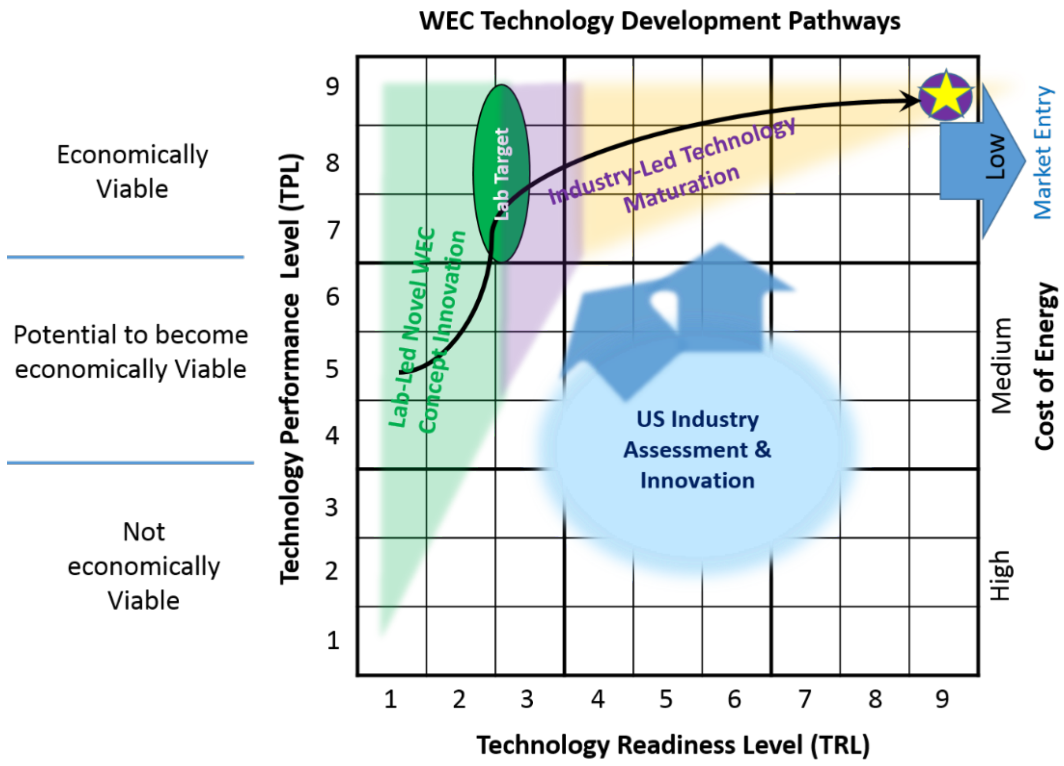
WBS 2.2.1.402 - Wave-SPARC:
Systematic Process & Analysis for Reaching Commercialization



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21 July 2022

NREL Transforming ENERGY | Sandia National Laboratories | Wave Venture | RAMBOLL

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Project Overview

Project Summary

Wave-SPARC is empowering the marine energy community with the tools necessary to achieve a significant improvement in techno-economic performance of wave-generated grid power. A detailed systems engineering approach simultaneously balances around 100 cost and performance drivers (functional requirements and capabilities) of wave energy converters (WECs). Publicly accessible technology innovation and assessment methods and tools (new to the wave energy sector) have been delivered. They guide technology development trajectories to successful outcomes in less time, at less overall cost, and with less encountered risk.

Intended Outcomes

- Invention, assessment, identification, verification and validation of novel and high techno-economic-potential WEC technology concepts to deliver high-confidence "seeds" for subsequent industrial development to full commercial application and economic viability
- Development and delivery of WEC technology innovation and assessment methodologies and tools and provision of these as services and for free use by industry and the entire sector
- International collaboration for global best practice alignment of assessment and innovation methods

Project Information

Principal Investigator(s)

- Jochem Weber, Chief Engineer, NREL
- Jesse Roberts, Principal Scientist, Sandia

Project Partners/Subs

- Sandia National Laboratories, Partner
- Wave Venture, Sub
- Ramboll, Sub

Project Status

Ongoing

Project Duration

- Project Start Date: October 1, 2014
- Project End Date: September 30, 2023

Total Costed (FY19–FY21)

$5,678k

Project Objectives: Relevance

WPTO Multi-Year Program Plan			Wave-SPARC	WPTO Multi-Year Program Plan		
Challenges	Approaches	Activities	Activities →	Intermediate Outcomes	Long-term Outcomes	Impact
Difficult engineering to convert marine energy	Foundational R&D	Drive innovation in components, controls, materials, manufacturing, and systems	Wave-SPARC develops, applies and refines technology assessment and innovation methodologies and delivers these and innovative technology concept solutions to the MHK industry for use and for full development and commercialization. Wave-SPARC drives innovation at farm system, device and sub-system levels, across all functional requirements.	Dramatic reductions in levelized cost of energy (LCOE) for MHK technologies driven by performance improvements and cost reductions	Significant deployment of grid-scale cost-competitive MHK projects, driven by dramatic MHK technology LCOE reductions	Energy affordability, Energy security, Economic growth
,,	,,	Develop and apply quantitative metrics to identify and advance technologies with high ultimate techno-economic potential	Wave-SPARC develops and applies holistic and quantitative techno-economic assessment metric systems to identify technology weaknesses and strengths, ultimately to advance technology towards their markets applications. To date Wave-SPARC covers continental grid, community microgrid, ocean observation, and desalination markets.	,,	,, Increased growth of Blue Economy businesses and improved ability to monitor the world's oceans through marine energy technologies	,,

Project Objectives: Relevance

WPTO Multi-Year Program Plan			Wave-SPARC	WPTO Multi-Year Program Plan		
			Activities →	Intermediate Outcomes	Long-term Outcomes	Impact
Installation and operation of reliable systems	Technology-specific system design and validation	Validate performance and reliability of systems through in-water tests of industry designed prototypes	Wave-SPARC supports the validation of performance and reliability of systems that are being tested in open waters by retiring critical risks prior to in-water testing, through detailed technology assessment and early-stage tank testing.	Dramatic LCOE reductions for MHK technologies driven by performance improvements and cost reductions	Significant deployment of grid-scale cost-competitive MHK projects, driven by dramatic LCOE reductions	Energy affordability, Energy security, Economic growth
,,	,,	Improve methods for safe, cost-efficient installation, grid integration, operations, maintenance, and decommissioning	Wave-SPARC, through the holistic TPL assessment methodology, considers all cost and performance drivers of the complete wave farm system over its life cycle.	Increased private investment in and commercial demonstration of MHK technology designs and/or IO&M strategies	,,	,,
,,	,,	Support the development and adoption of international standards for device performance and insurance certification	Wave-SPARC team actively contributes to international collaborations, EU or global projects on technology assessment, metrics development, innovation techniques, and is a key contributor to international standards and collaboration including IEA-OES.	Widespread utilization of agreed upon international standards and performance metrics for device performance and insurance certification	,,	,,

Project Objectives: Approach

Research Questions:

What are the core learnings from two eras of wave energy technology development regarding the development methodology and what is the best, most effective, and most efficient technology development trajectory?

How can such development trajectories be implemented and what methods and tools are required?

How can labs

- develop the required methodology and tools,
- initiate technology development, and
- provide both tools and high-potential technology concepts for use in U.S. industry and for full development

to achieve commercial deployment with success for the industry and the sector as whole?

Project Objectives: Approach

Technical Approach:

- Analyze strengths, weakness and learnings of technology development since the 1970s and identify best technology development trajectory regarding cost, time, risks and success. Identify methodological flaws and required improvements.
- Develop, test and apply required methods and tools including:
  - Formulate complete and agnostic set of functional requirements and capabilities for wave energy farms.
  - Develop realistic and effective technology assessment methodology and tools, applicable at all technology readiness levels.
  - Identify and apply the most potent and promising structured inventive techniques.
- Engage and deliver to industry and sector
  - All assessment and innovation methodologies and tools as service to and internal use by industry.
  - All invented high-potential WEC system and subsystem solutions to industry with easy and nonexclusive access.

Management Approach:

- Deliver results with world-class team of experts from labs and subcontractors.
- Maintain close engagement with DOE, Marine Energy Council, industry, and users.
- Disseminate project approach, progress, and outcome via continuous publications, conferences, workshops.
- Provide free services to industry applying and deploying the developed tools with mutual benefit and learning.
- Develop and maintain domestic and international collaboration for dissemination, learning, and global alignment and maximal impact.
- Empower R&D community with publicly accessible tools and information.

Project Objectives: Expected Outputs and Intended Outcomes

Outputs:

Novel wave energy converter (WEC) technology concepts with high techno-economic potential that will deliver high-confidence “seeds” for subsequent industry development to full commercial viability.

Best-practice WEC innovation and assessment methodologies and tools, disseminated through publications and webinars and via innovation and assessment as a free service.

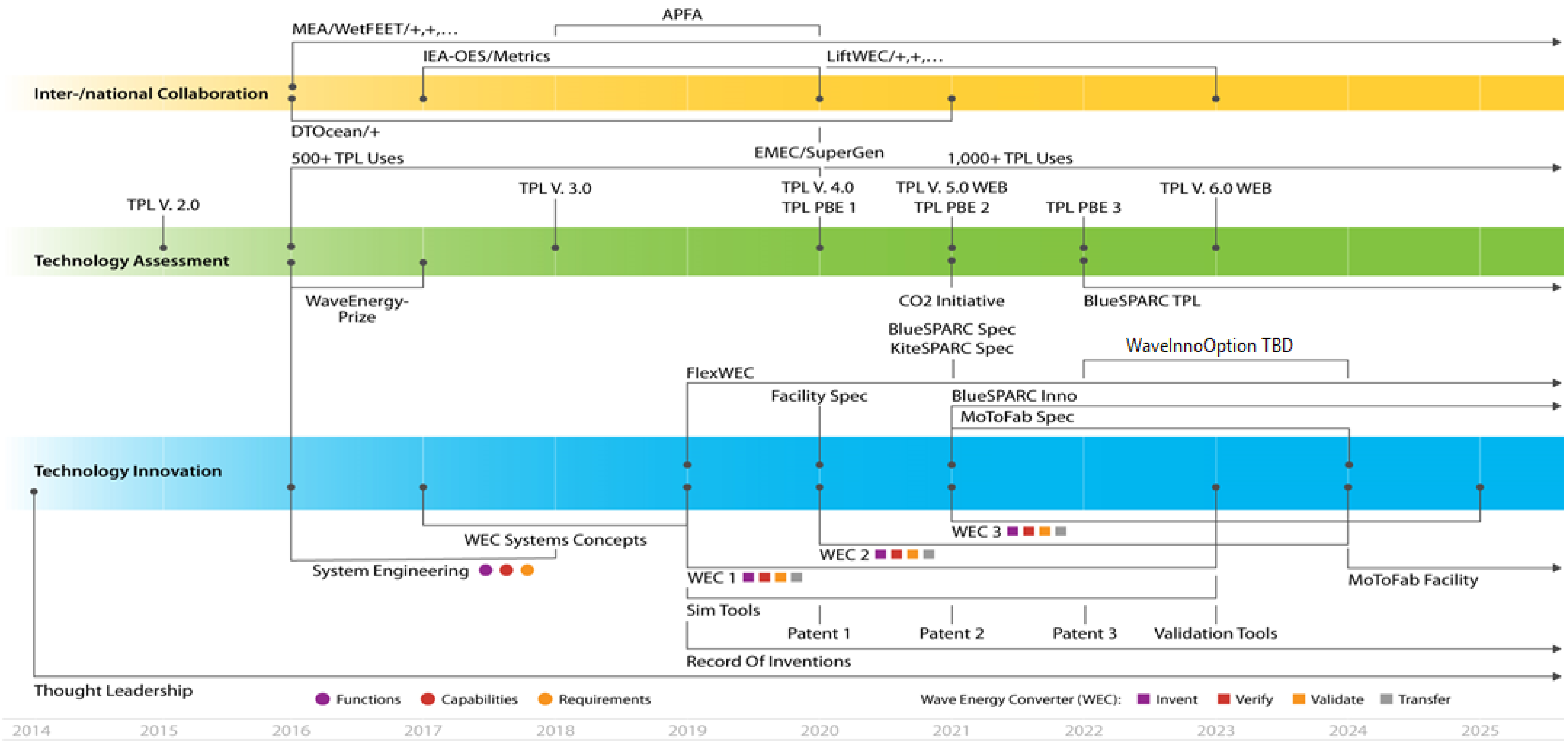
International collaboration and outreach to guarantee intake of related efforts, ensure global alignment on best practices, validate project deliverables, and provide significant benefits for global application.

Outcomes:

- **WEC developers:** Vastly improved WEC technology development strategy that significantly reduces time, cost, and risk, leading to substantially improved likelihood of commercial success.
- **Supporting and investing in original equipment manufacturers:** Clarity and involvement through high-performance technology convergence.
- **Supply chain:** High demand and client base through technology convergence and commercialization.
- **Certifying bodies:** More accurate assessments of WEC technology value at crucial early stages.
- **Financing community:** Higher confidence and less uncertainty in technology value and technology choice.
- **Public funding bodies/DOE:** Better strategic investments and accelerated development with higher success.

Project Timeline

Overview of multitude of outputs, products & synergies from the three project branches



Project Budget

Item/Year	FY19	FY20	FY21	Total Actual Costs FY19–FY21
LAB	**Costed**	**Costed**	**Costed**	**Total Costed**
NREL	$899K	$1,382K	$1,071K	$3,352K
Sandia	$758K	$791K	$777K	$2,326K
Total	$1,657K	$2,173K	$1,848K	$5,678K

- COVID impact managed through virtual work meetings, division in sub-teams, document sharing, etc. without impacting budget, timeline or project outputs.
- Project team also services TEAMER and SBIR clients with Wave-SPARC methods and tools and advised multiple international projects teams with mutual and synergetic benefits.

End-User Engagement and Dissemination

Wave-SPARC methodology and tool applied in TEAMER and SBIR projects

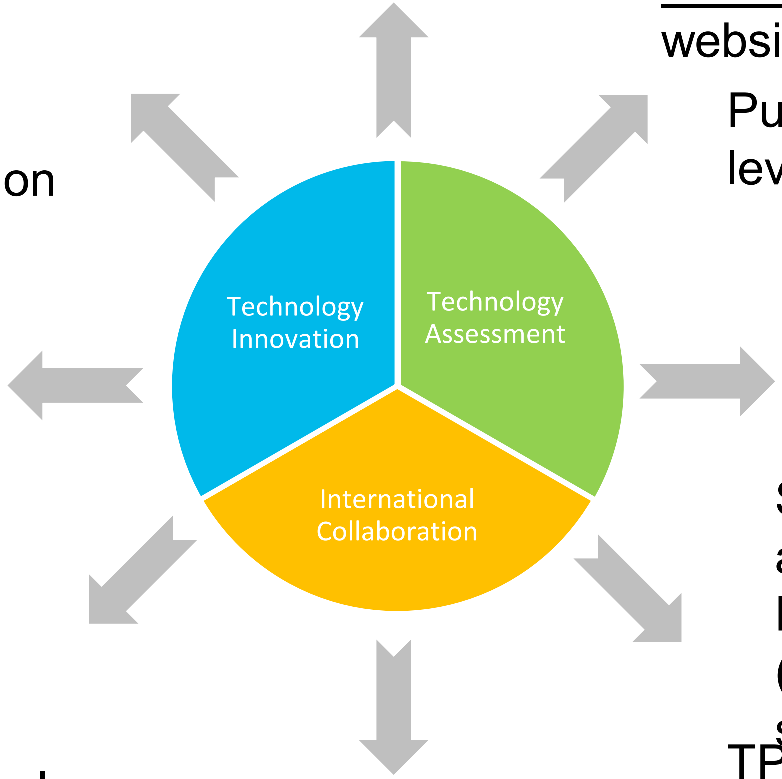
Work with funding agencies, DOE, WES, EU

Briefing of TIPS/TRIZ application to wave energy problem

NREL and Sandia project websites

Public-facing technology performance level (TPL) assessment web app

Structured Innovation collaboration and application in EU projects: DTOceanPlus



Briefing and feedback, Marine Energy Council

Industry application: service, tool handover, industry application and feedback for utility-scale wave farm assessment

Advise on technology development strategy, Partner or Advisory Board in EU projects

Stakeholder engagement and feedback for adapting TPL to Powering the Blue Economy^{TM} (PBE) and alternative markets (e.g., carbon capture, utilization, and storage (CCUS))

1 book chapter, 11 peer-reviewed papers, 3 technical reports, 10+ presentations (5 papers and 4 presentations since last peer review)

TPL Assessment applied in EU projects: WETFEED, MEA,…

Webinars, workshops

Metrics, standards, IEA-OES

Selected Publications:

Book chapters, lab reports, journal and conference peer-reviewed papers

1. J. Weber and D. Laird, “Structured Innovation of High-Performance Wave Energy Converter Technology,” Proceedings of the 11th European Wave and Tidal Energy Conference, Nantes, France, September 6–11, 2015.
2. D. Bull, J. Roberts, R. Malins, J. Weber, K. Dykes, K. Neilson, C. Bittencourt, A. Babarit, R. Costello and B. Kennedy, “Systems engineering applied to the development of a wave energy farm”, 2nd International Conference on Renewable Energies Offshore, 24 - 26 October 2016, Lisbon, Portugal
3. Ben Kennedy, Ronan Costello, Kim Nielsen, J. Hanafin, Jochem Weber, “Wave Farm Design: Optimization of O&M With Respect to Weather Window Criteria”, Proceedings of the 12th European Wave and Tidal Energy Conference, Cork, Ireland, August 27–September 1, 2017.
4. J. Weber, D. Laird, R. Costello, B. Kennedy, J. Roberts, D. Bull, A. Babarit, K. Nielsen, and C. B. Ferreira, “Cost, Time, and Risk Assessment of Different Wave Energy Converter Technology Development Trajectories,” Proceedings of the 12th European Wave and Tidal Energy Conference, Cork, Ireland, August 27–September 1, 2017.
5. D. Bull, R. Costello, A. Babarit, K. Nielsen, B. Kennedy, C. Bittencourt, J. Roberts, and J. Weber, “Scoring the Technology Performance Level (TPL) Assessment,” Proceedings of the 12th European Wave and Tidal Energy Conference, Cork, Ireland, August 27–September 1, 2017.
6. D. Bull, R. Costello, A. Babarit, K. Nielsen, C. B. Ferreira, B. Kennedy, R. Malins, K. Dykes, J. Roberts, and J. Weber. “Systems Engineering Applied to the Development of a Wave Energy Farm,” Sandia National Laboratories. Albuquerque, NM, USA. SAND2017-4507, Version 1.01, April 2017.
7. Diana Bull, Ronan Costello, Aurélien Babarit, Kim Nielsen, Claudio Bittencourt Ferreira, Ben Kennedy, Robert Malins, Kathryn Dykes, Jesse Roberts (co-PI), and Jochem Weber (PI), “Technology Performance Level Assessment Methodology”, Version 3.01, SANDIA REPORT SAND2017-4471, April 2017
8. Kim Nielsen, Ben Kennedy, Diana Bull, Ronan Costello, Jesse Roberts, Jochem Weber, “Technical Submission Form, Technical Specification of a Wave Energy Farm”, Version 2.01, SANDIA REPORT SAND2017-4474, April 2017
9. A. Babarit, D. Bull, K. Dykes, R. Malins, K. Nielsen, R. Costello, J. Roberts, C. B. Ferreira, B. Kennedy, and J. Weber, “Stakeholder requirements for commercially successful wave energy converter farms,” Renewable Energy, vol. 113, pp. 742–755, 2017. DOI: 10.1016/j.renene.2017.06.040.
10. Jochem W. Weber, 272 Wave Energy 3565, in Encyclopedia of Maritime and Offshore Engineering, Editors: John Carlton, Paul Jukes, Yoo-Sang Choo, online©2018 John Wiley & Sons, Ltd., ISBN: 978-1-118-47635-2, July 2018, 4320 Pages
11. Ronan Costello, Kim Nielsen, Jochem Weber, Nathan Tom and Jesse Roberts, “WaveSPARC: Evaluation of Innovation Techniques for Wave Energy”, Proceedings of the 13th European Wave and Tidal Energy Conference, Naples, Italy, September 1–6, 2019.
12. J. Weber, R. Costello, K. Nielsen, and J. Roberts, “Requirements for Realistic and Effective Wave Energy Technology Performance Assessment Criteria and Metrics,” Proceedings of the 13th European Wave and Tidal Energy Conference, Naples, Italy, September 1–6, 2019.
13. Nicole Mendoza, Thomas Mathai, Dominic Forbush, Blake Boren, Jochem Weber, Jesse Roberts, Chris Chartrand, Lee Fingersh, Budi Gunawan, William Peplinski, Robert Preus, and Owen Roberts, “Developing technology performance level assessments for early-stage wave energy converter technologies,” Proceedings of the 14th European Wave and Tidal Energy Conference, Plymouth, UK, September 5–9, 2021.
14. Nicole Mendoza, Thomas Mathai, Blake Boren, Jesse Roberts, James Niffenegger, Volker Sick, Arno Zimmermann, Jochem Weber, Joshua Schaidle, “Adapting the Technology Performance Level integrated assessment framework to low-TRL technologies within the Carbon Capture, Utilization, and Storage industry, Part I”, Frontiers in Climate, Volume 4, 2022, DOI: 10.3389/fclim.2022.818786, https://www.frontiersin.org/article/10.3389/fclim.2022.818786
15. Ali Trueworthy, Aeron Roach, Bryony DuPont, Thomas Mathai, Jesse Roberts, Jochem Weber, Robert Preus, Benjamin D. Maurer, “Wave Energy Converter Technical Performance Level Assessment Uncertainty”, submitted to Applied Energy

Performance: Accomplishments and Progress

Technology Innovation: Overview

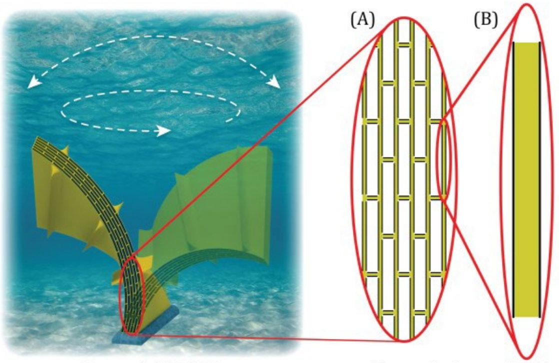
- Wave-SPARC has produced multiple WEC innovations including:
  - System concepts – farm level
  - System concepts – device level
  - Subsystem concepts
- These innovations led to:
  - Novel concepts with low, medium to high performance promise
  - Alteration and increase of TPL of invented and existing concepts
  - Alteration and increase of TRL of invented and existing concepts due to the use of high TRL subsystems or components
- Some undisclosed innovations turned out to be principal concept variants related to leading WEC technologies with promise of high TPL
- 3 patents and multiple records of invention

Closely aligned WPTO Multi-Year Program Plan Intermediate Outcome
Dramatic LCOE reductions for MHK technologies driven by performance improvements and cost-reductions

Performance: Accomplishments and Progress

Technology Innovation: System Concept Innovation Samples

- Bottom mounted flexible multi-modal and multi-dimensional deformer with embedded PTO



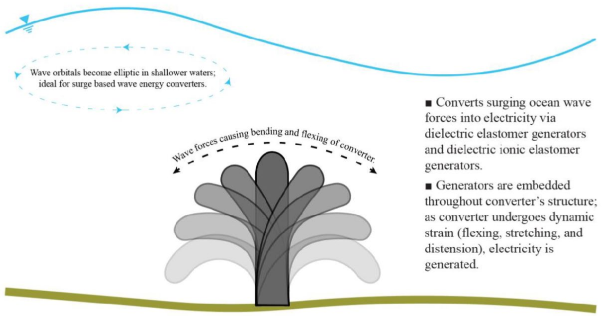


Figure 22: General overview of flexible distributed power take-off energy converter's operation under surging waves; illustrating main mode of movement and flexing of the converter's structure.

- Communicating volume clusters, interconnected through PTOs with integrated resonance adjustment

Figure 6: A 75-MW FlexWEC is a cluster comprised of an integrated set of 5-by-15 deformable absorbers with turbine generators in connecting ducts.

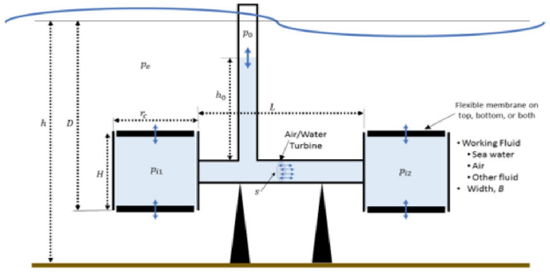


Figure 2: Schematic of a two-chamber pressure differential WEC with air/water turbine and surface piercing water column.

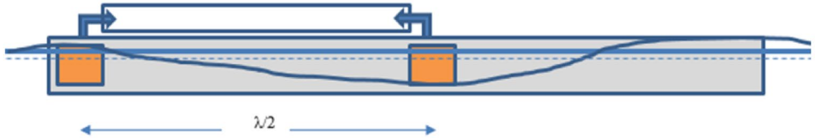


Figure 14: Side view of the novel WEC system B a multi flexWEC ship like structure.

Closely aligned WPTO Multi-Year Program Plan Intermediate Outcome
Dramatic LCOE reductions for MHK technologies driven by performance improvements and cost-reductions

Performance: Accomplishments and Progress

Technology Innovation: Subsystem Concept Innovation Samples

- Variations of Integrated PTO subsystem innovations boosting both TPL and TRL
  - Belt and winch (displayed here)
  - Micro hydraulics

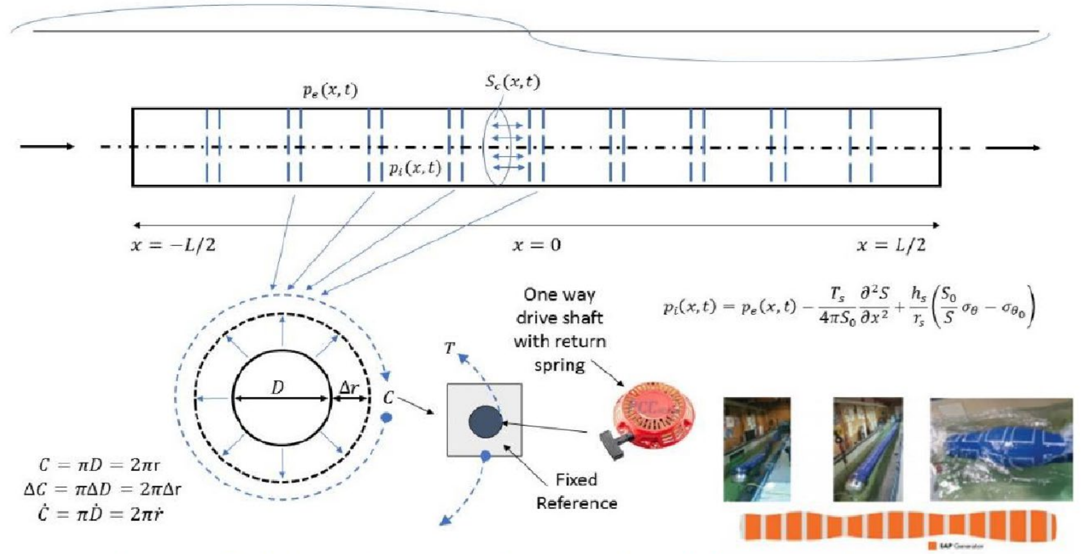
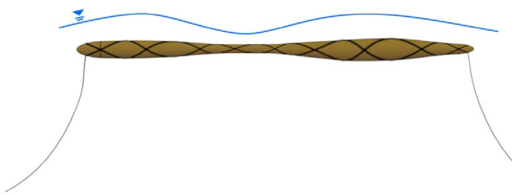


Figure 5: Schematic of a bulging tube WEC with one-way driveshaft couple to direct drive generator.

- Benefitting Example WEC System



Closely aligned WPTO Multi-Year Program Plan Intermediate Outcome

Dramatic LCOE reductions for MHK technologies driven by performance improvements and cost-reductions

Performance: Accomplishments and Progress

Technology Assessment

- Formal systems engineering process per ISO 15288 completed
- Technology Performance Level (TPL) assessment methodology developed as a holistic metric for how well the technology will perform
- Assessment adapted to PBE applications, and current energy converters*
- Assessment extended to other technology domains (e.g., CCUS)*

*indicates accomplishments and progress since last peer review


SANDIA REPORT
SAND2020-XXXX
Printed

Sandia National Laboratories

Adapting the Technology Performance Level Assessment Tool for Isolated Grid Markets

Dominic D. Forbush, Nicole Mendoza, Vincent S. Neary, Budi Gunawan, Thomas Mathai, Chris Chartrand, Robert Preus, Blake Boren, Lee-Jay Fingersh, Jochem Weber (PI), Jesse Roberts (PI)

SANDIA REPORT
SAND2017-4471
Unlimited Release
April 2017

Technology Performance Level Assessment Methodology

Version 3.01

Diana Bull, Ronan Costello, Aurélien Babarit, Kim Nielsen, Claudio Bittencourt Ferreira, Ben Kennedy, Robert Malins, Kathryn Dykes, Jesse Roberts (co-PI), and Jochem Weber (PI).

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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SANDIA REPORT
SAND2017-4507
Unlimited Release
April 2017

Systems Engineering Applied to the Development of a Wave Energy Farm

Version 1.01

Diana Bull, Ronan Cos
Ben Kennedy, Robert I
Weber (PI).

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 871

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frontiers

"Adapting the Technology Performance Level integrated assessment framework to low-TRL technologies within the Carbon Capture, Utilization, and Storage industry, Part I"

Nicole Mendoza[1]*, Thomas Mathai[2], Blake Boren[2], Jesse Roberts[3], James Niffenegger[2], Volker Sick[4], Arno Zimmermann[5,6], Jochem Weber[2], Joshua Schaidle[7]

Wind Energy Systems, National Renewable Energy Laboratory, Arvada, CO, United States

Closely aligned WPTO Multi-Year Program Plan Intermediate Outcome

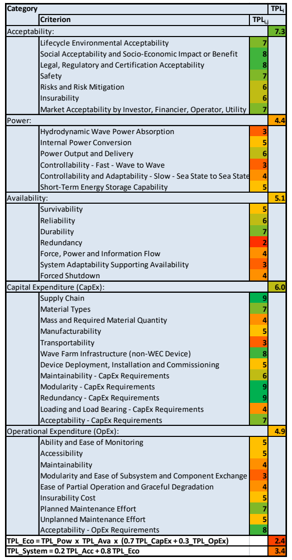
Performance: Accomplishments and Progress

Technology Assessment

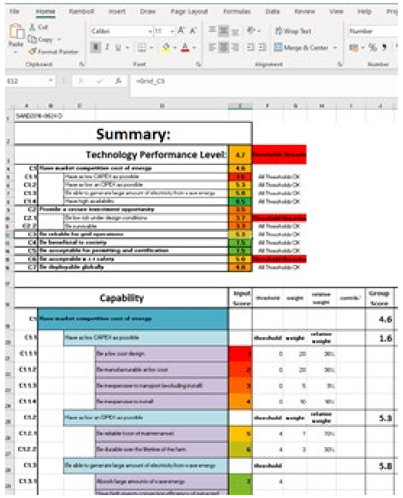
*indicates accomplishments and progress since last peer review

- Continuous improvement, development, and release of TPL assessment tool
- TPL Assessment: Versions 1 to 4 over 500 use cases of over 100 technologies
- Free TPL Assessments for US and global industry & internal use in AOP & FOA projects*

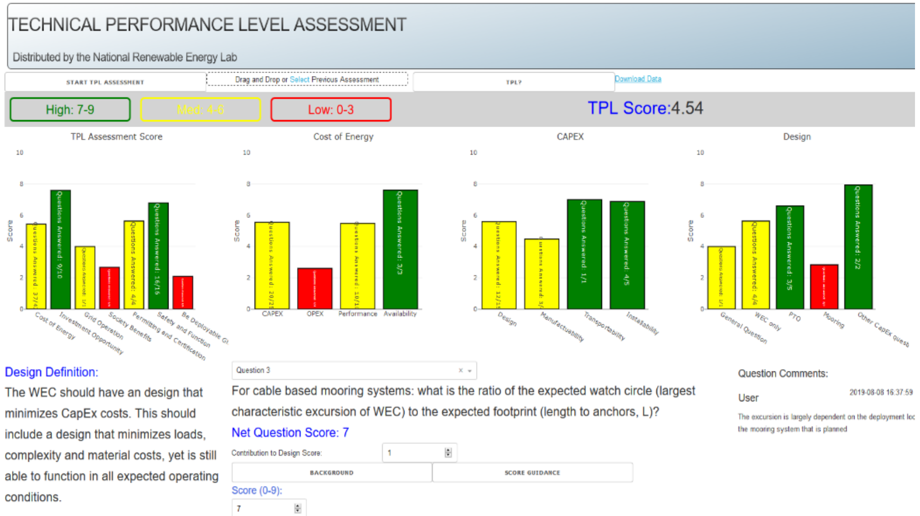
Version 2



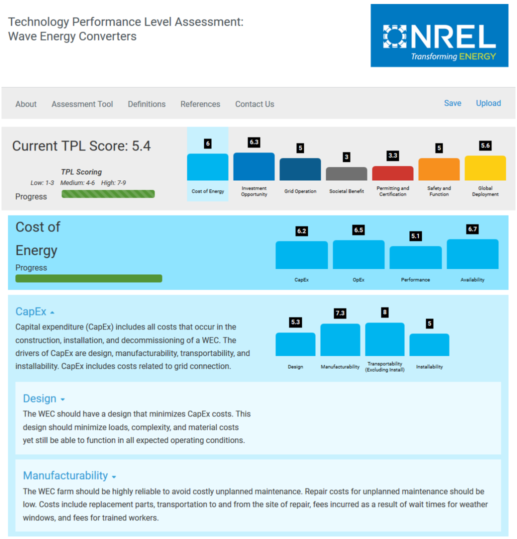
Version 4



Version 5



*Version 6, https://tpl.nrel.gov/

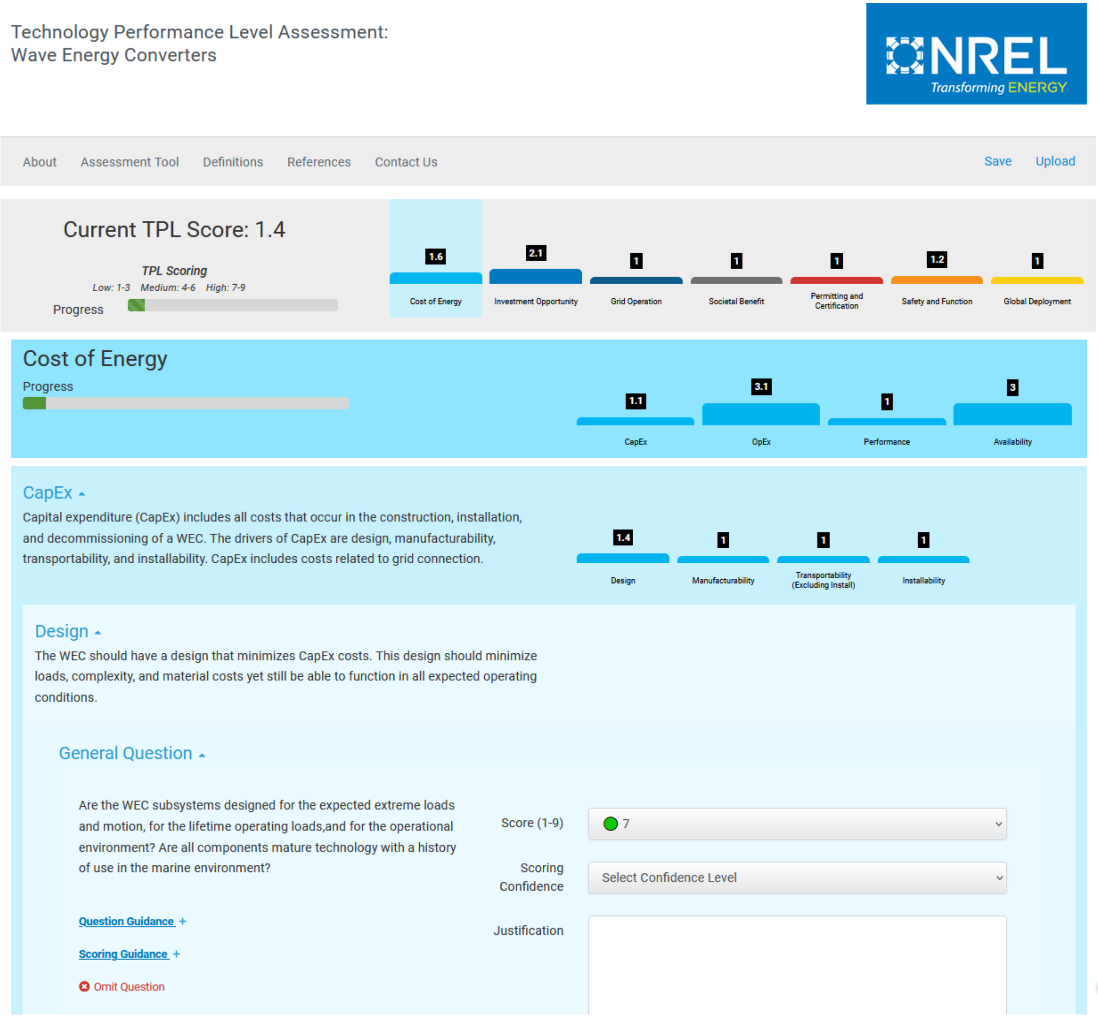


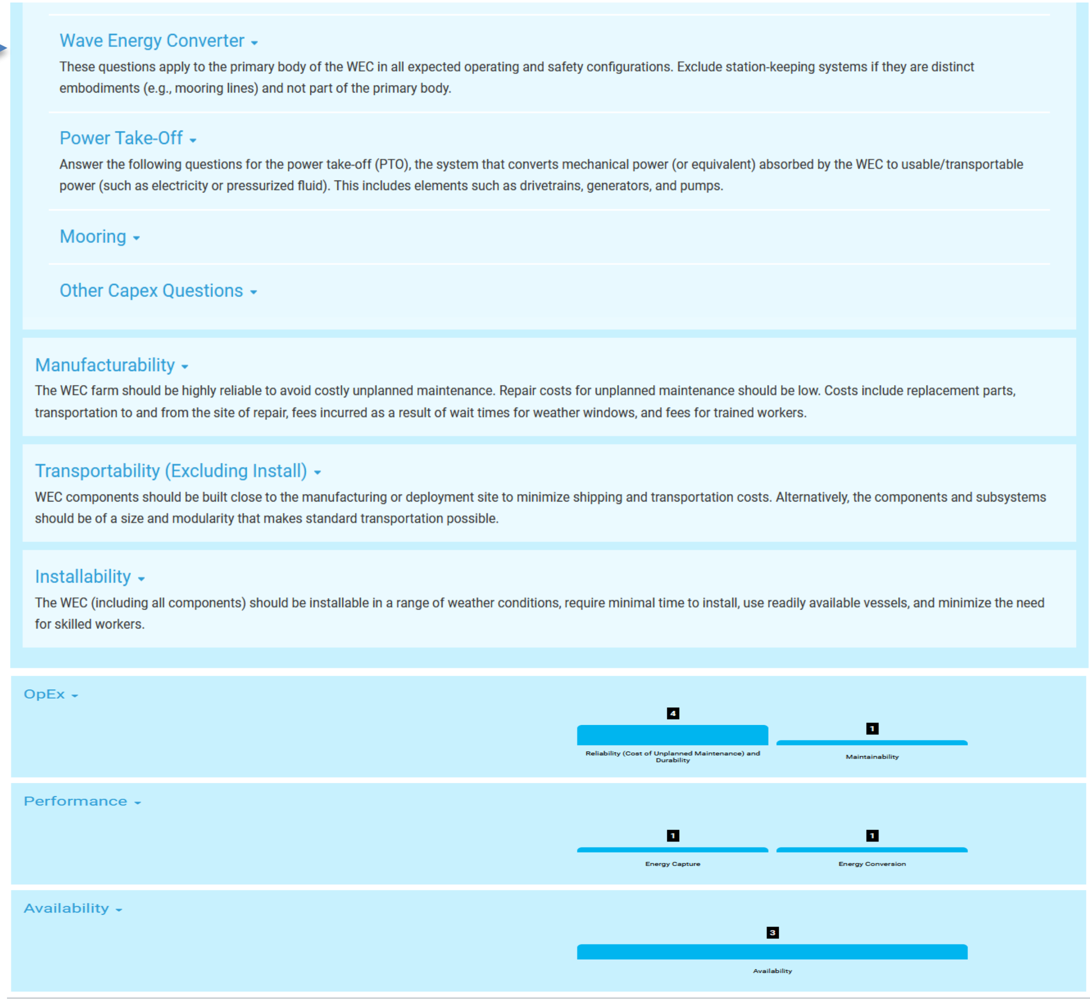
Closely aligned WPTO Multi-Year Program Plan Intermediate Outcome

Widespread utilization of agreed upon international standards and performance metrics for device performance and insurance certification

Performance: Accomplishments and Progress

Technology Assessment: Sample View of TPL Tool Version 6.0





Performance: Accomplishments and Progress

Technology Assessment: Anonymized Client Assessments

		Dev-1	Dev 2 2018	Dev 2 2020	Dev 3	Dev 4	Dev 5	Dev 6	Dev 7
Technology Performance Level:		7.22	3.05	6.70	5.50	6.78	6.65	5.65	6.51
Have market competitive cost of energy		7.03	3.31	6.60	5.37	6.61	5.79	5.98	6.64
	Have as low CAPEX as possible	7.56	6.30	7.41	6.88	7.24	6.30	6.95	6.83
	Have as low an OPEX as possible	6.00	1.60	6.85	5.00	6.20	5.20	5.90	5.65
	Be able to generate large amount of electricity from wave energy	8.25	4.65	6.61	5.77	6.98	6.13	5.71	6.85
	Have high availability	6.00	2.33	6.00	4.33	6.00	5.33	5.67	6.67
Provide a secure investment opportunity		6.75	1.72	5.99	5.29	6.86	7.47	6.28	6.93
Be reliable for grid operations		7.00	1.00	9.00	5.00	6.00	9.00	6.00	7.00
Be beneficial to society		6.33	2.00	7.17	7.00	7.83	7.33	2.33	7.00
Be acceptable for permitting and certification		7.65	5.94	8.28	5.16	7.00	6.07	6.32	4.58
Be acceptable w.r.t safety		7.47	3.39	7.65	5.62	6.55	6.45	6.66	6.24
Be deployable globally		7.88	4.13	5.88	5.75	6.88	6.50	4.88	6.75
Thresholds Breached		1	13	1	9	1	2	5	6

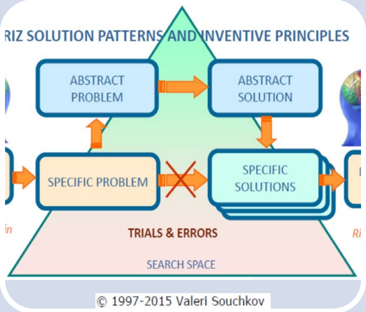
Performance: Accomplishments and Progress (cont.)

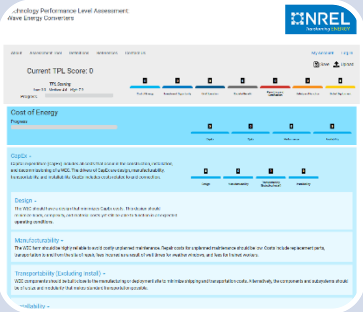
International Collaboration

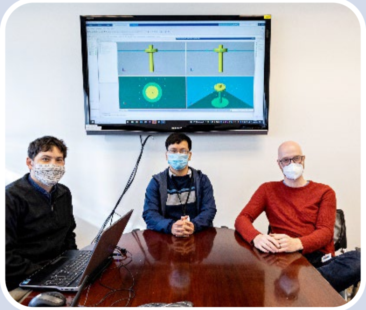
- Wide adaptation and use of the developed techniques and tools globally
- Labs and partners are engaged in large, impactful projects globally
- Exchange and mutual learning in all project-relevant methods and tools
- Deployment of TPL as service, progress assessment, and fund allocation

Closely aligned WPTO Multi-Year Program Plan Intermediate Outcome
Widespread utilization of agreed upon international standards and performance metrics for device performance and insurance certification

Future Work







ICOE
INTERNATIONAL CONFERENCE ON OCEAN ENERGY

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- Continue novel WEC technology concept innovation using TRIZ and other inventive techniques
- Improve assessment tools (e.g., utility-scale wave farm assessment web app)
- Assessment as a service, technology-specific improvements and resolution of limiting trade-offs through the focused application of TRIZ
- Disseminate results via journal papers, conferences, webinars, workshops
- Adapt to PBE markets and current energy converters
- Extend to other domains (e.g., carbon capture, utilization, and storage (CCUS))

Closely aligned WPTO Multi-Year Program Plan Intermediate Outcomes

a) Dramatic LCOE reductions for MHK technologies driven by performance improvements and cost-reductions b) Increased private investment in and commercial demonstration of MHK technology designs and/or IO&M strategies c) Widespread utilization of agreed upon international standards and performance metrics for device performance and insurance certification

Q&A