A comprehensive assessment tool for low-TRL current energy converters

Dominic D. Forbush, Jonathan A. Colby, and Nicole Mendoza

Abstract—**Along with a market-competitive levelized cost of energy, a current energy converter technology strongly benefits from an extensive consideration of socioeconomic, environmental, and regulatory factors early in the design process. As part of a technology performance level assessment, a series of assessment questions and guidance are developed and presented to evaluate an early-stage current energy technology on holistic criteria considering the entire device lifecycle. The assessment represents an accumulation of industry and research experience to date and relies on regular updates to ensure alignment with industry best-practices, regulatory requirements, and up-to-date technical understanding. A cradle-to-grave (materials, manufacturing, installation and deployment, operations and maintenance, and end-of-life) assessment of capabilities and functional requirements for tidal, river, and ocean current technologies has been completed. This work presents the evaluation questions and qualitative performance criteria for current energy converters deployed in tidal, ocean current, and/or river applications. Key considerations related to manufacturing and installation include supply chain robustness, manufacturability and related job creation in the end-user and/or adjacent communities, and the time-to-repayment of the embodied energy debt. During deployment and maintenance operations, the safety of the device and subsystems during disconnect or grid failure, the difficulty and frequency of offshore heavy-lift activities, the avoidance or mitigation of area-use conflicts, the sea-states and weather conditions that permit maintenance access, and the availability of contingency plans (should conditions change unexpectedly) are a portion of the considered assessment criteria. Results include the potential impact of early-stage design decisions on the socioeconomic, environmental, and regulatory performance of a technology that allows developers to increase the product value and probability of success, and minimize costly late-stage design iterations through early and broad consideration of factors affecting overall performance and acceptability.**

Index Terms—**Industry Support, Technology assessment, tidal, river, ocean current**

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I. INTRODUCTION

CURRENT energy converters (CECs) are more broadly deployed around the world than their wave energy converter (WEC) counterparts and share the advantage of energy sources that are relatively consistent and predictable among renewable technologies. While rapidly evolving and improving, deployed CECs presently do not consistently produce electricity that is cost-competitive with other renewable technologies [1] due to a variety of factors, not all of which are technical or performance related. There are numerous examples across industry and academia of techno-economic assessments of innovative approaches expected to improve performance [2] [3] [4] [5] (and ultimately reduce LCOE), but there are limited examples of holistic assessment criteria that extend beyond the performance and cost metrics of a device that can guide the design decisions of early stage developers in a concrete way.

For wave energy converting technologies, the Technology Performance Level (TPL) assessment tool was developed in a joint venture by Sandia National Laboratories and the National Renewable Energy Laboratory. Technology Performance Level represents an orthogonal axis to Technology Readiness Level (TRL) and measures a technology's potential or value, which can increase the probability of it's success in global markets [6]. The TPL assessment criteria is informed by industry best practices and understanding, technological advances, stakeholder interviews, and a detailed systems-engineering review of wave energy converter key functions, and therefore is updated periodically to reflect best-available knowledge. Use cases of the tool have included informing high-impact areas of design iteration or research and development for a self-assessing CEC technology developer, highlighting potential problem areas for a third-party, and serving as design consideration checklist for early stage concepts. Notably, the assessment is intended to evaluate a particular technology and not a specific site-and-technology pairing: while this allows a single assessment tool to be more broadly useful and insensitive to the particular nuances of a specific site, it is not

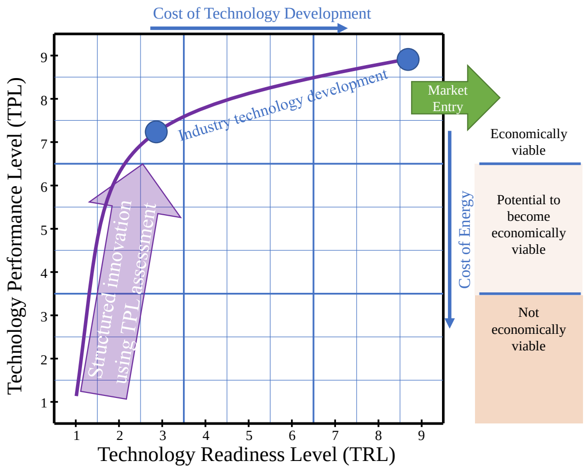

Fig. 1. TPL–TRL–matrix with technology development trajectory. Adapted from [7].

intended to predict the success of any one particular deployment of the technology, but the probability of the broadly-applied technology's success. In this work, we detail efforts to develop a similar tool for grid-connected CEC technologies.

II. Background

The structure of the TPL assessment subdivides the determination of device performance into capabilities (i.e., what a successful device must *be*). The first seven of these capabilities are also shared by the WEC TPL assessment, for which a more detailed hierarchy can be found in [8].

1) Have a market-competitive cost of energy
2) Provide a secure investment opportunity
3) Be reliable for grid operations
4) Benefit society
5) Be acceptable for permitting and the environment
6) Be safe
7) Be deployable globally
8) Adhere to standards

The presented CEC assessment has an eighth capability related to the referencing of and adherence to standards. The CEC industry as a whole is a relatively more technically mature field and has created a significant knowledge and tool base to aid further design that the TPL assessment tool can leverage, and has similarly elevated expectations when it comes to developing novel devices. Particularly, the suite of standards developed by IEC TC 114, including the IEC TS 62600-2, IEC TS 62600-200, IEC TS 62600-201, IEC TS 62600-300, and IEC TS 62600-301 standards, among others, provide best practices for design, power performance assessment, and resource characterization for tidal and river energy converters [9]. Adherence to standards, and certification by the relevant third-parties, may have a strong influence on the potential commercial marketability and success of a device. Similar standards (IEC TS 62600-100 and IEC TS 62600-101 for example) exist for WEC type devices and will be similarly incorporated into future revisions of the WEC TPL assessment.

Aspects of a single capability are evaluated as sub-capabilities (and sub-sub-capabilities), which are themselves comprised of several functional requirements [8]. The assessor answers questions that evaluate these functional requirements by providing a score from 1 (low, extremely poor performance of the function) to 9 (high, ideal performance of the function). To aid the assessor, the tool provides scoring guidance and thresholds/examples for each question. Questions can be excluded from the calculations if they do not apply to a particular technology. An example question is pictured in Fig. 2 to illustrate the assessment interface. For each question, the user is also required to provide a confidence level (high, medium, low) for the score, which will populate uncertainty bounds for every question. While the assessment is intended for low TRL devices and thus some uncertainty is inevitable, the comparison of low and high uncertainty areas is itself useful feedback. The numerical scores are averaged to provide sub (sub-sub, if necessary) capability scores, which are in turn weighted in alignment with a systematic quantification of stakeholder values and averaged to a capability score, and finally to a single final TPL score.

In order to create well-posed questions with concise, clearly stated scoring guidance, it is sometimes necessary to split multiple considerations associated with a function over multiple questions. This approach leverages the "ideal system" design paradigm, a hypothetical system that perfectly achieves the objective without any negative effects [10]. As an example, consider the function associated with efficiently capturing power. A highly efficient power-take-off (PTO) subsystem may wholly achieve this function, but it may increase the cost/complexity of the system. This is evaluated over multiple questions, including:

1) What is the efficiency between the absorbing element of the prime mover (e.g., turbine shaft) and the component that produces transportable power (e.g., a gearbox, alternator, power conditioning in the CEC)?
2) What is the cost of the system that converts mechanical power to power exported from the CEC, prior to any conditioning necessary for transportation/grid integration?
3) Are the PTO components difficult to source, made of specialty material (e.g., very high cost, unknown properties for use/environment, or specially made/ordered) or require specialized manufacturing/repair (e.g., difficult to work with or not suitable for conventional manufacturing methods)?

To evaluate the different factors affecting this particular example, the "ideal system" is one that, for no added cost or complexity, provides the most efficient power capture. A system that approaches ideality will achieve a higher score.

It is important to note that the single top-level TPL score cannot describe a device' strengths and weaknesses, but the set of capability scores and uncertainty estimates can provide useful information to device de-

Question	Score Guidance	Score	Confidence	Include	Net scores			Question Guidance
Is the CEC insensitive or able to adjust to changes in the principle flow direction?	High: The CEC can capture power from all flow directions with equal efficacy (i.e., a system that adjusts its yaw angle to provide flow alignment) or innate property of design (vertical axis rotor). Med: The CEC can capture power from some flow directions with equal efficacy but is limited in the extent to which it can adjust to assymmetric flows (i.e., a cross-flow turbine with a horizontally-oriented axis of rotation). Low: The CEC shows significantly reduced power capture if there is any flow misalignment or assymmetry in the tidal flow (i.e., cases where ingoing and outgoing tides are not separated by 180 degrees).	8	High	Yes	7.84	8	8.16	The CEC should not be limited to operating in a narrow resource found at limited sites but should be able to produce its nominal peak power for many different resources and, thus, at many different sites. Most sites do not have completely consistent flow directions throughout the deployment period. Tidal ebb and flow directions are not likely to be perfectly opposing.

Fig. 2. CEC TPL example question.

Summary:			Score confidence lower bound	Input Score	Score confidenc e upper bound		
		Technology Performance Level:	4.4	4.9	5.4	Potentially econ. viable	Not econ. viable
C1	Have market competitive cost of energy		4.7	5.4	6.1	4	3
C1.1		Have as low a CAPEX as possible	4.9	5.7	6.3		
C1.2		Have as low an OPEX as possible	4.0	4.6	5.2		
C1.3		Able to generate a large amount of electricity from wave energy	5.4	6.2	6.9		
C1.4		Have high availability	4.3	4.9	5.4		
C2	Provide a secure investment opportunity		4.7	5.3	5.9	4	3
C3	Be reliable for grid operations		4.6	4.9	5.1	3	2
C4	Be beneficial to society		5.1	6.0	7.0	3.5	2
C5	Be acceptable for permitting and environment		5.1	5.5	5.8	7	4
C6	Be acceptable with respect to safety		4.1	4.6	5.0	7	4
C7	Be deployable globally		6.2	7.0	7.8	5	3
C8	Standards and Certification		4.2	4.9	5.6	5	3

Fig. 3. CEC TPL top sheet score summary.

Fig. 4. CEC TPL capability-level scores. The score increases towards the outside of the spider-graph. The size of the marker illustrates the importance of the respective capability to the top-level TPL score. The distance between marker and confidence bounds indicates the uncertainty in a capability score. The shaded areas illustrate thresholds for technology to become viable. The numeric values shown in the spider graph are merely illustrative and are not based on an actual device.

velopers and assessors. The tool provides the capbility level scores in tabulated form, illustrated in Fig. 3, and in the form of a spider-plot, Fig. 4.

III. Methods

While device developers, users, or external evaluators (e.g., funding agencies, investors) are the intended users of the TPL assessment tool, they do not comprise all of the stakeholders that will determine the success of the device. As a holistic assessment tool, the TPL assessment incorporates their perspectives through literature reviews, case studies, and/or stakeholder interviews. In developing the CEC assessment from the WEC assessment, it is recognized that there are a number of common stakeholders on the basis that both technologies are to be deployed in diverse ways in a marine environment and both are intended (within the scope of the tools under discussion) to provide grid-scale power. In this way, the set of novel stakeholders that are unique to the CEC application is substantially reduced. These include:

- CEC device developers and operators
- CEC-specific component (e.g., blades) manufacturers and suppliers
- CEC site-specific environmental and marine spatial planning stakeholders

In the latter case, because tidal and river CEC devices will be deployed in areas of high-velocity flow, this implies they are likely deployed in areas where the water area is constricted, which raises unique environmental concerns and elevates the level of concern for potential area use conflicts like maintaining shipping lanes above those predicted impacts for WEC technologies [11]. While ocean current technologies likewise rely on high-velocity flow, this velocity is not generally created by a constriction of water area and thus does not raise the same set of marine-spatial planning concerns.

Similarly, while the minute-to-minute operations of harvesting power may look identical between the three technologies, longer time-scale characteristics of tidal, river, and ocean current energies differ significantly and require unique considerations of device operation and maintenance in each setting. For instance, while there may be some seasonal variation or extreme flows due to hydrologic events, river flow is consistent in time, and though the most desirable flow may meander over time, it does so over relatively short length scales [12] [13]. River flow is similar in this way to ocean flow, but the latter demonstrates far more significant meandering on the order of kilometers [14]. Considered in the context of power capture, it is more important for an ocean current device to be able to adapt its position to changing inflow and/or harvest efficiently over a broader range of flow conditions than it is for a river device, though the two devices may be quite similar in form. In contrast to a tidal device, which sees periodic flow variation and reversal multiple times per day, the ability to yaw or harvest bi-directional flows is of paramount importance.

The implications of site/resource characteristics extend to power delivery and device maintenance as well. By necessity, river and tidal CECs are relatively close to land (though perhaps not to power infrastructure). However, only a tidal CEC enjoys a regular and predictable period of low-speed flow that might facilitate maintenance activities.

Thus, although river, tidal, and ocean current technologies can be collectively termed "current energy converters", the distinct social, environmental, and technical requirements that collectively determine their overall performance implies that a development of a separate TPL assessment tool for each deployment environment would ensure that each assessment can directly consider these important distinctions. For CECs, this critical subdivision is drawn among much clearer lines than WEC counterparts. There are many commonalities in the resulting tidal, river, and ocean CEC assessments: in the forthcoming section, distinctions in the assessment content and method between resources are indicated when they occur.

IV. Results

The resulting river, tidal, and ocean CEC assessments consist of a series of unique questions in total spanning the 8 above capabilities. In the following section, we present a selection of questions and scoring criteria for each resource type and capability as examples of assessment content. An emphasis was placed on presenting the questions that are distinct to each resource type.

A full version of the WEC TPL tool can be found at https://tpl.nrel.gov/assessment, and release of the CEC TPL tool is forthcoming. For access to the full CEC assessment tools, please contact the lead author.

A. Cost of Energy

Cost of energy has the vast majority of questions (though many questions first presented here also contribute to scores in other capability areas) and is highly important among stakeholders, though the exact cost-of-energy at which CEC becomes market-competitive varies, at a minimum, by region. Cost of energy is subdivided into CAPEX, OPEX, Performance, and Availability sub-capabilities (which are somewhat overlapping).

TABLE I
Example CAPEX question for a river CEC

Question	Scoring Guidance
Will the device experience large structural loads because of debris or other environmental forces, and will large structural components be needed to resist that force?	**(High)** The structure will not experience large structural loads during extreme events because of design (e.g., bottom mounted) or a load mitigation strategy. **(Medium)** The structure will experience some high loading because of some sorts of extreme events, having a mitigation strategy of limited scope, such as a load-mitigating control approach that limits drive-train but not structural loads. **(Low)** The device will experience large structural loads and does not have a mitigation strategy to avoid those loads other than through direct structural resistance.

1) CAPEX: Versions of this question in the tidal and ocean assessments also appear but with additional emphasis on waves, though debris is still considered as it presents a risk in some form. This question is presented similarly with respect to OPEX as well, as certain mitigation strategies (or lack thereof) may increase the frequency of maintenance intervals [15] [16].

TABLE II
Example OPEX question for an Ocean CEC

Question	Scoring Guidance
What are the limiting wave heights that allow maintenance access? How is relative motion between the CEC and work platform minimized? Or motion between the CEC and mooring?	**(High)** The CEC can be serviced in wave heights in excess of 2 m. **(Medium)** The CEC can be serviced in wave heights of 1-2 m, with some but not all tasks potentially doable in larger waves. **(Low)** The CEC can be serviced in wave heights less than 1 m, with most tasks not doable in larger waves.

2) OPEX: This question is presented among others that ask similarly about wave period, wind speed, and current speed (though the river CEC omits wave consideration). A similar set under the CAPEX sub-capability asks the same about allowable sea states for installation. Quantitative guidance for this sea-state evaluation is roughly correlated with the Beaufort sea-state scale, but is presented over several questions because particular maintenance operations may be difficult in large waves but simple in substantial wind, and limitations on a service vessel/task may be more strongly affected by a particular condition.

TABLE III
Example Performance question for a tidal CEC

Question	Scoring Guidance
Is the CEC insensitive or able to adjust to principle flow direction?	**(High)** The CEC can capture power from all flow directions with equal efficacy (e.g., a system that adjusts its yaw angle to provide flow alignment) or innate property of design (vertical-axis rotor). **(Medium)** The CEC can capture power from some flow directions with equal efficacy but is limited in the extent to which it can adjust to assymmetric flows (e.g., a cross-flow turbine with a horizontally-oriented axis of rotation.) **(Low)** The CEC shows significantly reduced power capture if there is any flow misalignment or asymmetry in the tidal flow (i.e., cases where incoming and outgoing tides are not separated by 180 degrees).

3) Performance: This question is presented as one of a set with others that evaluate the cost and complexity of the subsystem performing this function: an ideal system will achieve a high score on this question without increasing cost or complexity [17]. Versions of this question also appear in the river and ocean assessments with significantly relaxed scoring guidance owing to the significantly reduced variation in flow direction present at those sites.

4) Availability: All questions in this subcapability are considered in at least one of the other cost-of-energy subcapability scores, as device down-time has implications on maintenance intervals (OPEX) and materials/design choices (CAPEX). This question (among

TABLE IV
EXAMPLE AVAILABILITY QUESTION FOR A TIDAL CEC

Question	Scoring Guidance
Are the CEC subsystems desiged for the lifetime loads (i.e. fatigue) for the intended life span and operational environment?	**(High)** All CEC subsystems and their components have safety margin for their expected lifetime/maintenance interval in the operational environment. Loads and conditions are well characterized. **(Medium)** Same as high except the loads and conditions are not as well characterized or some uncertainty exists within the structural reliability modeling. Components and subsystems are designed with easy access for replacement. **(Low)** Fatigue loads or operating conditions are not well characterized. Some components may fail in fatigue prior to intended design life.

others) suggests the importance of understanding, modeling, and designing for fatigue in the marine environment. [18] [5].

B. Investment Opportunity

This is a highly important capability as any low-TRL device with ambitions of deployment must attract funding, and it is broadly affected by performance in other capability areas: a device providing a secure investment must also have an attractive LCOE, be safe, etc. As such, many relevant questions also exist in these capability areas.

TABLE V
EXAMPLE INVESTMENT OPPORTUNITY QUESTION FOR A TIDAL CEC

Question	Scoring Guidance
Is your device vulnerable to supply chain risk? For example, are any material types used in the CEC rare or located only in particular parts of the world? What material types are vulnerable to price fluctuations?	**(High)** Components/material types vulnerable to supply chain uncertainty are less than 10% of the CEC cost. **(Medium)** 10%–30% of the CEC cost is for component/material types vulnerable to supply chain uncertainties (e.g., rare earth magnetic material). **(Low)** More than 30% of the CEC cost is for component/material types subject to price fluctuations (e.g., rare earth magnetic material).

This question specifically addresses vulnerabilities to supply-chain risk, as this can affect manufacturing, installation, and maintenance costs and time-tables, and appears similarly in river and ocean assessment tools. Supply chain risk can add significant uncertainty to the investability of a particular concept.

C. Grid Integration

Interconnection of a CEC to a continental grid is governed by standards [19] and local requirements. The extent to which the connected CEC is useful to the grid is determined by its forecastability/availability and its performance of ancillary services. Because grid characteristics are not strong functions of resource type (tidal, river, or ocean), these capability questions do not vary between assessments.

TABLE VI
EXAMPLE GRID INTEGRATION QUESTION

Question	Scoring Guidance
Are the power electronic components of the CEC/array adjustable to meet the interconnection standards of various grids?	**(High)** The CEC/array power electronics are modular and modifying to meet local grid requirements is a low-complexity operation. **(Medium)** The CEC/array power electronics are modular, but somewhat inaccessible and modifying is a high-complexity operation. **(Low)** The CEC/array power electronics are customized to the CEC PTO: meeting various standards requires various custom manufacturing steps.

D. Beneficial to Society

An ideal CEC will be beneficial to the society in which it is deployed and more broadly to the world as a whole. While this is certainly a multifaceted and holistic question, we attempt to evaluate this in terms of job creation, and energy debt, and the use of recyclable materials. For a low TRL device, it is expected that job creation numbers are approximate, but low level estimations may be possible [20], and industry experience can better inform these estimates as time progresses. These questions are consistent across resource types, although the definition of a “local” community for an ocean current device is necessarily more flexbile.

TABLE VII
EXAMPLE IMPACT ON LOCAL COMMUNITY QUESTION

Question	Scoring Guidance
How many operating jobs (life of the project) will the CEC contribute to the local community where it is deployed, in full-time-equivalent jobs per gigawatt of installed capacity?	**(High)** The farm will generate more than 50 FTE/GW lasting the lifetime of the farm in the local community. **(Medium)** The farm will generate 20–50 FTE/GW lasting the lifetime of the farm in the local community. **(Low)** The farm will generate less than 20 FTE/GW lasting the lifetime of the farm in the local community.

1) Impact on local community: This question might be seen as an inverse framing of OPEX: a device with low OPEX (and thus a high score in relevant areas) will likely require fewer personnel and score low here. However, an ideal device might have low OPEX but also facilitate development of significant local industry. That said, the validity of the provided scoring guidance is highly uncertain owing to the relatively small number of CEC deployments at grid-scale.

2) Greenhouse Gas Emission and pollution: Quantitative guidance here is rough: aside from being desirable that a device repays its energy debt in a small fraction of its lifetime [21], there is not consensus on how long this ought to take. Though embodied energy data exists [22] [23] , there is lack of manufacturing and materials data from existing devices.

E. Permitting and Environment

Current events [24] emphasize that the success of even the most technically promising devices are jeop-

TABLE VIII
EXAMPLE GREENHOUSE GAS EMISSION AND POLLUTION QUESTION

Question	Scoring Guidance
How long will it take for the CEC device to repay its energy debt? Include energy for material production, manufacturing of components, procurement, construction, and decommissioning.	**(High)** Less than 5 years in a 2 m/s resource. **(Medium)** Less than 10 years in a 2-m/s resource. **(Low)** More than 15 years in a 2-m/s resource.

ardized by the permitting process and their perceived environmental impacts and/or area use conflicts.

TABLE IX
EXAMPLE RIVER CEC AREA USE CONFLICT QUESTION

Question	Scoring Guidance
Do any characteristics of the system restrict its application in environmentally sensitive locations?	**(High)** The system is benign and can be deployed in all but the most sensitive areas. **(Medium)** The system is not completely benign, but impacts are minor and of only one type, such as sediment impact or noise, that is acceptable or reasonably mitigated in most locations. **(Low)** The system will have an impact in several ways, or the impact will likely require extensive mitigation or eliminate many sites from consideration

1) Environmental Impacts: This question is repeated for the ocean and tidal environments. Although the assessment tool itself is site-agnostic, it rewards technologies that will be suitable for a broad range of sites, as this question demonstrates. However, it remains necessary for any project to engage with the particular stakeholders of a proposed site, as the definition of an "environmentally sensitive location" is highly flexible.

TABLE X
EXAMPLE TIDAL CEC AREA USE CONFLICT QUESTION

Question	Scoring Guidance
What is the potential impact of a damaging turbine blade strike on marine mammals?	**(High)** There is little to no probability of blade strike, either because the system does not use blades, the turbine rotor is shrouded and/or of low solidity, or the device utilizes some other effective mitigation strategy. **(Medium)** There is a low probability of blade strike, but such an instance would be unlikely to cause damage to the marine mammal because rotor components are not moving significantly faster than the surrounding flow (i.e., a cross-flow turbine rotor), or components are designed to absorb/mitigate the damage done during a blade strike event. **(Low)** There is a moderate probability of blade strike and an instance may cause damage to the marine mammal because rotor components sweep a large area and are moving much faster than the surrounding flow, and no mitigation strategy exists (i.e., a large, unshrouded, horizontal axis rotor).

2) Ecological Impacts: There is a significant collection of data that suggests CECs do not pose a risk to passing fish populations, but concerns surrounding blade impacts on marine mammals continue [11]. Scoring guidance follows recommendations in [25].

TABLE XI
EXAMPLE TIDAL CEC AREA USE CONFLICT QUESTION

Question	Scoring Guidance
Given the desired farm rated power and the expected horizontal footprint, what area will the farm occupy per rated farm power? Use the layout of a typical array and consider the total exclusion area. This does not include area between devices sufficiently spaced to allow vessel navigation between them.	**(High)** $2.5x10^3$ m ^{2}/MW **(Medium)** $1x10^4$ m ^{2}/MW **(Low)** $5x10^4$ m ^{2}/MW

3) Area Use Conflicts: This question is used as a coarse evaluation of potential conflicts with other marine users. This question also appears for river and ocean CECs, though the scoring guidance is relaxed for the ocean devices. A similar question evaluating the vertical footprint (i.e., occupied area of the water column) for river and tidal environments which are more frequently depth-constrained. The quantitative scoring guidance is rough: as more devices are deployed, the bounds of acceptable footprints across a myriad of sites will become more apparent.

F. Safety and Function

The safety and survivability of a deployed device is a highly important concern among all stakeholders. Though the assessment is intended for low-TRL devices that are not likely to have developed detailed procedures for installation, maintenance, and decommissioning, the early incorporation of design-for-safety principles can save costly iteration at later design stages. It is similarly vital that the various potential failure modes cause the device to enter a safe state where it can easily be returned to service.

TABLE XII
EXAMPLE TIDAL CEC SAFETY QUESTION

Question	Scoring Guidance
Is there a threat to human health and safety during any life cycle stage? Consider all life stages, including design, manufacturing, assembly, lifting, transport, installation, operation, maintenance, removal, and decommissioning.	**(High)** All activities are well understood, and adequate safety systems and procedures have been documented. No access to dangerous parts is available to third parties. The risk to human health and safety is low. **(Medium)** All activities include documented safe operating procedures, but one or more activities is novel and not yet well understood or access to dangerous parts by third parties is discouraged but can't be prevented. There is a medium threat to human health and safety. **(Low)** Human health and safety are not considered, or operation and maintenance procedures do not have adequate safety guidance. The risk may be high.

1) Safety: The "safety" subsubcapability refers particularly to human health and safety. These questions also appear for river and ocean CECs. Other questions in this capability relate to the sea-states in which it is possible to perform installation/maintenance activities. For an ideal system, it will be possible to perform installation and maintenance activities in rough seas without endangering equipment or personnel.

TABLE XIII
EXAMPLE RIVER CEC SURVIVABLE QUESTION

Question	Scoring Guidance
How susceptible are the CEC device and systems fixing CEC position to increasingly energetic flow conditions? How do they react (in terms of motions and loads) to highly energetic environments (i.e., large return period environments)?	**(High)** CECs is designed to decouple, reduce flow area, or otherwise mitigate loads in overly energetic flow automatically.This mitigation strategy can reduce loads to safe levels. **(Medium)** CECs is designed to decouple, reduce flow area, or otherwise mitigate loads in overly energetic flow.This mitigation strategy cannot wholly reduce loads to safe levels. **(Low)** CECs is not designed to decouple, reduce flow area, or otherwise mitigate loads in overly energetic flow.

2) Survivable: The "survivable" subsubcapability refers particularly the resiliency of device subsystems and components to natural forces. These questions also appear for tidal and ocean CECs, but the emphasis is placed on large return period sea-states (e.g., extreme waves) given the predictability of flows in these environments. Other questions in this subsubcapability evaluate device behavior in grid loss, collision, changes to a "survival mode" configuration, and the extent to which fatigue has been modeled and considered in design.

G. Globally Deployable

This capability evaluates how much of the potential global current energy resource the device would be well-suited to harvest. Though low TRL technologies are likely targeting proof-of-concept deployments at a particular site, designing for large-scale deployment early may save costly iteration later. Questions consider the acceptable deployment conditions and performance sensitivities to site conditions such as waves (except for river CEC) and depth as well as repeating the consideration of specialty materials or manufacturing requirements that may hinder scale-up. This example question deals explicitly with bottom type.

TABLE XIV
EXAMPLE TIDAL CEC GLOBALLY DEPLOYABLE QUESTION

Question	Scoring Guidance
What geophysical conditions are required to deploy this concept?	**(High)** Any bottom type acceptable **(Medium)** Limited options acceptable for bottom material **(Low)** Only one bottom type, such as solid rock, acceptable

H. Certification and Standards

This capability consists of only 2 questions and is consistent across tidal, river, and ocean CEC assessments. Adherence to marine standards during device development and pursuit of third-party verification efforts from an early stage can ensure performance and an efficient certification workflow. Certification according to internationally-accepted standards can increase investor confidence, improve the terms of insurance, and streamline global permitting and deployment.

TABLE XV
CERTIFICATION AND STANDARDS QUESTIONS

Question	Scoring Guidance
Have marine and current energy standards been incorporated into the device design and performance estimates?	**(High)** Standards have been thoroughly incorporated in the design process. Performance estimates are based on relevant testing standards **(Medium)** Standards have been considered in some aspects of the design process. Performance estimates are reasonable, but deviate from relevant testing standards. **(Low)** Relevant standards have not been considered.
Has third-party verification been performed?	**(High)** Third party verification of the CEC design and performance has been completed, or plans to pursue third party verification have been integrated from an early stage in the development process. **(Medium)** Third party verification of some aspects of the design/performance has been completed. Plans to pursue third party verification exist for the future, but have not been integrated from an early stage in the development process **(Low)** Third party verification has not been completed and there are no plans to pursue it.

At an early stage of development, it is likely that the device under assessment is at an early stage in the verification process [9].

V. DISCUSSION

Any TPL assessment tool for a rapidly developing industry is best regarded as a living document that continuously integrates best-available knowledge and practices. Of particular interest to tool developers is quantitative scoring guidance like that in Tables 2, 5, 9, and other questions not presented here. At present, the amount of available data that informs these estimates of scoring guidance varies sharply from question-to-question: while many resource-related calculations are informed by substantial literature, other quantitative metrics like cost estimates and footprint area is much less available. Accurate scoring guidance ensures that the resulting capability score is a useful predictor of competitiveness in the industry at present. Additionally, as the collective understanding of stakeholders' needs and values increases, the scope of the assessment may need to shift or expand. For example, the concerns related to CEC noise emissions were a significant concern that has diminished significantly in recent years thanks in part to a quorum of studies around deployed devices that found them to be significantly quieter than other sources of marine emissions [11] [25].

It is important not to conflate the number of evaluating questions with the importance of a (sub) capability. For example, cost of energy has, by a significant margin, the most questions of any capability across each resource type. In this case, there are many established and quantifiable contributing factors to cost of energy that facilitate numerous questions. Safety, for example, is similarly of high importance, but contains fewer questions because in the available literature and shared industry experience, there is less detailed discussion of safety practices and philosophies. While cost-of-energy is universally applicable to any CEC archetype, safety is more often nuanced to a specific device and deployment and may not be so readily generalized into a TPL assessment-suitable question. It can be assured in the calculation of the TPL score that the number of questions does not affect relative capability importance but this sort of disparity can suggest needed areas of research and discussion. In other words, knowledge related to cost-of-energy might be easier to share with early-stage developers than knowledge related to safety. It is for these and similar reasons that regular engagement with the various stakeholders at all stages of development is necessary for the tool to be both used and useful.

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