REFINEMENT OPTIONS OF THE TECHNOLOGY PERFORMANCE LEVEL METRIC FOR THE DEVELOPMENT OF WAVE ENERGY CONVERTERS

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INTRODUCTION

This paper describes one option for the refinement and further development of the Technology Performance Levels (TPL) as a metric for the identification of the techno-economic performance potential of wave energy converters (WEC). This optional TPL metric refinement focuses of the use of the TPL metric particularly at low Technology Readiness Levels (TRL). This publication is intended to invite and generate stakeholder feedback and influence the direction the refinement and further development of the TPL will take. It will describe the current TPL development status and outline the proposed refinement options.

TPL DEVELOPMENT – TO DATE

The TPLs were introduced in [1] and further detailed in [2] and [3]. Analogous to the TRLs as defined in [4], the TPLs are categorized into nine levels quantifying the techno-economic, functional, and lifecycle performance of the WEC system. The nine TPLs are listed in Table 1 with their category and primary characteristics. This metric considers all key cost and performance drivers in the form of a large number of system attributes that serve as assessment criteria that are categorized into five groups—acceptability; power absorption, conversion, and delivery; system availability; capital expenditure (CapEx); and operational expenditure (OpEx).
Within each of the five categories, a number of applicable cost and performance drivers are assessed to determine the techno-economic performance potential for each group. The key criteria include:

1. Acceptability:
Lifecycle environmental acceptability; social acceptability and socio-economic impact and/or benefit; legal, regulatory, and certification acceptability; safety; risk mitigation; insurability; and market acceptability by investor, financier, operator, or utility

2. Power absorption, conversion, and delivery:
Hydrodynamic wave power absorption; internal power conversion; power output and delivery; controllability with fast, wave-by-wave control; controllability and adaptability with slow, sea-state-by-sea-state control; and short-term energy storage capability

3. System availability:
Survivability; reliability; durability; redundancy; force, power and information flow; system adaptability supporting availability; and forced shutdown

4. Capital Expenditure:
Supply chain; material types; mass and required material quantity; manufacturability; transportability; wave farm infrastructure (non-WEC device); device deployment, installation, and commissioning; maintainability; CapEx requirements; modularity CapEx requirements; redundancy CapEx requirements; loading and load-bearing CapEx requirements; and acceptability CapEx requirements

5. Operational Expenditure:
Ability and ease of monitoring; accessibility; maintainability; modularity and ease of subsystem

and component exchange; ease of partial operation and graceful degradation; insurability cost; planned maintenance effort; unplanned maintenance effort; acceptability OpEx requirements.

TABLE 1. TECHNOLOGY PERFORMANCE LEVEL CATEGORIES AND CHARACTERISTICS.

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

The TPL assessment is supported by a detailed comprehensive document listing all sub-criteria to be considered in each of the criteria within the 5 criteria groups. For instance, within the criteria group power absorption, conversion, and delivery the assessment of the hydrodynamic wave power absorption capability covers aspects of the ability to effectively absorb wave energy from ocean waves to a useful next form of energy and includes the following sub-criteria.

- Class of absorption
  - Terminator, attenuator, and point absorber
- Type and number of degrees of freedom (DOF) utilized for power absorption. These include motion and deformation DOFs
  - Heave, pitch, surge, etc., relative, absolute, other modes, combinations thereof
- Theoretical limits (high) as upper bounds for the hydrodynamic power absorption capability of the technology dependent on the types and number of DOFs used for power absorption
- Wave radiation capability of the system (high)
- Capacity factor of wave power absorption subsystems (high)
- Capability to:
  - Absorb wave power over a wide frequency bandwidth (high)
  - Deliver high wave power absorption (high) in high-energy-content sea states (i.e., with high annual energy contribution) and reduced wave energy absorption and reduced load generation (low) in less frequent high power and low-energy-content sea conditions
  - Convert the absorbed wave power into a subsequent and usable energy form (high) e.g., low losses in the flow field that absorb a portion of the wave power but are not converted to power producing surface pressure field, thus keeping wave power absorption losses low
- Need to
  - Create residual and/or non-power producing loads (low).

The classification of each sub-criterion into “(low)” and “(high)” indicates the orientation if low or high levels of the system characteristics with respect to this criterion will lead to a high TPL score. In order to arrive at criteria score all sub-criteria need to be considered.
Along with the sub-criteria list the category characteristic for low (TPL 1 – 3), medium (TPL 4 – 6) and high (TPL 7 – 9) are described to guide the scoring with respect to the given criterion in the group.

The methodology to evaluate the system TPL value of a WEC system is based on all individual criteria scores and the following simple arithmetic:

1. A given WEC technology is evaluated against all criteria and a $TPL_{i.j}$ score ranging from 1 to 9 is allocated with respect to each criterion 'j' within each group 'i'.
2. Each $TPL_{i.j}$ score is checked against an independent minimal threshold value that a given WEC technology needs to satisfy irrespective of any of the other $TPL_{i.j}$ criteria scores.
3. The $TPL_{i.j}$ criteria scores of each of the five criteria groups 'i' are weighted averaged to determine the five group TPL_i scores TPL_{Power}, $TPL_{Availability}$, TPL_{CapEx}, TPL_{OpEx}, and $TPL_{Acceptability}$.
4. The combined value $TPL_{Economic}$ is determined via
$$TPL_{Economic} = \left(TPL_{Power} \cdot TPL_{Availability} \cdot \left(0.7\,TPL_{CapEx} + 0.3\,TPL_{OpEx}\right) - 1\right) \frac{9-1}{9^3-1} + 1$$
This equation reflects the multiplicative nature of power, availability, and cost-effectiveness in the techno-economic performance. Subsequently the product is linearly scaled back to the TPL scale ranging from 1 to 9.
5. The overall system value TPL_{System} is determined via
$TPL_{System} = 0.8\,TPL_{Economic} + 0.2\,TPL_{Acceptability}$.

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

TPL DEVELOPMENT – REFINEMENT OPTIONS

Through a number of workshops in Europe and the United States, stakeholder feedback is being sought for further refinement and TPL metric and methodology. Following a workshop held in November 2015 at Ecole Centrale de Nantes, France, on the structure, applicability and potential refinement of the TPL metric and methodology a number of possible changes have been proposed. At the same time, the TPL metric was acknowledged as an extensive and potentially the most complete known and holistic consideration of WEC techno-economic performance criteria and related metric. It was found that the TPL metric and methodology works well to support structured guided expert judgement. It was pointed out that, as in its application in the Wave Energy Prize, the TPL assessment should be based on a corresponding structured technical documentation and description of the WEC technology under consideration.

The key aspect in the proposed refinement of the TPL metric is the transfer from assessment criteria and sub-criteria to a construct of questions so that the user of the methodology will address a sequence of hierarchical and closed questions and will evaluate the criteria by selecting a weighted score and answers from a list provided. At the highest levels these questions are motivated by a small set of fundamental questions for each of the five criteria groups acceptability; power absorption, conversion, and delivery; system availability; capital expenditure (CapEx); and operational expenditure (OpEx). These fundamental questions reflect on the end-user requirements and may accordingly be non-technical. In the group of power absorption, conversion, and delivery these fundamental questions are as follows

- FQ1- How much energy will the wave energy converter and the plant produce (assuming 100% availability) and what is the confidence level?
- FQ2- Can the energy be sold (is the produced energy compliant with customer requirements) and what is the confidence level?
- FQ3- How attractive, useful and dependable is the produced energy (is the long term variability large or small) and what is the confidence level?

Based on these fundamental questions, a significant number of technical questions are formulated and need to be answered. These technical questions are at the criteria and sub-criteria level and are developed by systematically considering each criterion and sub-criterion of the current methodology. For the power absorption, conversion, and delivery group a total of 56 technical questions have been formulated. Each question is supported by explanatory text for clarification. A sample of technical questions and explanatory text is listed here:

- Q1 – Is the working principle of the system relevant and functional (high)?
Explanatory text: For new concepts, the working principle may never have been demonstrated. For any concepts that are not obviously functional and/or for which the proof of concept has not been demonstrated, the answer to this first question should not be high until a proof of concept can be given. On the opposite, the answer is obviously high for devices using well-known working principles (OWC, overtopping, heaving buoys, …)
- Q2 – Does the geometrical configuration match well with the overall working principle (high)?
Explanatory text: WECs can usually be classified according to their geometrical configurations in one of the following categories: attenuator, terminator and point absorber. Not all working principles can be arranged in any geometrical configuration. If the geometrical configuration does not obviously fit well with the working principle, the answer should not be high, unless a proof of concept can be given
- Q2.1 – If the system will be deployed in intermediate water depth or deep water and if the system is sensitive to wave direction, can it orient itself in the correct direction (high)?
Explanatory text: In intermediate water depth and deep water, real ocean waves are directional, with mean direction changing slowly with time (typical scale is hours). For most locations with significant wave resource, typical change in the direction can be of order +/-60° around the annual average. If the system is sensitive to wave direction and cannot orient, a significant share of the wave resource will not be accessible to the device, thus affecting the power performance.
- Q2.1.1 – Is the correct orientation with respect to wave direction obtained using a passive system (high)?
- Q3 – If information on approximate capture width is not available, is the system able to modify significantly the incident wave field (high)?
Explanatory Text: Interaction of the system with the incident wave field creates disturbances in the flow. These disturbances are the so-called scattered/radiated waves. Physically, wave energy absorption is obtained through destructive interference between these scattered/radiated waves and the incident wave field[]5,6]. Thus, a necessary requirement of a highly efficient wave energy converter is that it is able to scatter/radiate waves in the far field of similar characteristics as incident waves (both in terms of wave height and wave period). For systems that are small with respect to the wavelength (point absorbers), radiated waves (waves that are generated by the motion of the body) are the most important source for the disturbance. For larger devices, scattered waves (waves reflected by the system held fixed) may be as important, or even more important than radiated waves.
- Q3.1 – Is the system able to scatter/radiate waves in a narrow angular sector (high)?
Explanatory text: Theory [7] shows that the most efficient WECs in terms of energy absorption are the ones that scatter/radiate waves in a narrow angular sector.
- Q3.2 – For wave activated bodies, does the system capability to scatter/radiate waves of similar characteristics as the incident wave go along with large amplification of motion response with respect to the incident wave amplitude (low)?
Explanatory text: In practice, large amplification of motion response with respect to incident wave amplitude is limited by non-linear effects and dissipation [8, 9, 10, 11]. Actual performance of systems that assume large amplification of motion response is expected to be significantly smaller than expectations.
- Q3.3 – Are there other sources of significant energy dissipation involved in this primary stage of the wave energy conversion process (low)?
Explanatory text: Typically, wave breaking in overtopping devices will lead to significant losses by dissipation.
- Q3.4 – If the ability of the system to scatter/radiate waves of similar heights and periods as the incident waves rely on fast wave-by-wave control, has the applicability of the envisaged fast Wave-by-Wave control already been successfully demonstrated (high)?
Explanatory text: Fast wave-by-wave active controls such as complex-conjugate control, latching, declutching are known to be very challenging because of robustness, non-ideal actuators [12-14] and possible requirements for the prediction of the future of the incident wave or wave force. The performance and applicability of the envisaged fast wave-by-wave control to the WEC system should have been demonstrated.
- Q3.4.1 – Is the system easily observable with respect to control requirements (high)?
Explanatory text: Fast Wave-by-Wave Control requires input signals to the controller. These inputs should be in small numbers, easily

measurable with common sensors and should involve limited signal processing. Otherwise, it is expected that the actual performance of the control may be significantly smaller than expectations.

- Q3.4.2 – Is the control dependent on information input external to the device and/or wave farm (low)?
  Explanatory text: Actual performance of control that requires input external to the device and/or wave farm may be significantly less than expectations, or may not even be feasible with current technology (for example, wave-by-wave control that relies on prediction of the future of the incident wave).
- Q4 – If information on approximate capture width is available, is it greater than for other WECs of similar active dimensions (high)?
  Explanatory text: Capture width is the ratio of absorbed power to incident wave power. It is a proxy for hydrodynamic efficiency. In [15], a database of capture width ratio of wave energy converters is provided for WECs as a function of active width. From the TPL point of view, it is an advantage that the system approximate capture width is greater than for other WECs of similar active dimensions.
- Q5 – What is the number of power conversion steps involved (low)?
  Explanatory text: There will be energy losses at each step of power conversion. Thus, the number of conversion steps should be as small as possible.
- Q6 – Are there power conversion steps with low conversion efficiencies, or significant system concept or engineering design solution inherent losses of power over each step of the conversion chain (low)?
  Explanatory text: Obviously, system concept and engineering design solution should favour solutions with small losses of power/high conversion efficiencies over the internal power conversion chain.
- Q7 - Is the short term variability in instantaneous wave power reduced significantly and early on in the internal power conversion chain (high)?
  Explanatory text: Reducing the short term variability (peak loading, peak power levels) early on in the internal power conversion chain will lead to better capacity factors for subsequent power conversion components and subsystems, thus reducing energy losses due to partial load utilization of these components and subsystems.
- Q8 – Does fast Wave-by-Wave control involved in hydrodynamic wave power absorption imply dealing with high levels of reactive power in the internal power conversion chain (low)?
  Explanatory text: Fast wave by wave control may require that the internal power conversion chain has to deal with high levels of reactive power (for example, if the effort required for controllability associated with stiffness or inertia of system dynamics is high). [16]. In that case, energy losses caused by power flow inefficiencies may be high. [14].
- Q9 – Can power output be conditioned to meet grid requirements (high)?
  Explanatory text: Typically, voltage and frequency of the electrical power output must be conditioned such as to meet grid requirements. The wave energy converter must implement means to achieve this.
- Q10 – Is the power output smoothed and controllable at the point-of-sale with respect to short term variability (high)?
  Explanatory text: Instantaneous wave power varies from 0 to max with a time scale of half the wave period. It is an issue with respect to *the compliance of the produced energy with point-of-sale requirements. Means must be implemented to control (smooth) the output power with respect to short term variability.*
- Q11 – Are there significant system concept or engineering design solution inherent losses of power over each step of the power delivery interface (low)?
  Explanatory text: Obviously, system concept and engineering design solution should favour solutions with small losses of power over the power delivery interface. For example, energy losses may be significant in electrical cables if the point-of-sale is far from the wave energy converter and if voltage cannot be increased.

Similarly to the classification of each sub-criterion, the classification of the technical questions into "(low)" and "(high)" indicates the orientation of the answer if low or high levels of the system characteristics with respect to this question will lead to a high TPL score.

The numbering scheme of the questions reflects the hierarchical structure of the questions and the fact that some questions are dependent upon the answers provided for the preceding questions. The organization of the questions, the provision of the possible answers to close and score these questions and the consequential logic for the activation of subordinate or subsequent questions would require the implementation in dedicated online software tool. Figure 1 shows the hierarchical structure of the technical questions.

FIGURE 1. HIERACHICAL QUESTIION STRUCTURE.

The determination of the TPL value for the group of power absorption, conversion, and delivery is implemented by the consideration of penalty factors that are determined by the selected answers. For instance, 0.8 is the penalty factor for low (TPL 1 – 3), 0.9 is the penalty factor for medium (TPL 4 – 6) and 1.0 is the penalty factor for high (TPL 7 – 9) for a question where a positive answer is characterized by "(high)", thus positive characteristics. The assessment is initiated with a maximal score of TPL 9 and subsequently applies the penalty factors obtained from the sequence of answers in a series of multiplications. After consideration of all penalty factors, the final TPL score for the group of power absorption, conversion, and delivery is determined. Furthermore, it is envisaged to associate levels of uncertainty with each of the answers which will lead to a statement of uncertainty of the group of power absorption, conversion, and delivery as a whole and subsequently to the overall system TPL score. If uncertainty is provided in the form of probability distributions, Monte Carlo simulations could be implemented to determine the probability distributions of the group values and the overall TPL system value. In order to increase and disseminate the knowledge base for the TPL metric user, each question is accompanied by an explanatory text and literature references relevant to the question and the related topic at hand. Potentially, users of the online software and TPL assessment tool could be provided with editorial access in order to add explanatory context and relevant literature references. This would facilitate a strengthening of the tool and the knowledge base offered to the user.

CONCLUSIONS

The TPL metric and methodology in its original form has served well during its use in the first down select in the Wave Energy Prize. The feedback of the judges that applied the TPL metric was consistent and positive. However, it is important to challenge and improve the metric and methodology and to make it available to the wider wave energy community.

The refinement options here presented are possible next steps in the development of the metric. At the time of writing, the precise development direction for the refinement of the TPL has not been finalized and it is hoped that feedback to this article and presentation at METS will be comprehensive and will positively influence further TPL development. Stakeholder feedback will also be gathered through international collaboration and dedicated workshops held in conjunction with the ICOE 2016 and IMREC/METS 2016 conferences in Europe and the US, respectively. The authors wish to encourage readers of this paper to provide feedback and share ideas for further development and refinement of the TPL metric and methodology in order to provide a useful tool to the wave energy community. It is envisaged that the TPLs will be used as the metric to guide technology evaluation and innovation in the US DOE program.

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