Structured Innovation of High-Performance Wave Energy Converter Technology

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Structured Innovation of High-Performance Wave Energy Converter Technology

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Abstract— **Wave energy converter (WEC) technology development has neither reached the desired commercial maturity nor, and more importantly, the techno-economic performance to achieve economic viability. The reasons for this delay in development success have been recognized and fundamental requirements for successful WEC technology development have been identified in [1] and [2]. This paper describes a multiyear project pursued in collaboration by the National Renewable Energy Laboratory and Sandia National Laboratories to innovate and develop new WEC technology. It specifies the project strategy, shows how this differs from the state of the art approach, and presents some early project results. Based on the specification of fundamental functional requirements of WEC technology, structured innovation and systemic problem-solving methodologies are applied to invent and identify new WEC technology concepts. Using technology performance level (TPL) as an assessment metric of the techno-economic performance potential, high-performance technology concepts are identified and selected for further development. System performance is numerically modeled and optimized and key performance aspects are empirically validated. The project deliverables are WEC technology specifications of high techno-economic performance technologies of TPL 7 or higher at a technology readiness level 3 (TRL 3) with some key technology challenges investigated at higher TRLs. These wave energy converter technology specifications will be made available to industry for completion of the technology development and commercialisation (TRL 4–TRL 9).**

Keywords— Wave energy converter, technology development, high techno-economic performance, structured innovation, techniques of inventive problem solving, TIPS, TRIZ, technology performance level, TPL, technology readiness level, TRL, DOE, NREL, SNL

I. Introduction and Motivation

To date, wave energy converter (WEC) technology development as a whole has neither reached the desired commercial maturity nor, and more importantly, the techno-economic performance that are required for commercial readiness and economic viability. In [1] and [2], the ways in which WEC technology are being developed has been analysed; deficiencies with these approaches have been recognized; and the following fundamental requirements for successful WEC technology development have been identified:

1. There is a need for holistic, detailed and to the furthest extent possible, objective technology performance assessment at all stages of development. Particularly, at early development stages, technology assessment is difficult and subject to high uncertainties, while at the same time essential for the definition of system fundamentals and thus for ultimate technology development success in a number of ways.
2. The technology innovation and development approach must not be confined to a single WEC concept species, but configured to facilitate cross-conceptual development. It must challenge and improve system fundamentals as required at the earliest stage possible and identify the concepts and system configurations that deliver the best potential for high techno-economic performance.
3. The innovation, engineering design, and technology development process is to be based on and driven by a comprehensive specification of functional requirements and subsequent functional decomposition. This is essential for the targeted and successful application of structured and methodological subsystem and system innovation and engineering design processes.

This paper describes how these essential requirements for successful WEC technology development are implemented and applied in a multiyear project, entitled “Structured Innovation,” performed in collaboration by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL). This paper also shows how this strategy profoundly differs from the state of the art approach, and some early project results are presented.

II. Comparison to State of the Art

Beyond the detailed analysis of the state of the art in WEC technology development presented in [1] and [2] and the therein-derived conclusions on how to improve a) the technology development process with respect to time, cost, and risk, and b) the outcome with respect to the techno-economic performance of the developed wave energy technologies, three key aspects shall be emphasized here that relate the three points made in Section I to characteristics of the state of the art.

As a renewable energy, ocean wave energy technologies clearly target high techno-economic performance to achieve economic viability. To gear the technology development towards this goal, it is essential to be able to assess, monitor, and optimize performance with a suitable metric. The state of the art choice for such a performance metric is cost of energy (COE) or more appropriately, levelised cost of energy (LCOE). For fully developed systems under commercial operation, LCOE is considered the suitable metric as at that stage, all necessary input parameters for the determination of LCOE are available. For technologies under development, however, a great part of that knowledge is not available, particularly at a low technology readiness level (TRL).

The state of the art approach is to determine simplified LCOE-related quantities based on a reduced set of known and estimated system parameters. Well-established examples are annual mean absorbed power per characteristic mass and surface area or power take-off force as used in the "Numerical Benchmarking Study of a Selection of Wave Energy Converters" [3]. Although such benefit-to-effort ratios are very valuable and quantify an important subset of the full set of cost and performance drivers of LCOE, other important unknown or rather uncertain system properties are not considered. Thus, the state of the art approach opts to use a focused and reduced set of input parameters while maintaining the arithmetic of LCOE. A significant downside of this approach is that key techno-economic system performance parameters—such as availability—and underlying system attributes—such as reliability, durability, or even survivability—are considered too late in the development process; after system fundamentals are defined and the technology value is associated with the related intellectual property (IP).

As opposed to this, and in reference to point 1 in Section I, the Structured Innovation project uses the technology performance level (TPL) as a metric to quantify the techno-economic performance potential of WEC technologies under development. The TPL metric provides a holistic assessment by considering all system attributes that have an influence on the techno-economic performance potential. Thus, this approach opts to use a complete set of relevant system attributes while accepting a reduced knowledge on the precise influence of these attributes on the overall performance metric, TPL, and the underlying arithmetic. This approach is well-suited to identify system weaknesses and potential showstoppers at the earliest possible opportunity and facilitates technology development on all fronts.

A further and widespread characteristic of the state of the art in WEC technology development practices is the early identification of and subsequent fixation on conceptual and operation system fundamentals. This phenomenon is primarily driven by the desire and often the need for start-up companies to secure IP as a core asset to facilitate the funding of the development program. These circumstances have, in many cases, been shown to entail huge limitations on possible technology performance improvement during the development process. The rigid fixation on a narrow, IP-driven, design space can lead WEC technology development paths to cul-de-sac situations and failure.

On the contrary, and with reference to point 2 in Section I, the Structured Innovation project uses a range of systemic inventive techniques (SIT) at system function and subfunction level, leading to a multitude of operational and functional technology concept solutions and combinations thereof. This approach is well-supported by the key project and development partners, NREL and SNL. For NREL and SNL, the early identification and securing of IP is not a predominate funding source but rather a limiting disadvantage.

Finally, it is essential to point out that the state of the art approach towards WEC technology concept invention and development is often based on a much too simplified and superficial set of functional requirements directly related to minimizing cost and maximizing energy yield. Furthermore, in many cases, intuitive inventive methods are used and are often driven by preconceived design philosophies. This combination led to the incoherent and wide diversity of WEC technology inventions and functional and operational concepts.

On the contrary, and with reference to point 3 in Section I, the Structured Innovation project dedicates considerable effort and focus towards the full and comprehensive specification of functional requirements and functional decomposition for WEC technology, as the appropriate and detailed form of the wave energy engineering problem statement. It is essential that this functional requirement specification be independent of any preconceived WEC technology concepts or designs. This detailed and fundamental definition of the functional requirements is an essential piece of work that has long been neglected or missing in the field of wave energy converter engineering. This definition will provide a sound and unbiased basis to facilitate and drive the application of structured and methodological subsystem and system invention, engineering design, and technology development processes.

Clearly, the descriptions provided here of the state of the art approaches towards WEC concept invention, performance assessment, and technology development do not allow a general conclusion on the quality of any specific WEC technology development effort; however, the authors feel that the analysis and insights in [1] and [2] capture the essential weaknesses of past technology development efforts.

III. Structured Innovation Project Goal

The goal of the Structured Innovation project is to innovate, identify, develop, and validate novel WEC technologies that demonstrate strong potential for high techno-economic performance when fully developed. The project does not aim to encompass the complete development of the technologies for commercial rollout; however, it aims to deliver high-confidence technology "seeds" for development by industry to full commercial viability. More precisely, the project deliverables are technology specifications of WEC systems with high techno-economic performance potential at TPL 7 or higher (7+) and at TRL 3 with some key technology challenges investigated at higher TRLs. Fig. 1 shows the position and role of the Structured Innovation project within the overall WEC technology development process displayed over the TRL-TPL-Matrix introduced in [1]. At the completion of the Structured Innovation project, the TRL 3– TPL 7+ developed wave energy converter technology specifications will be made available to industry for full development and commercialization through the achievement of economic viability. The U.S. Department of Energy will continue supporting these industrial WEC technology maturing and refining developments through a range of existing support mechanisms.

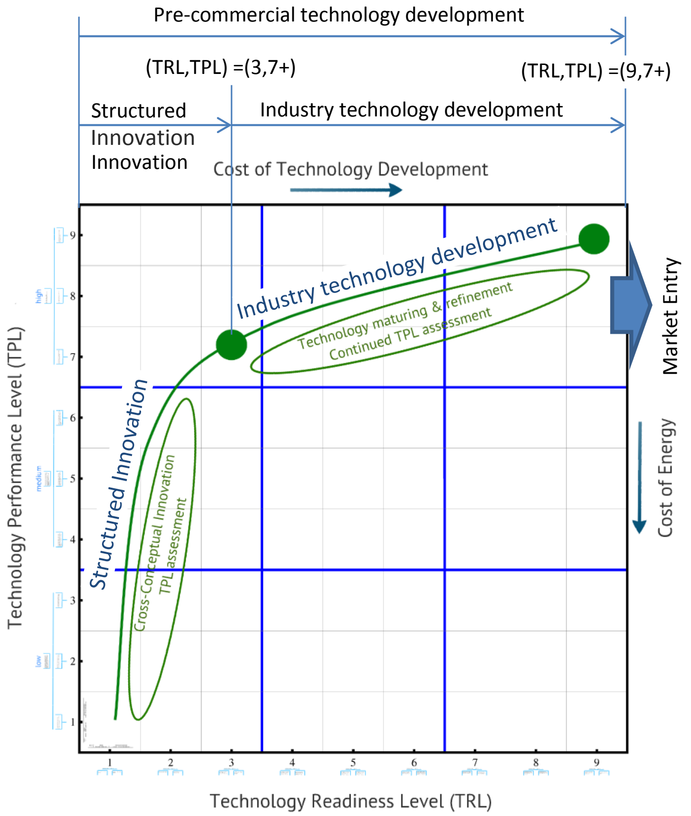

Fig. 1 Position and role of the Structured Innovation project within the overall WEC technology development process displayed over the TRL-TPL-Matrix.

In a broad sense, the Structured Innovation project and the U.S. Department of Energy Wave Energy Prize competition [4] are similarly positioned in the TRL-TPL-Matrix. Both projects aim to identify and deliver WEC technology concepts at TRL 3 with significantly increased techno-economic performance potential over the state of the art. The Wave Energy Prize also employs the TPL assessment methodology and metric to rank the submitted WEC technology concepts during the first technology gate and down-select those technologies that move forward to the technology gate 2 of the competition; however, the fundamental approaches implemented in the two campaigns are entirely different. As a competition, the Wave Energy Prize attracts and accepts a multitude of externally conceived WEC technology concepts that are evaluated with a three-stage process, using the TPL metric and other performance metrics based on two wave tank testing campaigns. The contestant's IP will remain in their possession. On the other hand, the Structured Innovation project implements a systematic sequential process of performance assessment tool development, functional requirement specification, methodological technology concept invention, evaluation and selection, followed by system optimisation, experimental performance validation through wave tank testing, and resolution of key technology challenges. Resulting high-performance WEC technology specifications and the associated IP will be made widely available to the wave energy industry for full development and commercialisation.

IV. Structured Innovation Project Overview

The Structured Innovation project is composed of five key modules, as displayed in Fig. 2. As initially introduced in [1], the TPLs are used to assess the techno-economic performance potential of WEC technology at all stages, i.e., at all TRLs of the technology development process. The development of the TPL assessment metric and methodology for application in the Structured Innovation project is a prerequisite for the subsequent project modules and has been completed within the first project phase since the project started in October 2014. Once the TPL assessment process and metric have been more intensively used in the Structured Innovation project and in the first technology gate of the Wave Energy Prize, the TPL methodology and metric will be refined and improved. This is part of the first project module (Technology Performance Levels) and indicated by the bidirectional arrow in Fig. 2. A verification and comparative opposition of the TPL metric to the conventionally used LCOE metric with the use of well-understood legacy WEC systems is part of the TPL refinement.

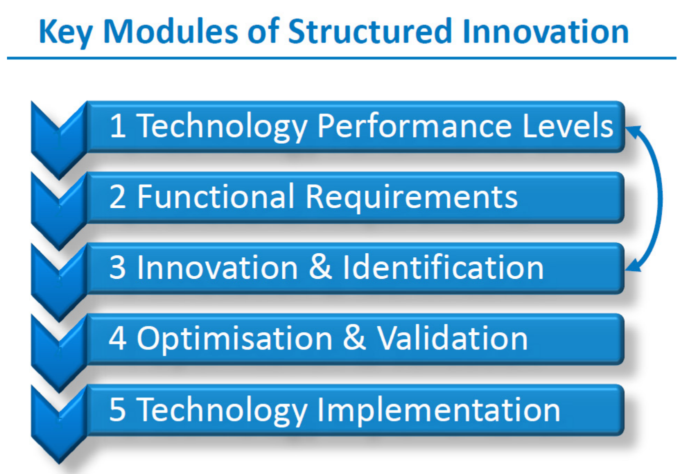

Fig. 2 Overview of the five key modules of the Structured Innovation project.

The formulation and precise specification of functional requirements is the basis of all engineering design efforts generally, and particularly in a system engineering sense. It is essential that these functional requirement specifications are entirely system-design-independent and not biased by any preconception of any envisaged WEC technology concepts or archetypes. Given the functional requirement specifications through the second project module (Functional Requirements), the innovation process has a sound foundation and can be targeted at satisfying these requirements.

As opposed to the widely applied intuitive invention techniques and as a result of the complexity and challenge of WEC technology innovation and development, systemic and methodological inventive techniques are applied in the Structured Innovation project to generate new WEC technology concepts. To identify the WEC technology concepts with high techno-economic performance potential among the newly generated concepts, the developed TPL assessment methodology is employed. Both the innovation and identification of high TPL WEC technology concepts take place in the third project module (Innovation & Identification). It is expected that a large number of WEC system and subsystem concepts will be assessed. This will provide a level of experience and learning that will be exploited in the improvement and refinement of the TPL metric.

Given a ranked list of high TPL WEC technology concepts, the top scoring and most promising concepts will be further investigated and optimised. This investigation includes, but is not limited to full wave-to-wire numerical modeling and simulation followed by overall optimisation of the design layout and the control schemes of the power absorption, power conversion, and system configuration, if applicable. The findings of the investigation and optimization will, as far as possible, be validated through wave tank testing. This system optimisation and validation is completed in the fourth project module (Optimization & Validation).

Finally, key technology development challenges associated with the technological implementation of the particular WEC system concepts will be identified and investigated to de-risk the subsequent WEC technology development process to full commercial readiness and economic performance. These focused and detailed technology development activities are at TRLs higher than TRL 3 and will take place in the fifth project module (Technology Implementation).

The subsequent sections give a more detailed account of the tasks and deliverables of each of the five key modules of the Structured Innovation project.

V. Technology Performance Levels

With regard to point 1 in Section I, i.e., the "need for holistic, detailed and to the furthest extent possible objective technology performance assessment," the TPLs introduced in [1] and further detailed in [2] provide a techno-economic performance assessment metric for WEC technology.

Analogous to the TRLs, the TPLs are categorised into nine levels quantifying the techno-economic, functional, and lifecycle performance of the WEC system. The nine TPLs are listed in Table 1 with their category and primary characteristics. This metric considers all key cost and performance drivers in the form of a large number of system attributes that serve as assessment criteria that are categorized into five groups—acceptability; power absorption, conversion, and delivery; system availability; capital expenditure (CapEx); and operational expenditure (OpEx).

Within each of the five categories, a number of applicable cost and performance drivers are assessed to determine the techno-economic performance potential for each group. The key criteria include:

1. Acceptability:
   Lifecycle environmental acceptability; social acceptability and socio-economic impact and/or benefit; legal, regulatory, and certification acceptability; safety; risk mitigation; insurability; and market acceptability by investor, financier, operator, or utility
2. Power absorption, conversion, and delivery:
   Hydrodynamic wave power absorption; internal power conversion; power output and delivery; controllability with fast, wave-by-wave control; controllability and adaptability with slow, sea-state-by-sea-state control; and short-term energy storage capability
3. System availability:
   Survivability; reliability; durability; redundancy; force, power and information flow; system adaptability supporting availability; and forced shutdown
4. Capital Expenditure:
   Supply chain; material types; mass and required material quantity; manufacturability; transportability; wave farm infrastructure (non-WEC device); device deployment, installation, and commissioning; maintainability; CapEx requirements; modularity CapEx requirements; redundancy CapEx requirements; loading and load-bearing CapEx requirements; and acceptability CapEx requirements
5. Operational Expenditure:
   Ability and ease of monitoring; accessibility; maintainability; modularity and ease of subsystem and component exchange; ease of partial operation and graceful degradation; insurability cost; planned maintenance effort; unplanned maintenance effort; acceptability OpEx requirements.

The TPL assessments can be applied at all technology development stages and associated TRLs while recognizing that the TRL significantly influences the comprehensiveness, level of detail, and achievable certainty of the TPL assessment. The different levels of assessment depth and associated confidence levels for TPL assessments at different TRLs are discussed in [2].

In the Structured Innovation project, which focuses on low TRLs, the TPL assessment metric is particularly useful as it considers a wide range of cost- and performance-related system attributes, whereas LCOE or related simplified LCOE proxies are often based on a much reduced scope of cost and performance drivers at low TRLs.

Furthermore, with this focus on attributes for high techno-economic performance WEC systems, the TPL metric and assessment approach is particularly suitable for the objective of inventing and identifying high techno-economic performance WEC systems rather than purely retrospective assessment for a given system.

TABLE I
TECHNOLOGY PERFORMANCE LEVEL CATEGORIES AND CHARACTERISTICS

<table>
<tr><th>TPL</th><th colspan="2">Category Characteristics</th><th>TPL Characteristics</th></tr>
<tr><td>9</td><td rowspan="3">high</td><td rowspan="3">Technology is economically viable and competitive as a renewable energy source</td><td>Competitive with other energy sources without any support mechanism</td></tr>
<tr><td>8</td><td>Competitive with other energy sources given sustainable (e.g., low feed-in tariff) support mechanism</td></tr>
<tr><td>7</td><td>Competitive with other renewable energy sources given favourable (e.g., high feed-in tariff) support mechanism</td></tr>
<tr><td>6</td><td rowspan="3">medium</td><td rowspan="3">Technology features some characteristics for potential economic viability under distinctive market and operational conditions. Technological or conceptual improvements may be required.</td><td>Majority of key performance characteristics and cost drivers satisfy potential economic viability under distinctive and favourable market and operational conditions.</td></tr>
<tr><td>5</td><td>To achieve economic viability under distinctive and favourable market and operational conditions, some key technology implementation improvements are required and regarded as possible.</td></tr>
<tr><td>4</td><td>To achieve economic viability under distinctive and favourable market and operational conditions, a number of key technology implementation and fundamental conceptual improvements are required and regarded as possible.</td></tr>
<tr><td>3</td><td rowspan="3">low</td><td rowspan="3">Technology is not economically viable</td><td>Minority of key performance characteristics and cost drivers do not satisfy potential economic viability and critical improvements are not regarded as possible within conceptual fundamentals.</td></tr>
<tr><td>2</td><td>Some key performance characteristics and cost drivers do not satisfy potential economic viability and critical improvements are not regarded as possible within conceptual fundamentals.</td></tr>
<tr><td>1</td><td>Majority of key performance characteristics and cost drivers do not satisfy and present a barrier to potential economic viability and critical improvements are not regarded as possible within conceptual fundamentals.</td></tr>
</table>

The methodology to evaluate the TPL level of a WEC system is based on a simple process and arithmetic:

1. A given WEC technology is evaluated against all criteria and a $TPL_{i.j}$ score ranging from 1 to 9 is allocated with respect to each criterion 'j' within each group 'i'.

2. Each $TPL_{i.j}$ score is checked against an independent minimal threshold value that a given WEC technology needs to satisfy irrespective of any of the other $TPL_{i.j}$ criteria scores.

3. The $TPL_{i.j}$ criteria scores of each of the five criteria groups 'i' are weighted averaged to determine the five group TPL_i scores TPL_{Power}, $TPL_{Availability}$, TPL_{CapEx}, TPL_{OpEx}, and $TPL_{Acceptability}$.

4. The combined value $TPL_{Economic}$ is determined via
$$TPL_{Economic} = \left(TPL_{Power} \cdot TPL_{Availability} \cdot \left(0.7\,TPL_{CapEx} + 0.3\,TPL_{OpEx}\right) - 1\right) \frac{9-1}{9^3-1} + 1$$
This equation reflects the multiplicative nature of power, availability, and cost-effectiveness in the techno-economic performance. Subsequently the product is linearly scaled back to the TPL scale ranging from 1 to 9.

5. The overall system value TPL_{System} is determined via $TPL_{System} = 0.8\,TPL_{Economic} + 0.2\,TPL_{Acceptability}$.

Evidently, the application of the present construct of the TPL metric and assessment methodology within the Structured Innovation project and also in the course of the Wave Energy Prize competition, (in which the TPL assessment is based on the technical submissions provided by the contestants and used as the first of three and stage gates with down-select) delivered valuable insight in relation to its practicability, effectiveness, completeness, and accuracy.

Fig. 3 shows the TPL assessment results of one of a number of example case studies that have been conducted within the Structured Innovation project. The assessed WEC technology is of the type of axisymmetric self-reacting two-body heaving buoy point absorbers of the design, dimensions, and as described in [4] and referred to as F-2HB.

The fields of the individual, group, economic, and system TPL values are colour-coded with low TPL values in red fields ranging through medium values in yellow fields to high values in green fields. It is important to note the magnitude of combined economic $TPL_{Economic}$ and system TPL_{System} values are well below the range of the five group TPL_i values. This may initially be unexpected, but is a reflection of the justified multiplicative nature of power, availability, and cost-effectiveness in the techno-economic performance metric. The validity of these circumstances becomes apparent when considering a case in which (for example) power and cost-effectiveness are optimal at TPL 9, whereas the availability is extremely poor at TPL 1.

The present and future experience and knowledge gathered through the use of the TPL assessment process and metric in the Structured Innovation project and in the Wave Energy Prize will facilitate a refinement and improvement of the TPL assessment process and metric for subsequent detailed public release for industry-wide usage. This refined and improved TPL metric will subsequently be used within the Structured Innovation project itself to verify the assessment and ranking of the identified novel WEC technology concepts and justify the down-select to a reduced set of WEC technologies that will be subject to further and refined investigation and development.

Category	Criterion	$TPL_{i,j}$	TPL_i
Acceptability:			7.3
	Lifecycle Environmental Acceptability	7	
	Social Acceptability and Socio-Economic Impact or Benefit	8	
	Legal, Regulatory and Certification Acceptability	8	
	Safety	7	
	Risks and Risk Mitigation	6	
	Insurability	6	
	Market Acceptability by Investor, Financier, Operator, Utility	7	
Power:			4.4
	Hydrodynamic Wave Power Absorption	3	
	Internal Power Conversion	5	
	Power Output and Delivery	6	
	Controllability - Fast - Wave to Wave	3	
	Controllability and Adaptability - Slow - Sea State to Sea State	4	
	Short-Term Energy Storage Capability	5	
Availability:			5.1
	Survivability	5	
	Reliability	6	
	Durability	7	
	Redundancy	2	
	Force, Power and Information Flow	4	
	System Adaptability Supporting Availability	3	
	Forced Shutdown	4	
Capital Expenditure (CapEx):			6.0
	Supply Chain	9	
	Material Types	7	
	Mass and Required Material Quantity	4	
	Manufacturability	5	
	Transportability	3	
	Wave Farm Infrastructure (non-WEC Device)	8	
	Device Deployment, Installation and Commissioning	5	
	Maintainability - CapEx Requirements	6	
	Modularity - CapEx Requirements	9	
	Redundancy - CapEx Requirements	9	
	Loading and Load Bearing - CapEx Requirements	4	
	Acceptability - CapEx Requirements	7	
Operational Expenditure (OpEx):			4.9
	Ability and Ease of Monitoring	5	
	Accessibility	5	
	Maintainability	4	
	Modularity and Ease of Subsystem and Component Exchange	3	
	Ease of Partial Operation and Graceful Degradation	4	
	Insurability Cost	5	
	Planned Maintenance Effort	7	
	Unplanned Maintenance Effort	5	
	Acceptability - OpEx Requirements	8	
TPL_Eco = TPL_Pow x TPL_Ava x (0.7 TPL_CapEx + 0.3_TPL_OpEx)			2.4
TPL_System = 0.2 TPL_Acc + 0.8 TPL_Eco			3.4

Fig. 3 TPL assessment results for an axisymmetric, self-reacting, two-body heaving buoy point absorber wave energy converter as described in [4] and referred to as F-2HB.

Furthermore, valuable insight and overview of the global WEC technology industry will be achieved through a public screening process and establishment of a full TPL-TRL value map of WEC technologies under development. Consequently, key tasks of this project module include:

- Refinement of TPL assessment criteria and metric criteria granularity resolution
- Implementation of basic WEC system design logic
- Extension of TPL assessment over the range of WEC technology development stages, i.e., over the TRLs with respect to the assessment depth and associated confidence levels
- Validation of TPL assessment process and metric with legacy systems
- Verification of high potential WEC systems
- Documentation for detailed public release of TPL-TRL assessment process and metric for WEC systems
- Public screening of global WEC technology industry and identification of full TPL-TRL technology value map.

VI. Functional Requirement Specification

The detailed formulation of functional requirements is essential to all technology developments. To date, the wave energy research and technology development community has no agreed detailed set of functional requirements. On the contrary, technology development has largely been driven on the back of intuitive WEC technology concept ideas. This project will define the complete set of functional requirements in collaboration (embedded and global workshops) with the WEC technology development industry and leading world experts. Key tasks of this project module include:

- Development of the full set of functional requirements for WEC technology
- Decomposition and aggregation of functional requirement groups
- Identification of functional requirement aspects with disruptive potential for economic performance improvement
- Identification of fundamental WEC system design approaches.

VII. Innovation and Identification

Based on the clear and detailed specification of functional requirements, systemic innovation techniques (SITs), and techniques of inventive problem solving (TIPS, originally known as TRIZ [Russian]) in [5] can be applied in a targeted way to innovate high-performance WEC technology concepts. The application of these proven techniques represents an entirely novel approach in the WEC technology development industry and signifies a paradigm shift from intuitive innovation to structured innovation. Key tasks within this project module include:

- Application of traditional engineering design methodologies like morphologic analysis alongside TIPS/TRIZ and SIT to innovate WEC technology solutions, both at subfunction and system-function levels
- Evaluation of innovated WEC subfunction and system-function solutions resulting from SIT/TIPS/TRIZ, through the use of the TPL assessment process and metric

- System syntheses of subfunction solutions to complete WEC technology concepts
- Assessment and ranking of WEC technology concepts according to their techno-economic impact potential.

VIII. OPTIMIZATION AND VALIDATION

The previously identified WEC technology systems will be theoretically and numerically modeled and optimized with respect to their overall configuration, system design, and system control. Experimental validation of the numerical models and the techno-economic system performance of the optimized systems will be performed through wave tank testing. Key tasks of this project module include:

- Numerical model development of the WEC systems with the use of in-house, leading-edge modeling tools
- Optimization of overall WEC system design and embedded system control
- Design, build, and system performance validation via wave tank testing
- Reassessment of the techno-economic performance potential through application of a refined TPL assessment process and metric.

IX. TECHNOLOGY IMPLEMENTATION

To reduce subsequent technology development cost, time, and risk, key technology challenges need to be identified and technical solutions for these challenges need to be found, investigated, and resolved. This effort will substantiate key elements of the technological viability of the novel high-performance WEC technology concepts. Detailed WEC system specification and documentation will facilitate the transition to industrial WEC development with the high-confidence "seed" technologies as the kick-start for full commercial development and economic viability and operation. Key tasks of this project module include:

- Identification of key technology challenges
- Investigation of solutions to technology challenges through relevant subsystem modeling, design, bench testing, and/or other required efforts where possible supported by industry collaboration
- Reassessment of the techno-economic performance potential through application of the TPL assessment process and metric
- Completion of TRL 3–TPL 7+ WEC technology system specifications and documentation for full subsequent WEC technology industry development towards successful commercialisation.

X. CONCLUSIONS

The multiyear Structured Innovation project pursued by the National Renewable Energy Laboratory and Sandia National Laboratories, working in collaboration, has two major objectives:

- Identification and specification of high-potential, early TRL WEC technology systems to act as high-confidence "seeds" for industrial WEC technology development to full commercial and economic viability
- Development of a vastly improved WEC technology evaluation process to enable both, the development of high-potential systems, and to focus public funding and private investment on true technology merit.

This overall WEC technology innovation and development approach represents a crucial advancement over the state of the art of the WEC technology development methods and has great potential for delivering WEC technologies of significantly higher techno-economic performance then the current WEC technologies.

For the project to fully succeed, its defining foundations, i.e., the specification of the functional requirements and the further development of the TPL metric and assessment methodology, will require significant international collaboration with a range of stakeholders. The authors wish to invite the global wave energy research and WEC technology development community to engage with the project team and consider active collaboration.

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REFERENCES

[1] J.W. Weber, "WEC Technology Readiness and Performance Matrix – finding the best research technology development trajectory", in *Proc. 4th International Conference of Ocean Energy*, Dublin, Ireland, 2012.

[2] J.W. Weber, "WEC Technology Performance Levels (TPLs) - Metric for Successful Development of Economic WEC Technology", in *Proc. Tenth European Wave and Tidal Energy Conference*, Aalborg, Denmark, 2013.

[3] A. Babarit, J. Hals, M. Muliawan, A. Kurniawan, T. Moan, and J. Krokstad, "Numerical benchmarking study of a selection of wave energy converters", in *Renewable Energy*, vol. 41, pp. 44–63, 2012.

[4] Wave Energy Prize (2015) homepage [Online]. Available: http://waveenergyprize.org/

[5] I. Bukhman, *TRIZ – Technology for Innovation*, R. M. Osgood, Jr., Ed. Berlin, Germany: Cubic Creative Company, 2012.