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Scoring the Technology Performance Level (TPL) Assessment

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***Abstract*—For energy generation devices such as wave energy converters (WECs), techno-economic performance should be considered early in the development process, when fundamental conceptual, operational and design choices are being made. Hence, the Technology Performance Levels (TPL) were designed to consider a wide range of WEC attributes that define the techno-economic performance potential as well as identify potential showstoppers at the earliest stages of WEC development. The original groups and attributes of the TPL assessment used in the Wave Energy Prize have been updated using a formal Systems Engineering approach. This paper will detail the process of determining the assessment questions for each capability (a condensed list of stakeholders' requirements) in the TPL taxonomy. These questions direct the assessor towards the most appropriate considerations for a given capability. The scoring criteria give guidance on how to rank the answer to the assessment questions. The assessment questions combined with the scoring criteria allow for the technology to be numerically ranked on the TPL scale. Details on the calculations required to obtain a TPL score for a device are presented.**

***Keywords*— Wave Energy, TPL, assessment, scoring criteria, Wave-SPARC**

I. Introduction

Technology development progress, technology value, and technology funding have largely been associated with and driven by technology readiness, measured in Technology Readiness Levels (TRLs) [1, 2]. Originating primarily from the Space and Defense industries, TRLs focus on procedural implementation of technology developments of large and complex engineering challenges where cost is neither mission critical nor a key design driver. However, wave energy converter (WEC) technology development as a whole has not yet delivered the desired commercial maturity or the desired techno-economic performance by following the TRLs.

For energy generation devices such as WECs techno-economic performance considerations should be considered early in the development process, when fundamental conceptual, operational and design choices are being made. Hence, the Technology Performance Levels (TPL) [3, 4] were designed to consider a wide range of WEC attributes that define the techno-economic performance potential as well as identify potential showstoppers at the earliest stages of WEC development. The original groups and attributes [3] of the TPL assessment used in the Wave Energy Prize [5] have been updated using a formal Systems Engineering approach [6, 7, 8].

Systems Engineering is a rigorous application of processes and methods across a system's life cycle in order to ensure the adequacy of a system. The heart of systems engineering is a step-wise decomposition and flow down of stakeholder needs to each element of the system. The decomposition, flow down, and tracing of allocations ensures that the requirements and specifications for each subsystem, assembly, and component fully reflect and address stakeholder needs and adequately contribute to overall system performance. This program has followed guidance from ISO 15288 [9], as well as IEEE 1233 [10] with some tailoring according to the process described in ISO 15288 Annex A.

Capabilities and functions are hierarchical structures (i.e. taxonomies) that enable the mission to be achieved; where the mission has been defined as:

> *The wave energy farm will convert ocean wave energy to electricity and deliver it to the continental grid market in a competitive and acceptable manner across the lifecycle.*

In the case of capabilities, the taxonomy embodies the list of characteristics that are desired, from the perspective of the stakeholders, for the system to be successful. This capability taxonomy now forms the basis of the technology performance levels [6, 7, 8]. In terms of the functions, the hierarchy represents the solution agnostic elements (i.e. independent of specific design embodiments) that are needed to meet the stakeholder requirements.

This paper will detail the process of determining the assessment questions and scoring criteria for each capability in the TPL taxonomy. These questions direct the assessor towards the most appropriate considerations for a given capability. The scoring criteria give guidance on how to rank the given answer (on a scale of 1-9) for each assessment question. A description of how the different levels of the taxonomy are combined into a single numerical ranking is then given. This full procedure

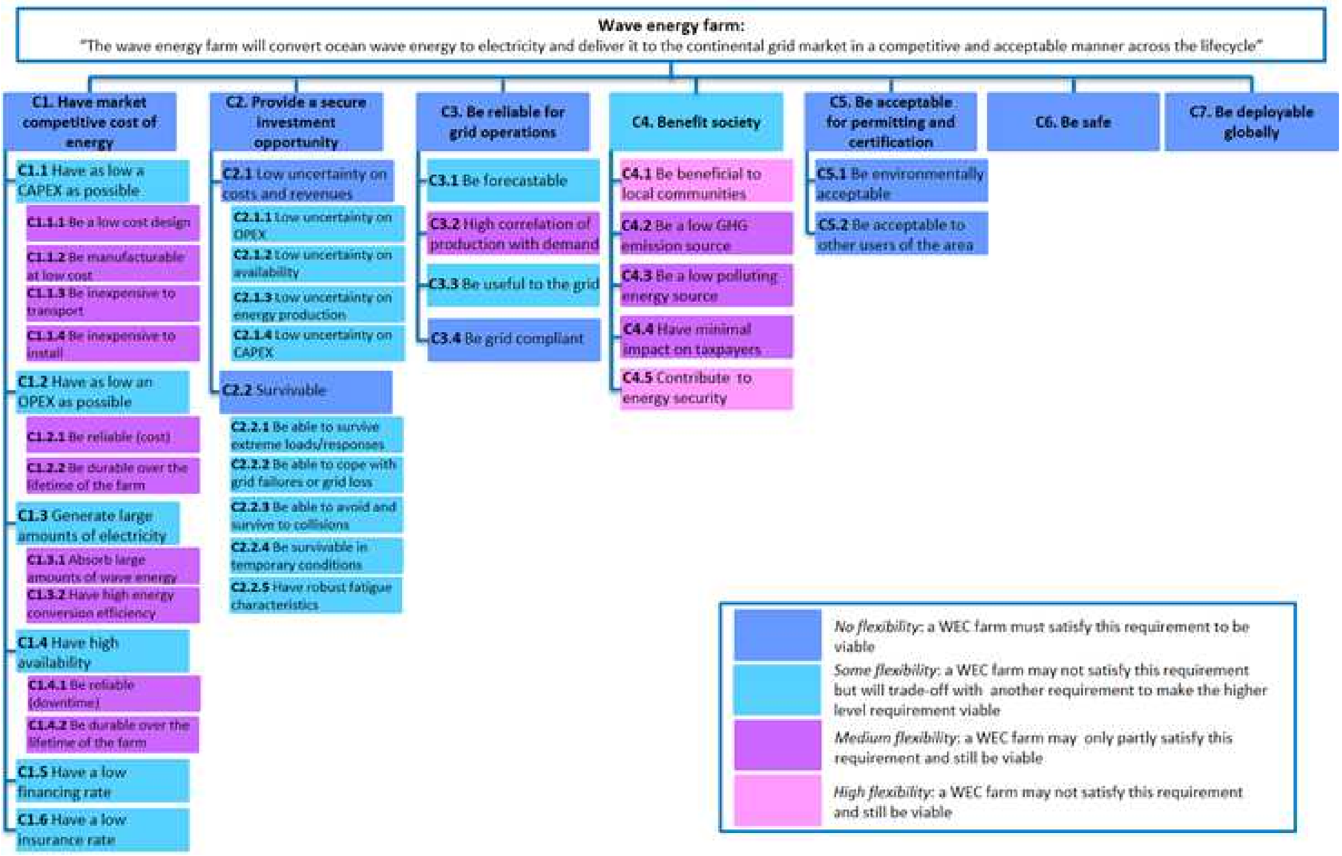

Fig. 1 TPL Taxonomy

details how a technology may be numerically ranked with a single value on the TPL scale of 1-9.

II. TPL Taxonomy

The TPL is designed to be an assessment of the suitability of the technical solution for the customers' needs. The capability taxonomy, which identifies what the system must *be* from the stakeholders' perspective, constitutes the TPL groups and attributes that were originally developed through experience [3].

Analysis of stakeholders' needs leads to the specification of seven high-level stakeholder requirements. Five of these have been split into sublevel requirements. Some of the sublevel requirements have been split into sub-sublevel requirements. The full taxonomy is shown in Fig. 1. Satisfaction of a requirement at a higher level depends on the satisfaction of the requirement at the sublevel. For example, the sub-capability *C1.1 Have as low a CapEx as possible* is achieved by: being a low cost design (C1.1.1), being manufacturable at a low cost (C1.1.2), being inexpensive to transport (C1.1.3), and being inexpensive to install (C1.1.4).

Further, the color-coding associated with the taxonomy is intended to highlight the flexibility associated with achieving the stakeholder need. For instance, at the highest level a farm may still be successful even if there is no benefit to society (C4).

III. Functions Taxonomy

The functions define the fundamental elements of the solution that must be provided in order to achieve the mission and deliver the capabilities. They identify the behaviours the farm must possess, i.e. the farm must be able to generate and deliver electricity from wave power. High-level functions are independent of the technology or design used to implement the function.

The wave energy farm is the *system* that is being optimized. The system is further broken down into subsystems and sub-subsystems and so on. It is not necessarily the goal to optimize these subsystems and sub-subsystems individually, but rather to optimize the farm.

The top level functions (5 of them) conceptually identify what the wave energy farm must do to meet its mission. The subfunctions below the top levels further decompose the top level functions (e.g. WEC or electrical substation). These subfunctions identify the unique aspects that must be achievable to satisfy the higher level function. Further breakdown is given to subfunctions in the form of sub-subfunctions, further focusing in on the details that are needed (e.g. PTO within a WEC). In all cases, sub-levels fully identify the aspects that must be achieved to fully satisfy the higher level details in the full taxonomy (Fig. 2).

IV. TPL Assessment

Trade-offs in the overall design manifest themselves in competing TPL criteria (the capabilities). The specific technical solutions chosen for a design are assessed and scored for each capability independently. When all of the capabilities are then combined for the final ranking, these trade-offs become clear.

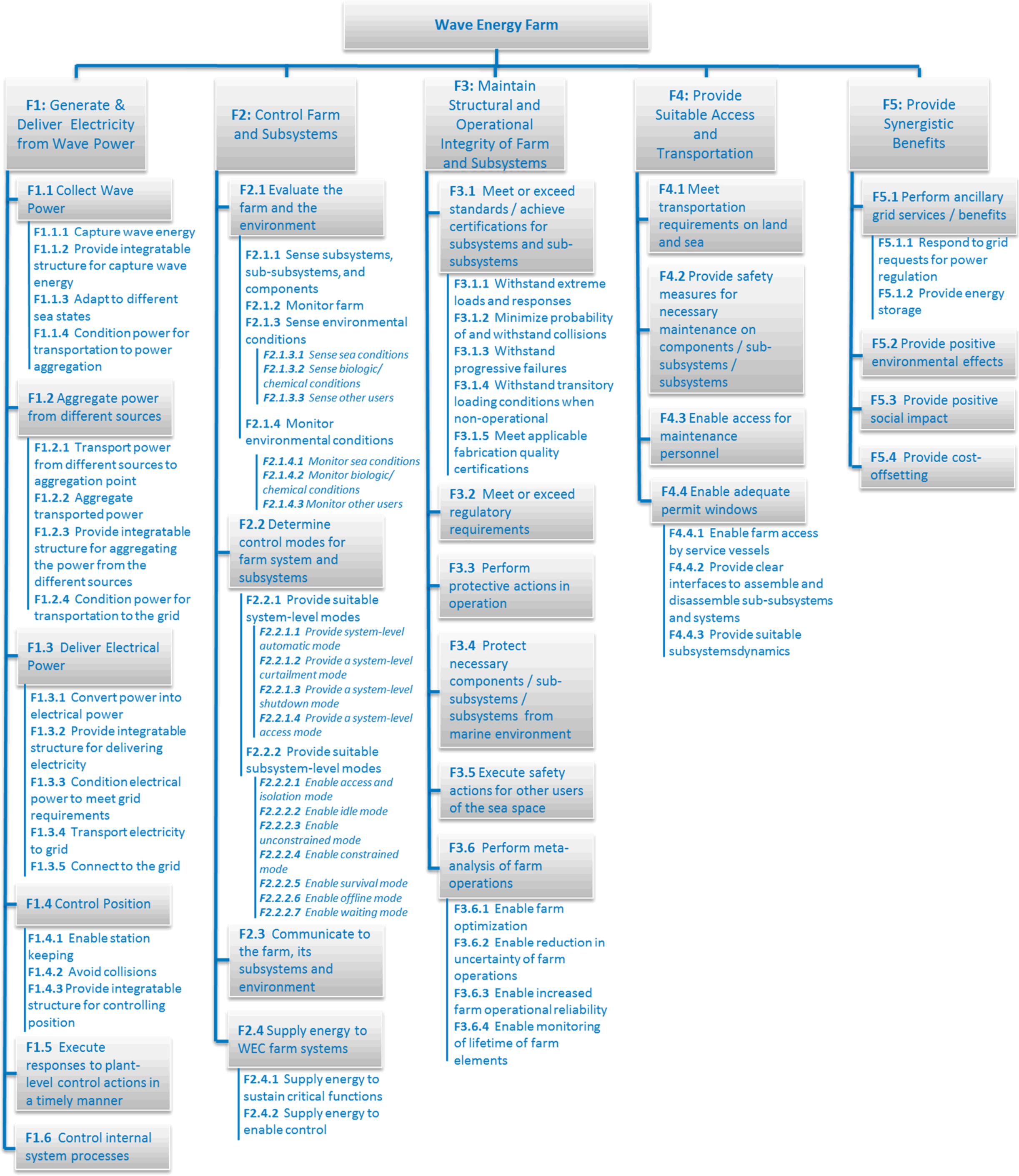

Fig. 2 Functions Taxonomy

For instance, favouring small amounts of material may receive a high score in terms of capital expenditure (CapEx), but this may be balanced by a low score in power generation due to small device size.

When determining the assessment questions, measures identified at the intersections of the functions and united capabilities were identified. Given that the functions identify what the system must *do* in order to achieve what the system must *be*, these measures identify the concrete basis for the assessment questions. Fig. 3 illustrates a generalized version of this concept. By compressing all of the measures that have been identified across all of the functions, i.e. by collapsing all columns into one, a series of assessment questions to assess the capability were generated.

In this new TPL approach, *C1: Have a market competitive cost of energy* contains all of the elements needed to calculate the levelized cost of energy (LCOE) for the technology, and at TRL5 it will be expected that this calculation is completed. The capital expenditure (C1.1), operational expenditure (C1.2) and energy production (C1.3 and C1.4) are all directly represented in this capability and at the lower TRLs each of these facets are queried with appropriate substitutes for cost depending upon the degree the technology has been developed.

Capabilities - functions mapping matrix		Functions			
		Function 1	*Sub-function 1.1*	Function 2	Function F
Capabilities	Capability 1	Measure 1			
	Capability 2			Measure 1	Measure 1
	Sub-capability 2.1		Measure 1 Measure 2		
	Capability C				Measure 1

Fig. 3 Generalized capabilities – functions mapping matrix.

The financing and insurance are also represented in the TPL taxonomy as these alter the LCOE, however since they are not technology specific they are not included in the TPL assessment.

A. TRL Dependence

This revised version of the TPL assessment addresses the question of appropriate levels of detail at different TRL levels. The assessment questions are grouped according to three levels of TRL (1-2, 3-4, and 5-6). The most basic questions are addressed for TRL 1-2 technologies. An expanded more detailed set of questions is addressed for TRL 3-4 technologies and these must also update their answers to the TRL 1-2 questions when requested. Finally, technologies at TRL 5-6 and above must present quantified and verified evidence for the assessment process.

For instance, assessment questions in *C1.1.1 Be a low cost design* at TRL 1-2 query the following concepts:

- The technical maturity of the subsystems (spanning new solutions that have never been tested before all the way to proven technologies tested in a relevant environment),
- WEC specific questions: size, dominate material type, loading, and physical profile changes,
- Position control specific questions: deployment depth and connections to sea floor.

TABLE I
EXPECTATIONS FOR VARIOUS TRL RANGES

Key TPL Factors	**TRL1-2**	**TRL3-4**	**TRL5-6**
Farm configuration	Number of devices, packing density	Number of devices, packing density, device arrangement / interaction	Layout considering local bathymetry, number, arrangement,
Energy in the deployment environment	-5 representative sea states, -Sensitivities to tidal, direction, current, etc.	-Generic scatter diagram & sea-state definition -No spreading but mean direction per sea state defined.	Actual deployment scatter diagram and sea conditions known including spreading, tide, current, etc...
Deployment	-Target location (near-shore, off-shore, etc.) -Sensitivities to seabed's	Targeted distances from shore, seabed types that would work	Actual farm location known and characterized (distances, seabed, etc.)
WEC Power Production	-Freq domain / estimation methods; average only -Single efficiency values.	-Linear time domain—30min rep's, averages and peak values -Dynamic analysis (i.e. frequency dependent, efficiencies, etc.)	-Time domain – 10yr history -Dynamic analysis, nonlinearities included,
WEC supporting Structure	Profile of design, CoG, CoB, MoI, dominant material types	~volume of material, large scale loads (bending moments)	Complete structural design capable of withstanding communicated loads
Failure Modes*	-Basic understanding of key failure modes -number and types of point loads	-Knowledge of the design loads and top 10 FMECA -Characteristic load and catastrophic load known as well as corresponding return period for characteristic load.	-Full & complete FMECA -Characteristic load and catastrophic load known as well as corresponding return periods.
Maintenance and installation.	Weather window known as % of time access in a year	Weather windows known as % of time per month access	Full weather window definition (# in each month for given duration)
Maintenance	Lifetime, basic failure pathways, location of maintenance (storyboard), MTBF of subsystems, # and type of vessel	Frequency (planned and unplanned), downtime, capacity reduction, permit windows, round trip time, inspection requirements	
Fatigue		Number and magnitude of point loads (cycle and magnitude)	Calculation of fatigue life.

In particular *F1.1.2: Provide integratable structure for capture wave energy* and *F1.4.3 Provide integratable structure for controlling position* in Fig. 2 are the focus of the assessment questions because they are the cost drivers that the assessor can reasonably expect the developer to know at TRL 1-2. Below, an excerpt from the full assessment for *C1.1.1 Be a low cost design* at TRL 1-2 focusing on the subsystem that collects wave power is shown.

For the subsystem that collects wave power, please answer the following questions:

a. Where in the water column is this subsystem located?
 High: Subsystems submerged far below the free surface will experience the smallest loads on the structure provided the pressure inside is equal to the hydrostatic pressure.
 Med: Minimal surface expression or only submerged minimally below the free surface.
 Low: Surface expression indicates susceptibility to higher global loads, slamming and greenwater loads, and additionally collisions with other users of the area.

b. What is the displaced volume?
 High: Displaced volume less than 500m^3/MW.
 Med: Displaced volume between 500 and 2500m^3/MW
 Low: Displaced volume greater than 2500m^3/MW

c. What is the dominant material type and what is its raw cost?
 High: traditional cheap material types in agreement with typical raw cost
 Med: traditional expensive material types
 Low: novel material types with uncertain raw cost data

d. What is the mass for structural members that are not intended to collect wave power, i.e. e.g. structural elements whose main purpose is not to provide surface area for wave power absorption? For example: Internal reaction masses, structural linkages such as beams, lattice structures, tie bars.
 High: a small fraction <10%
 Med: between high and low
 Low: a large fraction >50%

e. How many sets of point loads (heave plate, mooring lugs, PTO, end stops) affect the subsystem that collects wave power? Note: Point loads occur when two bodies connect for which the forcing profiles are distinct (general hull withstands hydrostatic pressure combining with the PTO attachment at which thrust forces must be mitigated); special structural solutions may be employed to distribute the point loads across a wider area. Identify the type and number.
 High: Only one set of point loads (for instance mooring attachment points or PTO attachment points)
 Med: Three sets of point loads (for instance mooring attachment points, end stops, and heave plate)
 Low: More than three sets of point loads

f. What is the total number of distinct physical/structural configurations, i.e. can the subsystem that collects wave power alter its physical profile by changing: the water plane area, swept volume of motion by more than just the limitations of the PTO, etc.)?
 High: Only one distinct physical/structural configuration
 Med: Two distinct physical/structural configurations that differ by less than 50%
 Low: More than two distinct physical/structural configurations or two distinct physical configurations that differ by more than 50%

These questions illustrate the type of knowledge that is expected at TRL1-2. Basic understanding of the WEC design, materials, and loads is expected. The scoring criteria are general yet directive enough to indicate appropriate scores. For instance, that if the structure has a very large displaced volume then material will be required to enclose this volume and thus increasing cost for any given material and negatively impacting *C1.1.1 Be a low cost design.* Since each capability is assessed independently, the effects of a large structure on cost can be detangled from the effects on power production. Thus, receiving a low score here is not indicative of an overall low score; it is simply showing that the design may end up being expensive and hence will need to compensate with high power conversion in order to obtain an overall high TPL value. The questions at TRL 3-4 and TRL 5-6 become much more specific and prescribed in terms of the accepted verification methodologies.

Scoring criteria is offered and this team has worked to ensure sound criteria. However, as this assessment is used it is fully expected that revisions to both the criteria and the assessment questions will be suggested and implemented.

At each intersection a similar process was followed: first the measures that allow one to assess how well a function is meeting a capability are identified. Then these measures are prioritized and crafted into TRL specific questions. In this manner assessment questions, targeting the lowest levels of the taxonomy in Fig. 1, have been generated to produce a comprehensive TPL assessment methodology.

TABLE ITABLE II presents a high level overview of the knowledge that a developer is expected to have for key TPL factors in each TRL range. The assessment questions have been developed following these expectations of development.

V. TPL Scoring

A. Combining Individual Assessment Scores

The lowest level of each capability has a series of questions that must be answered and scored. For instance, determining the score for the capability *C1.1.1. Be a low cost design* at the TRL 3-4 level, requires answering 27 questions. Each question is scored with a value between 1-9 with scoring guidance given at a fidelity that separates Low (1-3), Med (4-6), and High (7-9). The assessor will use the scoring guidance to determine the exact TPL score value between 1-9 by considering the deviation from the target value given in the scoring guidance. For instance, when applying the scoring guidance to determine an exact TPL value for the displaced volume (question b): if the technology displaces 1800m^3/MW, then a TPL value of 5 should be assigned. Alternatively, if the displacement were 500m^3/MW then a TPL value of 7 should be assigned.

Given the large volume of information that the assessor collects, it is important to ensure that this information is used

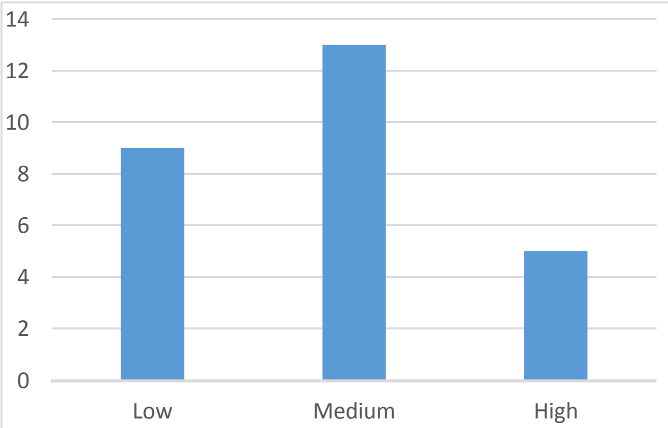

Fig. 4 Histogram of TPL groupings

to guide the final score without being prescriptive. In general, two methods are recommended to be used together to determine the final TPL score for the capability:

- plot a histogram of the number of occurrences of Low, Medium, and High scores, and
- compute both the average value and the standard deviation of the numerical (1-9) scores.

As an example, these two methods have been applied for the capability *C1.1.1 Be a low cost design*. Here the 27 questions were scored; Fig. 4 shows a histogram of the TPL groupings and TABLE II shows the occurrence of TPL scores. An initial look at Fig. 4 clearly indicates that the majority of the questions were scored at a Medium level, skewed towards the Low end. This result indicates the assessor should be considering a TPL score of around 4.

Further analysis of TABLE II results in an average value of 4.3 and a standard deviation of 1.9. This further solidifies the overall TPL score of 4. However, the standard deviation indicates that the assessor has the right to choose a score anywhere between TPL 2 and 6—this is at the assessor's discretion based on their understanding of the novelty, defendability, and clarity of the concepts presented for the technology. It could be that the assessor has determined that there is a fundamental flaw in the design that will cause the technology to fail—the assessor has the freedom to highlight this flaw in the final score by assigning a low TPL value. This choice can be made even if the rest of the TPL scores do not support this assignment; the assessor should highlight this fundamental flaw in the technology when returning the score to the developer.

B. Determining Group Scores

The next level (or group score) is then calculated from a mathematical calculation of the underlying levels. Three different ways of combining the lowest level scores (e.g. C1.1.1, C1.1.2, C1.1.3, and C1.1.4 to create C1.1) are used in the revised formulation. These are *arithmetic mean, geometric mean* and *multiplication with normalisation. Arithmetic mean* is used when combining scores that measure similar attributes e.g. used for combining costs. The arithmetic mean has the property that it is similar to a logical OR e.g. when combining

TABLE II
EXAMPLE SCORING RESULTS FOR 'BE A LOW COST DESIGN'

TPL	Occurrence of Score
1	3
2	1
3	5
4	7
5	4
6	2
7	4
8	1
9	0

costs it does not matter what the individual costs are only what the combined cost is. *Geometric mean* and *Multiplication* are used when combining scores that measure disparate attributes. *Multiplication* is similar to a logical AND, it is used to combine 'must haves'. As a result, this method is more punitive than the geometric mean; to get a good score in the combined result it is necessary to have a good score in ALL of the inputs. e.g. the different types of survivability are 'must haves'.

The calculations will be shown for *C.1 Have market competitive cost of energy*, all other calculations are detailed in [6]. The TPL_{C1} value is calculated from two levels of nested sub-capabilities. C1 is scored as the geometric mean of the TPL scores for total cost, generation, availability, with equal weighting to each.

$$TPL_{C1} = (TPL_{COST} \cdot TPL_{C1.3} \cdot TPL_{C1.4})^{1/3} \tag{1}$$

The score for total cost is a combination of the CAPEX and OPEX scores and relies on a CAPEX:OPEX weighting of 70:30.

$$TPL_{COST} = \frac{1}{\frac{0.7}{TPL_{C1.1}} + \frac{0.3}{TPL_{C1.2}}} \tag{2}$$

C1.1 is scored as a weighted sum of the individual cost TPL scores in CAPEX.

$$TPL_{C1.1} = \frac{1}{\frac{0.36}{TPL_{C1.1.1}} + \frac{0.36}{TPL_{C1.1.2}} + \frac{0.09}{TPL_{C1.1.3}} + \frac{0.18}{TPL_{C1.1.4}}} \tag{3}$$

C1.2 is scored as a weighted sum of the individual cost TPL scores in OPEX.

$$TPL_{C1.2} = \frac{1}{\frac{0.7}{TPL_{C1.2.1}} + \frac{0.3}{TPL_{C1.2.2}}} \tag{4}$$

C1.3 is scored as the product of the inputs and then scaled to a range of 1-9. Each input is equally important.

$$TPL_{C1.3} = (TPL_{C1.3.1} \cdot TPL_{C1.3.2} - 1)\left(\frac{8}{9^2 - 1}\right) + 1 \tag{5}$$

C1.4 is scored as the weighted average (arithmetic mean) of its inputs. Weights are 50:50.

$$TPL_{C1.4} = 0.5 \cdot TPL_{C1.4.1} + 0.5 \cdot TPL_{C1.4.2} \quad (6)$$

C. Determining Final TPL Score

Lastly a calculation is performed on the seven highest level capabilities to determine the final TPL score. Threshold TPL values have been associated with the lowest levels of the capabilities. In the calculation tool these thresholds do not alter the score, however a tally of the breached thresholds is kept. This should help identify areas that are of great concern for the technology.

The overall TPL score is calculated from scores for the seven high level capabilities arranged in in three categories as shown in TABLE III.

The overall TPL is calculated as a weighted average (arithmetic mean) of the scores for these three categorizations. The weightings for the categories are 0.7:0.2:0.1 for economics, acceptability and benefits respectively. The equation is:

$$TPL = 0.7 \cdot TPL_{eco} + 0.2 \cdot TPL_{acc} + 0.1 \cdot TPL_{ben} \quad (7)$$

The combined scores for each of the categories that are passed as inputs to equation 1 are calculated as a geometric mean of their respective inputs. The equations used are:

$$TPL_{eco} = (TPL_{C1} \cdot TPL_{C2} \cdot TPL_{C7})^{1/3} \quad (8)$$

$$TPL_{acc} = (TPL_{C5} \cdot TPL_{C6})^{1/2} \quad (9)$$

$$TPL_{ben} = (TPL_{C3} \cdot TPL_{C4})^{1/2} \quad (10)$$

D. Calculating Tool

A calculating tool is provided in the form of an excel spreadsheet. The tool will take the input scores from the lowest level capabilities (see Section A) to determine the Group Score (see Section B) and then the final TPL score (see Section C). In this excel tool, if a threshold has been breached the threshold box will change to red and the text will indicate the number of thresholds that have been breached. Fig. 5 is a still shot of an example that has been input into the calculator tool. Note, the weights and threshold TPL values associated with each of the sub and sub-subcapabilities are subject to revision

VI. Conclusions

This paper has presented the results of applying Systems Engineering to a wave energy farm and the resulting revision to the TPL structure. The methodology to assess and score a technology using the TPL framework has been presented. The complete assessment and scoring criteria can be found in [6]. Methodologies that should be followed to determine the numeric input scores for the lowest levels of the TPL have been presented as well as the calculations that are being used to determine the group values and finally the single TPL score for an assessed technology.

TABLE III
Capability Category

Capability	**Category**
C1: Have market competitive cost of energy.	Economics
C2: Provide a secure investment opportunity.	Economics
C3: Be reliable for grid operations.	Benefits
C4: Benefit society.	Benefits
C5: Be acceptable to permitting & certification.	Acceptability
C6: Be safe.	Acceptability
C7: Be deployable globally.	Economics

The TPL assessment identifies the technology independent "performance requirements" by offering a holistic approach to assessing a technical solution. It is not enough to simply have a low LCOE, one must also mitigate risk and uncertainty as well as consider the ability to be globally deployable. By achieving a high score in the TPL assessment, the technical solution has met the "performance requirements" of the stakeholders. Hence, the TPL assessment identifies the *technology independent* "performance requirements."

The highlights of the revised TPL methodology include:

- Integration of LCoE calculation into the TPL.
- More complete inclusion of investment security and risk.
- Harmonization of TPL with terminology of certification and standards.
- Reconciliation of TPL with Systems Engineering.
- TPL is now assessed using a list of detailed questions and scoring guidance.
- Significantly expanded depth of coverage.
- Updated calculation methodology.

As part of the Wave-SPARC project, the updated TPL, assessment, scoring criteria, and calculations will be used on industry partners within the US. It is expected that this process will result in strong feedback and will offer pathways to improve the assessment of WEC technologies. This team will continue to improve the assessment methodology as feedback is provided by users.

Acknowledgment

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Summary:

	Technology Performance Level:	4.0	9 Thresholds Breached
C1	Have market competitive cost of energy	4.8	
C1.1	Have as low CAPEX as possible	1.6	All Thresholds OK
C1.2	Have as low an OPEX as possible	5.3	All Thresholds OK
C1.3	Be able to generate large amount of electricity from wave energy	6.4	All Thresholds OK
C1.4	Have high availability	8.5	All Thresholds OK
C2	Provide a secure investment opportunity	1.8	
C2.1	Be survivable	2.0	3 Thresholds Breached
C2.2	Be low risk under design conditions	1.6	4 Thresholds Breached
C3	Be reliable for grid operations	4.0	All Thresholds OK
C4	Be beneficial to society	7.5	All Thresholds OK
C5	Be acceptable for permitting and certification	7.0	1 Threshold Breached
C6	Be acceptable w.r.t safety	5.0	1 Threshold Breached
C7	Be deployable globally	4.0	All Thresholds OK

Note 1: Preliminary version - 30 June 2016.
Note 2: The weights are subject to revision. This is not the final version.

	Capability	Input Score	threshold	weight	relative weight	contrib.'	Group Score	Threshold	Notes:
C1	Have market competitive cost of energy						4.8		Note: C1 is scored as the geometric mean of: 1/total cost, generation, availability. With equal weighting to each. CAPEX:OPEX weighting within 'total cost' is 70:30.
C1.1	Have as low CAPEX as possible		threshold	weight	relative weight		1.6		Note: C1.1 is scored as a weighted sum of the "value for money" scores. Weights are shown.
C1.1.1	Be a low cost design	1	0	20	36%			Threshold OK	
C1.1.2	Be manufacturable at low cost	2	0	20	36%			Threshold OK	
C1.1.3	Be inexpensive to transport	3	0	5	9%			Threshold OK	
C1.1.4	Be inexpensive to install	4	0	10	18%			Threshold OK	
C1.2	Have as low an OPEX as possible		threshold	weight	relative weight		5.3		Note: C1.2 is scored as a weighted sum of the "value for money" scores. Weights are shown.
C1.2.1	Be reliable (cost of maintenance)	5	4	7	70%			Threshold OK	
C1.2.2	Be durable over the lifetime of the plant	6	4	3	30%			Threshold OK	
C1.3	Be able to generate large amount of electricity from wave energy		threshold				6.4		Note: C1.3 is scored as the product of the inputs. Each input is equally important.
C1.3.1	Absorb large amounts of wave energy	7	4					Threshold OK	
C1.3.2	Have high energy conversion efficiency of extracted energy to electrical energy	8	4					Threshold OK	
C1.4	Have high availability		threshold	weight	relative weight	contrib'	8.5		Note: C1.4 is scored as the weighted average (arithmetic mean) of its inputs. Weights are shown.
C1.4.1	Be reliable (lost revenue w.r.t time taken)	9	4	5	50%	4.50		Threshold OK	
C1.4.2	Be durable over the lifetime of the plant	8	4	5	50%	4.00		Threshold OK	
C2	Provide a secure investment opportunity						1.8		Note: C2 is scored as the geometric mean of its inputs. Each input is equally important.
C2.1	Be survivable		threshold				2.0		Note: C2.1 is scored as the product of its inputs. Each input is equally important.
C2.1.1	Be able to survive extreme loads/responses (can be caused by extreme weather conditions or high power operational conditions)	7	7					Threshold OK	
C2.1.2	Be able to cope with grid failures, grid loss or grid interruption (black start capability); coupling grid loss with a communication loss	6	7					Threshold Breached	
C2.1.3	Be able to avoid and survive to collisions (ships, other marine users, mammals)	5	7					Threshold Breached	
C2.1.4	Be survivable in installation (& tow-out)	4	7					Threshold Breached	
C2.2	Be low risk under design conditions		threshold				1.6		Note: C2.2 is calculated to reflect the impact of the inputs on cost of energy. CAPEX:OPEX weighting is 70:30
C2.2.1	Be low uncertainty on OPEX	3	4					Threshold Breached	
C2.2.2	Be low uncertainty on availability	2	4					Threshold Breached	
C2.2.3	Be low uncertainty on energy production	1	4					Threshold Breached	
C2.2.4	Be low uncertainty on CAPEX	2	4					Threshold Breached	
C3	Be reliable for grid operations		threshold	weight	relative weight	contrib.'	4.0		Note: C3 is scored as a weighted average (arithmetic mean) of its inputs. Weights are shown.
C3.1	Be forecastable	3	1	1	33%	1.00		Threshold OK	
C3.2	Have stable annual power production	4	1	1	33%	1.33		Threshold OK	
C3.3	Be useful to the grid	5	1	1	33%	1.67		Threshold OK	
C4	Be beneficial to society		threshold	weight	relative weight	contrib.'	7.5		Note: C4 is scored as a weighted average (arithmetic mean) of its inputs. Weights are shown.
C4.1	Be beneficial to local communities	6	1	1	25%	1.50		Threshold OK	
C4.2	Be low carbon emission energy source	7	4	1	25%	1.75		Threshold OK	
C4.3	Be a low polluting energy source	8	4	1	25%	2.00		Threshold OK	
C4.4	Minimize impact on taxpayers	9	4	1	25%	2.25		Threshold OK	
C5	Be acceptable for permitting and certification		threshold				7.0		Note: C5 is scored as a geometric mean. Each input is equally important.
C5.1	Be environmentally acceptable	8	7					Threshold OK	
C5.2	Be acceptable to other users of the area	7	7					Threshold OK	
C5.3	Be grid compliant	6	7					Threshold Breached	
C6	Be acceptable w.r.t safety	5	7				5.0	Threshold Breached	
C7	Be deployable globally	4	4				4.0	Threshold OK	

Fig. 5 Example TPL calculation inside of excel calculator tool.

REFERENCES

[1] J.Fitzgerald et. al., 2012 "Technology Readiness for Wave Energy Projects; ESB and Vattenfall classification system", In Proc. 4th International Conference on Ocean Energy (ICOE2012), Dublin, Ireland.

[2] K. Ruehl and D. Bull, 2012 "Wave Energy Development Roadmap: Design to commercialization," in *OCEANS '12. "Harnessing the Power of the Ocean". Proceedings*, Hampton Roads, VA, pp. 1–10.

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

[4] J.W. Weber, R. Costello, J. Ringwood, 2013, "WEC Technology Performance Levels (TPLs) – metric for successful development of economic WEC technology", in Proc. Of the 10th European Wave and Tidal Energy Conference (EWTEC2013), Aalborg, Denmark

[5] U.S. Department of Energy, "Wave Energy Prize," 2016. [Online]. Available: http://waveenergyprize.org

[6] Bull, D., Costello, R., Babarit, A., Nielsen, K., Bittencourt Ferreira, C., Kennedy, B., Malins, R., Dykes, K, Roberts, J., Weber, J., "Systems Engineering Applied to the Development of a Wave Energy Farm", Sandia National Laboratories, SAND Report: SAND2017-XXXX, March 2017

[7] Bull, D., Babarit, A., Weber, J., Malins, R., Costello, R., Nielsen, K., Roberts, J., Kennedy, B., Dykes, K, Bittencourt Ferreira, C., "Systems Engineering applied to the development of a Wave Energy Farm", 2nd International Conference on Renewable Energies Offshore, Lisbon, Portugal.

[8] Babarit, A., Bull, D., Dykes, K, Malins, R., Nielsen, K., Costello, R., Roberts, J., Bittencourt Ferreira, C., Kennedy, B., Weber, J. , "Stakeholders' requirements for a commercially successful farm of wave energy converters," Renewable Energy. Submitted.

[9] International Organization for Standardization, 2008. ISO/IEC 15288:2008 Systems engineering -- System life cycle processes.

[10] IEEE 1233, R2002 "Guide for Developing System Requirements Specifications". Institute of Electrical and Electronics Engineers. 1998 Edition(R2002) (http://www.standards.ieee.org/)