Developing Technology Performance Level Assessments for Early-Stage Wave Energy Converter Technologies

Preprint

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2 Sandia National Laboratories

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Developing technology performance level assessments for early-stage wave energy converter technologies

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Abstract—**The advantage of using technology performance level (TPL) in conjunction with technology readiness level (TRL) assessments in guiding technology development trajectories to successful outcomes in less time, at less overall cost, and with less encountered risk has been well articulated in the literature. In partnership with industry and international collaborators, a TPL assessment methodology for grid-connected wave energy farms has been developed by applying a systems engineering approach. Metrics under seven different categories have been developed, weighted based on their relative relevance, and combined to yield a composite score. The methodology has been implemented in a spreadsheet tool plus a web application specifically aimed at assessing early-stage (TRL 1–3) concepts. The target use cases are (1) technology developers improving their design to find fatal flaws early, get feedback on current design, and identify areas of improvement that will yield the highest return on investment; (2) reviewers assessing technologies in competitions or making funding decisions; (3) investors or project developers doing due diligence; and (4) policymakers landscaping the technology domain for formulating research and development strategy. The methodology is also being adapted for assessing wave energy converters servicing markets outside the continental grid—broadly categorized as Powering the Blue Economy (PBE) applications. This paper presents the latest status of the TPL assessment methodology and tools, and describes (at a high level) how the methodology could be adapted to select PBE markets or extended to other domains where it could provide a comprehensive and holistic measure of a nascent or disruptive technology's techno-economic performance potential.**

Keywords—**Metrics, technology performance level, technology readiness level, wave energy converter.**

I. Introduction

THE need for holistically assessing a wave energy converter (WEC) technology, complementary to technology readiness level (TRL), has been previously established in the literature [1], [2], [3], [4], [5]. It is well understood by the global research and development community that 80% of a technology's costs and impacts are decided early in the design process. However, the TRL system does not address the design drivers that affect these life cycle costs and impacts; TRL represents how ready a technology is. An orthogonal metric, the technology performance level (TPL), was therefore introduced in [1] to represent how well a technology will perform (i.e., its promise when fully developed). The TPL assessment methodology accounts for the technical performance, life cycle costs, environmental and social impacts, safety aspects, and risks of a technology. Some of the benefits of the TPL assessment include:

- TPL can provide technology developers with guidance on improving their design, detection of cost and impact drivers (hot spots), and fatal flaws
- TPL can identify the optimal technology development trajectory by identifying areas to target with funding and resources
- TPL can provide investors with guided expert judgement of the promise of a technology
- TPL can help select and drive convergence to the most promising technologies
- TPL can incorporate both quantitative and qualitative design drivers, even if immeasurable
- TPL can address trade-offs between competing design goals such as performance, life cycle costs, and environmental impacts.

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The TPL methodology can be applied continuously throughout the development of a technology. In other words, it is ideally performed not just once for a technology, but rather evolves with the technology, informing decision-making along the way.

Like TRL, TPL is categorized into nine levels; the definitions of each level are presented in Table I.

TABLE I
TPL DEFINITIONS

TPL		Characteristics
Low Technology is not economically viable.	1	Majority of key performance characteristics and cost drivers do not satisfy, and present a barrier to, potential economic viability.
	2	Some key performance characteristics and cost drivers do not satisfy potential economic viability.
	3	Minority of key performance characteristics and cost drivers do not satisfy potential economic viability.
Medium Technology features some characteristics for potential economic viability under distinctive market and operational conditions. Technological or conceptual improvements may be required.	4	To achieve economic viability under distinctive and favorable market and operational conditions, some key technology implementation and fundamental conceptual improvements are required.
	5	To achieve economic viability under distinctive and favorable market and operational conditions, some key technology implementation improvements are required.
	6	Majority of key performance characteristics and cost drivers satisfy potential economic viability under distinctive and favorable market and operational conditions.
High Technology is economically viable and competitive as a renewable energy form.	7	Competitive with other renewable energy sources given favorable support mechanism.
	8	Competitive with other energy sources given sustainable support mechanism.
	9	Competitive with other energy sources without special support mechanism.

This work builds upon published literature [1], [6], [7] for early-stage (low-TRL) WECs for the continental grid application by: (1) demonstrating improvements made to the methodology based on stakeholder feedback, (2) providing new results, and (3) expanding the methodology to other applications, such as those presented in the Powering the Blue Economy (PBE) report [8].

II. Methodology

The TPL assessment methodology is derived from the systems engineering framework for wave energy farms [9]. Systems engineering is a disciplined approach to holistically evaluating the goals that must be achieved by a technology and the fundamental elements of the solution that enable achievement of the goals. This formal process, which involves analyzing customer and stakeholder needs through the discipline of systems engineering, offers a method to develop the requirements that will enable technical solutions that comprehensively address the needs of the stakeholders [9]. The systems engineering approach generally consists of four steps:

1. Define the system, boundaries, and scope
2. Develop the capabilities taxonomy
3. Derive the functional requirements and taxonomy
4. Quantification: Assign weights, formulas, detailed guidance, and relevance specific to the application.

This framework is intended to evaluate a wide range of WEC archetypes whose techno-economic performance may be impacted differently by different evaluation criteria. Similarly, the systems engineering approach may be extended to other domains beyond WECs by following these steps in the new technology domain.

A. *Define system, boundaries, and scope*

For WECs, the system is defined as the wave energy farm, up to the interconnection with the continental grid. The complex system can then be decomposed into subsystems, those subsystems into sub-subsystems, and so forth. The functional requirements can then be flowed down to each component of the system, and rigorous tracing of allocations can be applied to ensure component traceability to the functional requirements [9]. Fig. 1 shows the system definition and decomposition for a WEC farm. Note that energy storage can be applied either at the subsystem or sub-subsystem level.

For the selected PBE applications, this system definition does not change. For other domains, the system definition must be modified appropriately.

B. *Develop the capabilities taxonomy*

Once the system is well defined, the TPL capabilities taxonomy can be developed from stakeholder input. The capabilities are the system goals as determined from an analysis of stakeholder needs and values.

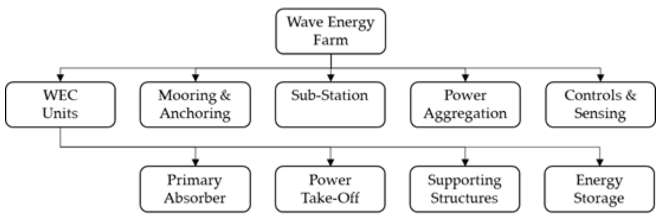


Fig. 1. System definition and decomposition.

For any technology, it is vitally important to collaborate with the wide variety of stakeholders involved and invested in the product. Stakeholders include but are not limited to technology developers, project developers, end users, regulators, investors, operators, and suppliers. Each stakeholder will have different needs and values, and some will have greater importance or relevance to the technology than others.

Babarit et al. [7] performed a stakeholder analysis for WECs for the continental grid application. For full details on methods, rankings, and stakeholder selection, please refer to [7]. They identified the following seven capabilities:

1. Have a market-competitive cost of energy (C1)
2. Provide a secure investment opportunity (C2)
3. Be reliable (for grid operations) (C3)
4. Benefit society (C4)
5. Be acceptable for permitting and certification (C5)
6. Be safe (C6)
7. Be deployable globally (C7).

The full capabilities taxonomy for the continental grid application is presented in Table II.

For PBE applications, two modifications are deemed necessary. First, the *cost of energy* capability must be expanded to be more general. Hence, it is renamed *cost of concept*. Second, for many of the PBE applications, a grid connection is simply not available, and thus the *grid operations* capability is irrelevant. However, the WEC is almost always providing power to another device or system, which has requirements on the quality of the power delivered. Furthermore, interfacing with the other device or system is important for product marketing and sales. Thus, the *grid operations* capability is replaced with a more relevant (and generally applicable) *use integration* capability. These changes are in accordance with the recommendations in [10].

For extension to other domains, the first capability must be closely tied to the primary technical performance. The others either directly or indirectly capture the other aspects of the system: life cycle costs, environmental and social impacts, safety aspects, and risks. These will ultimately depend on the values and needs of the stakeholders of the technology and should be tailored to that technology domain.

C. *Derive the functional requirements*

From these capabilities, the functions can be derived. The functions define the fundamental actions that the system must perform and the behaviors that the system must possess to achieve the mission and deliver the aforementioned capabilities. High-level functions are independent of the technology or design used to implement the function; however, detailed functions may reflect specific design choices [9].

The functions identify what the system must do and the behaviors the system must have to satisfy its mission [9]. The following are the high-level functions for a WEC farm servicing the continental grid [6]:

- Generate and deliver electricity from wave power
- Control the system and its subsystems
- Maintain the structural and operational integrity of the system and its subsystems
- Provide suitable access and transportation
- Provide synergistic benefits.

These functional requirements are further decomposed into subfunctions, sub-subfunctions, and so forth. For PBE application(s), these functions have to be adapted to the specific needs of the application. For other domains, they have to be modified as appropriate for the technology domain.

D. *Quantification*

Once the functions are derived, specific assessment questions are identified at the intersection of the capabilities and functions. The assessment questions form the backbone of the assessment and have four independent qualities or attributes:

- Question
- Question guidance
- Scoring guidance
- Weight.

To modify a TPL assessment from one application to another, one can adjust these attributes based on the new capabilities and/or functions, as well as add or remove question(s). There are 88 questions in the current version of the continental grid assessment tool. Out of these, 19 are duplicates because some questions are important from multiple perspectives and are therefore repeated. A compilation of all questions is available in the web version of the tool [11].

It is important to recall that the assessment questions may be qualitative or quantitative in nature, to account for measurable and immeasurable design drivers. The scoring guidance for each question provides the mechanism for converting a qualitative response into a quantitative value (1–9) that can be utilized in systematic calculations. The scoring guidance typically distinguishes between a low (1–3), medium (4–6), and high (7–9) scoring range.

The individual assessment questions can be assigned weights (in agreement and collaboration with the stakeholder community), and these weights can be employed to calculate a score for the sub-subcapability (CX.Y.Z). However, in the current version of the continental grid assessment tool, in lieu of weights, a feature is provided to turn a question on or off depending on whether or not it is relevant.

The calculations employ three mathematical functions: *arithmetic mean*, *geometric mean*, and *harmonic mean*. Details of the calculations for the capabilities taxonomy in Table II are given next. All sub-subcapability scores (CX.Y.Z) are calculated as the arithmetic mean of their question scores. The subcapability scores (CX.Y) are calculated from the sub-subcapability scores using (1)–(5):

$$C1.1 = 0.365C1.1.1 + 0.365C1.1.2 + 0.09C1.1.3 + 0.18C1.1.4 \quad (1)$$

$$C1.2 = 0.7C1.2.1 + 0.3C1.2.2 \quad (2)$$

$$C1.3 = (C1.3.1 \times C1.3.2)^{1/2} \quad (3)$$

$$C2.1 = [(0.7C2.1.1 + 0.3C2.1.2) \times C2.1.3 \times C2.1.4]^{1/3} \quad (4)$$

$$C6.2 = (C6.2.1 \times C6.2.2 \times C6.2.3 \times C6.2.4 \times C6.2.5 \times C6.2.6)^{1/6} \quad (5)$$

Additionally, when a subcapability has no sub-subcapabilities, the subcapability score is calculated directly from the question scores via an arithmetic mean. Furthermore, when a subcapability has only one sub-subcapability, the subcapability score equals the sub-subcapability score. Once the subcapability scores have been computed, the capability scores (CX) are calculated from them using:

$$C1 = \left[\frac{1}{\frac{0.7}{C1.1} + \frac{0.3}{C1.2}} \times C1.3 \times C1.4\right]^{1/3} \quad (6)$$

$$C4 = 0.5C4.1 + 0.5C4.2 \quad (7)$$

$$C5 = (C5.1 \times C5.2 \times C5.3)^{1/3} \quad (8)$$

$$C6 = (C6.1 \times C6.2)^{1/2} \quad (9)$$

The other capabilities currently only have one subcapability; in such cases, the capability score equals the subcapability score. Finally, the TPL score is computed via the following relationship from the capability scores:

$$TPL = 0.7 \times (C1 \times C2 \times C7)^{1/3} + 0.1 \times (C3 \times C4)^{1/2} + 0.2 \times (C5 \times C6)^{1/2} \quad (10)$$

Equations 1–10 have been modified and adapted from previously published literature [6] to improve transparency and clarity, maintain expected mathematical relationships, and better reflect stakeholder values. The assessment tool is available via a spreadsheet or web application [11].

The various weights in (1)–(10) can be adjusted based on the application and stakeholder decisions, provided they are suitably normalized. For example, PBE applications have vastly different functional requirements entailing a modification of the methodology to account for such factors as their higher risk tolerance, reduced price sensitivities, lower power needs, and different permitting protocols.

Finally, it can be argued that a single number does not convey the technology's strengths and weaknesses; however, the top-level capability scores, if well defined, can provide meaningful information to assessors. When extending to other technology domains, the stakeholder communities can determine the most meaningful and useful capabilities.

III. Results

First, an example assessment of a reference model is presented. Second, a sensitivity analysis of the TPL score with respect to the capabilities is included to reveal the sensitivity of TPL to changes in capability scores in the current implementation of the continental grid assessment.

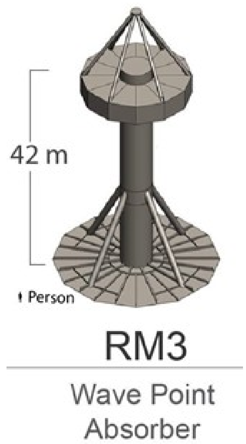


Fig. 2. Illustration of point absorber (Reference Model 3).

A. Reference model assessment

Consider an example assessment for the point absorber illustrated in Fig. 2. A description of the reference model is given in [12].

To do an assessment, representative data regarding the physical system must first be collected. It is important to note that the assessment results are only as valuable as the quality of the input data. It is understood that the input system data are continuously evolving, and the assessment results should do likewise. Finally, protecting the confidentiality and privacy of the input data is of paramount importance for success and collaboration. The technical, performance, and cost data for the reference models are publicly available and do not represent any single industry partner.

This assessment was completed by multiple assessors. The assessors discussed and collaborated to come to a consensus score for the reference model.

Table II shows the results by capability for the reference model. Fig. 3 shows the top-level capability scores graphically. The final score of 5.4 reflects a combination of scores ranging from 1.5–8.0. The highest scores are for *manufacturability* (C1.1.2), *transportability* (C1.1.3), and *capital expense uncertainty* (C2.1.1). Note *transportability* excludes tow out to deployment site which is considered an installation activity and scored as part of *installability* (C1.1.4). Also, *capital expense (CAPEX) uncertainty* represents, not CAPEX per se which is covered separately under C1.1, but the uncertainty in its estimation which begets investment risk. The point absorber scores high on *manufacturability* because even though its structure is of welded steel and requires full penetration welds which are labor intensive especially those in confined spaces, the fabrication methods fall under routine shipyard practices that do not require dedicated or specialized infrastructure. It gets a high score on *transportability* (which excludes installation) because its fabrication and assembly will be at a coastal shipyard near to the deployment site and overland transportation is limited to components (e. g. power conversion chain) transportable to the assembly location by conventional means. It scores high on *CAPEX uncertainty* (meaning there is less uncertainty) thanks to the use of commonly available materials and standard manufacturing techniques. The familiarity of these methodologies also facilitated the application of known structural analysis techniques, reducing uncertainty related to reliability and availability. However, overall the device was not found to perform highly in terms of *cost of energy* (C1), in part because the predominantly steel construction was not conducive in this case to a high power-to-cost ratio. The large footprint of the proposed mooring system and the surface profile of the device also create potential conflicts with other ocean users. A web of interconnect cables, riser cables and three catenary lines per device (Fig. 5-4 of [12]) will hinder marine traffic thru the site. For these reasons, the lowest score is for *area use conflicts* (C5.3). Such trade-offs are inevitable in design and represent the strengths and weaknesses of this technology implementation. As previously stated, the TPL assessment can aid in identifying:

- Which aspects of the technology might prove prohibitively expensive to address at later stages if not given attention at earlier stages
- Potential improvements likely to yield high return on investment
- Gaps requiring additional resources (e.g., funding, development).

TABLE II
ASSESSMENT RESULTS FOR POINT ABSORBER

	Score
C1 Cost of energy	5.9
C1.1 CAPEX	6.2
C1.1.1 Design	5.3
C1.1.2 Manufacturability	7.3
C1.1.3 Transportability	8.0
C1.1.4 Installability	5.0
C1.2 OPEX	6.5
C1.2.1 Reliability	6.5
C1.2.2 Maintainability	6.5
C1.3 Performance	5.0
C1.3.1 Energy capture	4.0
C1.3.2 Energy conversion	6.3
C1.4 Availability	6.7
C1.4.1 Availability	6.7
C2 Investment opportunity	6.3
C2.1 Investment opportunity	6.3
C2.1.1 CAPEX uncertainty	7.7
C2.1.2 OPEX uncertainty	6.7
C2.1.3 Performance uncertainty	5.0
C2.1.4 Availability uncertainty	6.7
C3 Grid operations	6.0
C3.1 Forecastable	6.0
C4 Beneficial to society	3.0
C4.1 Impact on local communities	1.7
C4.2 Greenhouse gas emission and pollution	4.3
C5 Permitting and certification	3.3
C5.1 Environmental impacts	5.0
C5.2 Ecological impacts	5.0
C5.3 Area use conflicts	1.5
C6 Safety and function	5.0
C6.1 Safety	4.7
C6.2 Survivable	5.4
C6.2.1 Extreme loads	3.5
C6.2.2 Grid failure	5.7
C6.2.3 Collisions	7.0
C6.2.4 Temporary conditions	5.0
C6.2.5 Fatigue	7.0
C6.2.6 Configuration changes	5.0
C7 Globally	5.5
C7.1 Deployment	5.5
TPL	**5.4**

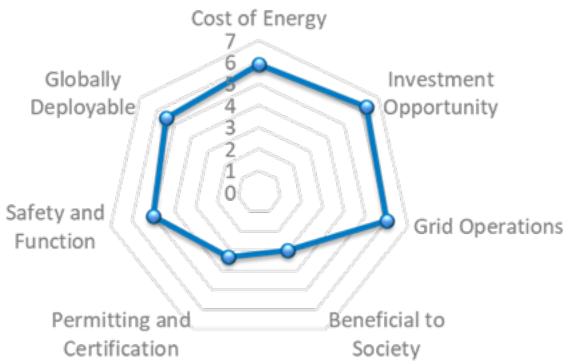


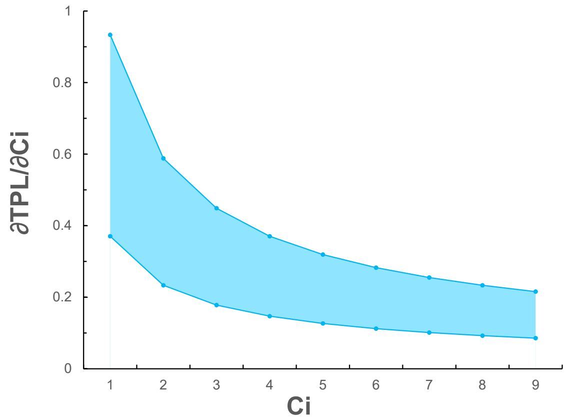
Fig. 3. Top-level capability scores for the point absorber.

B. *Sensitivity analysis*

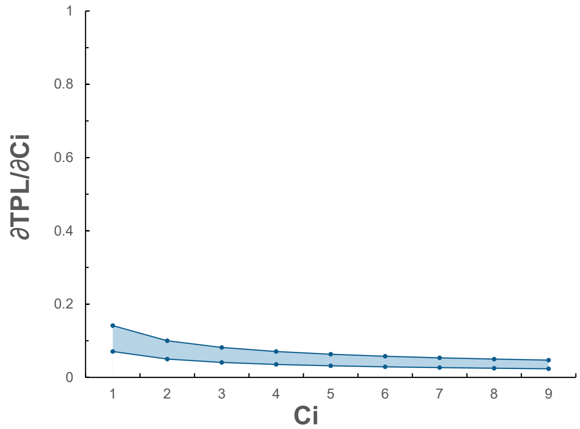
One of the areas in which the TPL framework can support technology developers is to illuminate which design drivers have the greatest impact on TPL, and thus which design features will yield the highest return on investment. This can be accomplished by changing the relevant score(s) to reflect a possible design change, and seeing how much the TPL has improved as a result. Another method is to do a sensitivity analysis, in which the change in TPL as a function of changes in a capability score is ascertained by determining the partial derivative of TPL with respect to that capability score. This is illustrated in Fig. 4 for the top-level capabilities. The partial derivative of TPL with respect to a capability score is plotted as a function of that capability score. The partial derivative gives the change in TPL due to a unit change in a capability score, all else remaining constant. The derivative is plotted with a broad brush, the width of the brush denoting a representative range. The maximum of that range corresponds to a high score of 8 on the other capabilities it is coupled to. The minimum of that range corresponds to a low score of 2 on the other capabilities it is coupled to.

Fig. 4 shows TPL is most sensitive to changes in a capability when that capability is low, and least sensitive when that capability is high. That is, investing in raising the lower scores (e.g., from 1 to 2) will have a greater effect on TPL than improving the higher scores (e.g., from 8 to 9). The narrower bands for C3 through C6 denote that the change to TPL due to a change in one of those capability scores only weakly depends on the other capability scores.

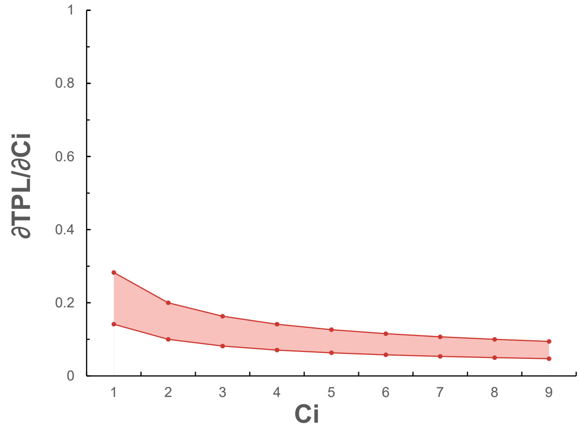
Sensitivity analyses help visualize the relative influence of a capability, subcapability, sub-subcapability, or a question on TPL. Thus, they are an aid to calibrating the TPL calculations for specific markets.



(a)



(b)



(c)

Fig. 4. Sensitivity analysis: (a) C1 cost of energy, C2 investment opportunity, and C7 globally; (b) C3 grid operation and C4 beneficial to society; (c) C5 permitting and certification, C6 safety and function.

IV. Conclusion

The TPL assessment methodology is continuously being updated to incorporate stakeholder and assessor feedback, include new applications and markets, and extend to other technology domains. Explanations are given for how the capabilities, functions, questions, and scoring may be adapted. The reference model assessment demonstrated how meaningful results can be extracted from the analysis, illuminating the strengths and weaknesses of the assessed technology. The sensitivity analysis showed how to identify the capabilities that the TPL metric is most or least sensitive to.

V. Acknowledgement

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