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Compilation of Development Metrics Applicable to Wave Energy Converters (WECs): Current Status and Proposed Next Steps

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ABSTRACT

As for any novel technology, the need to consider, identify and formulate performance requirements and related assessment criteria has been an important subject in the development of Wave Energy Converters (WECs). These allow the characterisation of each technology through techno-economic indicators, which in turn allow comparisons between different technologies, and an assessment of alternative solutions throughout all the development stages.

Such assessment is ideally carried out through the application of metrics, which should comply with several attributes, such as being objective, quantitative, specific, measurable, repeatable, and independent.
In the present work, more than 50 metrics to monitor the development of WECs are compiled, explained, and discussed. These metrics are divided in the following evaluation areas: 1) Performance; 2) Reliability; 3) Survivability; 4) Techno-economics. In addition, the important evaluation area of Environmental Impact is briefly discussed concerning the need for common metrics.

The compilation summarised in this paper and its discussion aim to provide a practical reference source concerning metrics for WEC development, which is currently unavailable in the published literature in terms of broadness and condensed presentation. Such compilation includes multiple formulations from the wave energy sector and other relatable industries (e.g. wind energy) that are typically diluted among specialist literature, standards, guidelines and recommendations, scientific papers, and project reports. The paper is concluded with a reflection of any salient gaps that are not addressed by current metrics, in a context of accelerating the development of WEC technologies.

KEY WORDS: Wave Energy; Technology Development; Metrics; Evaluation Areas; Assessment Criteria; Gap Analysis.

INTRODUCTION

The assessment of performance requirements and related criteria allow to characterise Wave Energy Converters (WECs) through techno-economic indicators. These provide a base set for comparing different technologies and enable assessing the goodness of the solutions and its components throughout all the development stages. This assessment is ideally carried out through the application of metrics, which should comply with the following attributes (Weber et al., 2019):

- Objective — Quantitative — Specific — Measurable.
- Certain — Precise — Repeatable — Transparent.
- Straightforward — Simple — Meaningful — Correct.
- Complete, capturing all relevant aspects.
- Balanced, reflecting the impact of diverse criteria.
- Interconnected, reflecting all relevant trade-offs.
- Independent, no need for subject matter experts.
- Ease of description, low effort in providing the system description as the basis for the assessment.
- Ease of use, low effort assessment process.
- Fast, short duration of assessment process.
- Cheap, low-cost assessment process.
- Supported, existing empirical and theoretical tools.
- Characterizing, capturing qualitative features of additional system performance information.
- Flexible, applicable at all development stages.
- Universal, applicable across systems levels, archetypes.
- Equitable, providing comparability across different technologies, archetypes, domains.
- Established, globally recognized.

Naturally, it is near to, if not completely, impossible to devise metrics that strictly comply with all the above listed criteria. Furthermore, one can argue that the last criterion ("established, globally recognized") encompasses a sufficient number of the previous criteria to be met.

Therefore, establishing metrics for the assessment of WECs and its components is fundamentally challenging. The reason is not only due to the difficult process of establishing metrics per se, but also due to issues which have specifically affected WEC development technology, such as: the great variability in designs, limited operation/testing of prototypes and lack of knowledge sharing by developers (EC, 2017d).

Notwithstanding the above difficulties, a considerable effort has been employed to establish WEC specific performance metrics, notably by the International Electrotechnical Commission (IEC), Ocean Energy Systems (OES) and the European Marine Energy Centre (EMEC), among others, in the form of technical specifications and guidelines; while several publications and research projects have analysed and proposed metrics to be applied. However, when comparing to established industries, dedicated metrics for WEC development are still very limited. A review of existing metrics is carried out in the present work targeting several evaluation criteria and considering:

- Metrics in standards, guidelines, and recommendations, specific to wave energy conversion. The sources comprise documentation published as a standard by a recognised agency (e.g. IEC), but also standards and recommendations from ocean energy test centres and reference organizations such as classification societies.
- Other published proposed metrics specific to wave energy conversion. The sources comprise research publications and reports from research projects where metrics specific to wave energy conversion are discussed or proposed.
- Relevant metrics in other relatable industries or sectors. Where relevant standards, guidelines, recommendations, and research outputs, are shortly reviewed.

This review is a result of work carried out in the IMPACT project. IMPACT (Innovative Methods for wave energy Pathways Acceleration through novel Criteria and Test rigs) is an ongoing European collaborative research and innovation project (Horizon 2020) which aims to develop and demonstrate a next generation testing approach for Wave Energy Converters (IMPACT, 2021). The project was initiated in January 2021 and has a duration of 3 years.

EVALUATION CRITERIA

The following selected evaluation criteria are addressed in this review:

- **Power capture.** The process of converting energy from the natural resource by the interaction with a device, making it available as an input to a power take-off (PTO) sub-system (Hodges et al., 2021).
- **Power conversion.** Represents the second step in the power conversion chain, whereby the mechanical power captured by the device is converted to electricity (Hodges et al., 2021).
- **Reliability.** The probability that an item can perform a necessary function under given conditions for a given time interval (Hodges et al., 2021).
- **Survivability.** A measure of the ability of a subsystem or device to experience an event ('Survival Event') outside the expected design conditions, and not sustain damage or loss of functionality beyond an acceptable level, allowing a return to an acceptable level of operation after the event has passed (Hodges et al., 2021).
- **Techno-economics.** Denotes evaluation of indicators which are related to costs. Sometimes identified as performance indicators, these include the following evaluation areas: availability, affordability, and maintainability.
- **Environmental impact.** Focusing on the evaluation of the impact of WEC installations on the surrounding environment.

POWER CAPTURE

It is noteworthy to establish the difference between Power Capture and Power Conversion, which together can form a Power Performance evaluation area. This separation allows for Power Capture evaluation metrics to focus on objective measurements and calculations that relate to the available wave energy resource. These can be expressed in terms of "how much of the energy in the waves is converted into mechanical power" but can possibly also go into detail on how the energy being harvested relates to specific characteristics of the wave field and of the device. In any case, the metrics under Power Capture provide a characterization of the hydrodynamic efficiency of a WEC device; they do not consider any cost factor (at least explicitly), and they are also separated from the PTO specific efficiency metrics related to converting mechanical work into electricity (although affected by the PTO actuation). This separation allows for better understanding of where improvements can be made.

Relevant identified metrics for the wave energy sector are listed in Table 1. A couple of notes is worth taking here. One is on the use of Power Capture matrices. Their most attractive property is their prospective usage across different deployment sites with differing wave climates. However, there are limitations to this. Through the usage of a validated numerical model, the sensitivity of the WEC power capture to the following parameters can be assessed (IEC, 2016): Water depth; Wave direction; Water current; and Tidal range. According to (IEC, 2016), when one of these impacts the power capture of the WEC in the new prospective deployment site by more than 10% relative to the testing conditions, then the dimension of the power capture matrices should be extended to account for such parameter.
Another is the interesting approach expressed by the Average Climate Capture Width (ACCW) metric, which allows for using a very reduced number of seas states deemed to be representative of the full scatter diagram. These representative sea states are a result of clustering the wave scatter diagram in terms of wave power in a location to arrive at "equivalent" energy sea states which are centroids of each cluster.

Table 1. Power capture metrics in the wave energy sector.

Name and Reference	Short Description
Power Capture (Hodges et al., 2021)	Matrix of average power capture in each sea state, in kilowatt (kW). Sea states are defined by combinations of significant wave height (H_s) and energy period (T_e), each split into bins (or intervals) along the matrix axes.
Capture Length (Hodges et al., 2021)	$L = P_C/A_P$, where L is the capture length in metres (m), P_C is the power capture, and A_P is the available power in kilowatt per meter (kW/m).
Capture Length Variability Matrix (Pitt, 2009)	Matrix with the standard deviation of the Capture Length in each sea state, in metres.
ACCW (Dallman et al., 2018)	Average climate capture width of a WEC at a specific location, in metres. Uses a set of weighted representative sea states in the scatter diagram to allow for testing WECs with a reduced number of environmental load conditions.
⟨ACCW⟩ (Dallman et al., 2018)	Average climate capture width of a WEC across representative locations of interest, in metres.

Capture Width Ratio (Babarit, 2015)	Nondimensional ratio between the capture length and a characteristic WEC dimension (both in metres). Also denoted as Hydrodynamic Efficiency. The diameter is used for circular devices while the characteristic dimension is based on the WECs maximum horizontal cross-sectional area for non-circular devices.
Duration Curves (Babarit et al., 2011)	Distribution of output power in function of fractions of the year.
Energy per Wave Force (Babarit et al., 2011)	Yearly energy output per unit characteristic excitation force, in kWh/kN.
Energy p/ Device Mass (Babarit et al., 2011)	Yearly energy output per characteristic mass, in MWh/ton.
Energy per Wet Surface (Babarit et al., 2011)	Yearly energy output per characteristic wetted surface area, in MWh/m^2.
q-factor (Folley and Whittaker, 2009)	Nondimensional ratio of the power output from a wave park to the sum of all the WEC if these were in isolation. Only applicable to wave parks.
Tank testing: continuous quantities (IEC, 2018)	For example, considering WEC dynamics and kinematics, identification of: Spectral response (spectral moments), Peak distribution (probability density function parameter values, mean, median, and 98th percentile), Onset of nonlinearity in regular waves.
Tank testing: discrete events (IEC, 2018)	For example, identification of: Local point loads, Green water occurrence, Slamming and Impact events.

Table 2. Selected metrics from the wind energy sector.

Name and Reference	Short Description
Power curve (IEC, 2017)	Averaged power output as a function of wind speed. Equivalent to an element in the Power capture matrix.
AEP (IEC, 2017)	Annual Energy Production. It can be expressed for reference wind speed frequency distributions or be site specific. Equivalent to MAEP (Table 3) when taken before the PTO.
Power coefficient (IEC, 2017)	Equivalent to the Capture Width Ratio, the power coefficient C_p is given by: $C_P(V) = \frac{P(V)}{\frac{1}{2}\rho_0 A V^3}$, where V is the defined wind speed, P is the power output, ρ_0 is the reference air density, and A is the swept area of the wind turbine rotor.
Wind farm efficiency (IEC, 2017)	Equivalent to the q-factor, the wind farm efficiency, e, is given by: $e = \frac{1}{N}\sum_{i=1}^{N}\frac{P_i}{P_{0,i}}$, where N is the number of turbines in the farm P_i is the power output of the i^{th} turbine, and $P_{0,I}$ is the power of the i^{th} free-stream turbine.

The physical processes involved in harvesting energy in wave energy are fundamentally different from those of other renewable sources. Therefore, it is difficult to find relatable power capture metrics that can be relevant for WECs, for which their wave energy equivalent has not already been formulated. As an example, the most important power capture metric in tidal energy and wind energy is the power curve, which relate the incoming air/water flow to the power output. The equivalent metric in wave energy is the power capture. Table 2 lists selected power capture related metrics in the wind energy sector and its closest equivalent in the wave energy sector. It is assumed that these have their equivalents in the tidal current energy sector. Metrics on other types of renewables, such as PV solar, OTEC, geothermal, etc, are considered to deviate drastically from wave energy, and so are not reviewed here.

POWER CONVERSION

Identified metrics listed in standards, guidelines, recommendations, and research papers addressing the wave energy conversion sector are listed in Table 3. It is important to clarify that the distinction between Power Capture and Power Conversion mentioned in the previous section is not universal. For example, in the IEC/TS 62600-100 "Electricity producing wave energy converters - Power performance assessment" (IEC, 2012) the evaluation criteria Power Capture and Power Conversion are already considered as a single power performance criterion. In that case, some of the metrics listed in Table 3 cover the entire energy conversion process.

Table 3. Power conversion metrics in the wave energy sector.

Name and Reference	Short Description
Power Conversion Efficiency (Hodges et al., 2021)	Matrix (or surface-plot) of power conversion efficiency vs. PTO input power (input torque and angular speed or force and linear speed). Defined as the measure of the electrical power output (P) divided by the PTO power input (P_{PTO}): $\eta = P/P_{PTO}$
Power Performance (IEC, 2012)	Normalized power matrix. Calculated using the capture length and the average bin power. In this case, the capture length in Table 1 is calculated using the net electrical power (in kW).
MAEP (IEC, 2012)	Mean annual energy production, in Wh or kWh.
Capacity factor 1 (Dallman et al., 2019)	The capacity factor is the average electrical power divided by the rated power of the plant: $CF1 = P_{avg}/P_r$.
Capacity factor 2 (Ibarra-Berastegi et al., 2018)	Other references consider the definition of capacity factor as the average power divided by the peak power of the generator: $CF2 = P_{avg}/P_{r,peak}$ The difference from CF1 is the use of rated peak power, not rated power.
Peak to average power (Dallman et al., 2019)	Ratio between peak and average mechanical absorbed power: $PAP = P_{m,peak}/P_{m,avg}$ Values close to one are favourable.
PEI (Ibarra-Berastegi et al., 2018)	Based on the capture width definition. PEI is defined as the ratio between the average power generated over 5 min [kW] by the active turbines in Oscillating Water Column (OWC) systems and the wave energy flux [kW/m] at a specific sea location.

Table 4. Metrics related to grid code requirements.

Name	Short Description
Active power gradient	Numerical value in MW/s or MW/min. Ramp rate of active power export during start-up and reconnection procedure of the power plant. Represents the active power increase during a specified period.
Controlled reduction of active power export	Value in MW/s. The generator must be able to reduce its active power following an external signal input. The rate of change for the output power should follow the grid code specifications.
Low Voltage Ride Through (LVRT)	Voltage profile representing voltage in p.u. and time in seconds. LVRT requirements specify minimum voltage amplitudes and time thresholds for which the generator must keep operation despite short-term low voltage conditions at PCC caused by grid faults.
Over Voltage Ride Through (OVRT)	Voltage profile representing voltage in p.u. and time in seconds. OVRT requirements specify maximum voltage amplitudes and time thresholds the generator must keep operation despite short-term over voltage conditions at PCC.
Controlled disconnection	Numerical value in seconds. Upon an external command signal, the plant must perform a controlled disconnection within a specified time.
Disconnection due to grid events	Unplanned disconnection caused by grid conditions outside the allowed frequency and voltage ranges, LVRT and OVRT thresholds, and trips due to protection systems.
Frequency range	Numerical range in % of nominal value (Hz) and time in seconds or minutes. Power plants should operate continuously within a specified frequency band. For frequencies outside the nominal band, the operation should last only for a specified time period.
Voltage range	Numerical range in % of nominal value (p.u). Power plants must operate continuously within a specified voltage range.
DC current injection	Numerical value in % kA. The amount of DC current injection in the grid is regulated by the grid code.
Flicker	Numerical value. As defined in (IEEE, 2015), “flicker is the subjective impression of fluctuating luminance caused by voltage fluctuations”. The monitoring procedure is standardized and can be found in Section 5.2 of (IEEE, 2015).
Harmonics	Harmonic spectrum or numerical values. Harmonics are current and voltage signals with higher frequency components than the fundamental grid frequency. It can be characterized by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component (IEEE, 2019).

Regarding the Power Conversion Efficiency, the input is the power at the PTO input, e.g., mechanical or hydraulic power, and the output is the electrical power. The PTO input power is characterized by, e.g., the force and velocity or torque and angular velocity in oscillating-body WECs, and pressure and flow rate in OWC systems. The power characterization can also include a representation of different damping settings.

The net electrical power should be measured at the electrical output terminals of the WEC to assess the Power Performance. From the electrical point of view, the electrical output is at the plant output; i.e. the total output of the wave farm and not of individual units, in case the WEC is composed of arrays. In addition, according to (IEC, 2012), the output terminal is at the point where the output power is in the form of AC at the network frequency for AC grid-connected WECs. For non-grid connected WECs, the output terminals should be at the point where the power is connected to the load – the output form is also in the form of AC at a commonly used network frequency and voltage level. For the Power Performance metric, the data shall be recorded at a minimum 2 Hz frequency, and the signal shall be subjected to a proper anti-aliasing filter. The minimum sample frequency for the wave data shall be 1 Hz (IEC, 2012).

Table 4 lists a set of grid code requirements relevant to the scope of this work, following the standards EN 50549 (CENELEC, 2019a) (CENELEC, 2019b) and IEEE 1547 (IEEE, 2018). Grid codes are national (or regional) technical specifications that define the requirements for interconnection of power plants and other facilities to the grid. Such requirements can be seen as indices or metrics related to the power conversion criteria, but they focus only on the electrical aspects of the generating plant. In addition, grid codes only cover the electrical conditions at the point of connection between the grid and the connected power plant, i.e. at the Point of Common Coupling (PCC). Thus, the performance of individual WECs in an array is not covered by such requirements. Furthermore, these requirements (or metrics) are general to any power plant connected to electricity grids, regardless of the primary energy source. However, the requirements differ depending on the power rating and voltage level of the power plant, and on the grid-connected technology. The last three metrics in Table 4 (DC-current injection, flicker and harmonics) are related to power quality phenomena. According to (IEEE, 2019), “the term power quality refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and location on the power system”. The power quality performance of any plant is heavily influenced by the grid connection characteristics. Strong grid connections result in lower measured emissions from the plant when compared to weak grid connections. Furthermore, the quantification of noise emissions of higher frequency phenomena (e.g., harmonics) using simulation models require detailed models of connected equipment and grid structure for an accurate estimation of the plant's performance. Thus, power quality is primarily handled during on-site compliance testing of new units and less likely to be tested by drivetrain test rigs.

RELIABILITY

The concept of Reliability is linked to that of ‘failure’, which may result in the item being unable to perform the “necessary function”. Moreover, the ability of a component to perform a necessary function is related to a defined required standard. While some failures can result in a complete failure of the system requiring immediate maintenance, other failures may result in a limited impact on functionality, to which measures to be taken become an operational decision based on a wide range of considerations. The assessment of the failures may include evaluation of the technical, economic, and safety impact of failures, with some resulting in complete system loss or complete failure to function and others resulting in relatively minor and acceptable degradation in performance (Hodges et al., 2021).

While it is advantageous to introduce WEC reliability assessment from the start of the development process, optimizing the systems towards power production is the typical path followed in early stages of WEC designs. Power production across sea states is a major component of the revenue potential and its maximization by targeting metrics such as Power Capture and Power conversion is paramount. On the other hand, large values of these metrics typically entail an increase of the loads to

which the components are subjected to. Thus, a design trade-off between power production and component reliability must be taken into account throughout the WEC development process (Clark et al., 2019). Furthermore, reliability is typically directly connected to cost. And achieving a fine balance between reliability level and cost depends on a good identification of the most important aspects, which contributes significantly to the overall performance of the devices (DNV, 2005).
In a broader sense, reliability is connected to the maintenance requirements and inspection regimes defined for the device. However, maintainability is not considered here; therefore following the approach in (Hodges et al., 2021).

Table 5. Reliability metrics used in the wave energy sector.

Name	Short Description
Mean Time to Failure (MTTF)	Numerical value expressed in hours. Reflects the component life expectancy.
Failure Rate	Probability of failure per unit time, in failures per hour, i.e. 1/MTTF.
MTBF	Mean time between failures. Reflects how long a component can operate without being repaired.
MFOP	Maintenance free operating periods. Reflects the component life expectancy, without maintenance.
ADP	Allowable degraded performance, non-dimensional.
MPPF	Maximum probability of premature failure.

Table 6. Selected cross-industry reliability metrics with prospective relevance for WEC systems and components.

Name and Reference	Short Description
Failure Rate in cycles (Wood, 2001)	Probability of failure per cycle. Standard metric for reliability when usage is more relevant than time.
MCBF (Wood, 2001)	Mean Cycles Between Failures. Standard metric for reliability when usage is more relevant than time.
Failure Rate in distance (Wood, 2001)	Probability of Failure per Unit of Distance. Standard metric for reliability when distance is more relevant than time.
MMBF (Wood, 2001)	Mean Miles Between Failures. Standard metric for reliability when distance is more relevant than time.
Probability Of Failure on Demand (PFD) (IEC, 2010)	Numerical value expressed in percentage. Used in IT services and software.
Asset Health Index (Durán et al., 2020)	Dimensionless number representing the state of a system in terms of its deterioration. Allows for estimating the speed with which it deteriorates and project at what point is it close to the end of its life.
Reliability growth (Fries, 1996)	Measures the gradual product improvement through the elimination of design deficiencies. Applicable to repairable/upgradeable components.

Relevant identified metrics for the wave energy sector are listed in Table 5. The Mean Time to Failure (MTTF) is here understood in the context of the life expectancy of a non-repairable component, while the Failure Rate is defined as the rate between the number of failures in a population of similar items and the sum of the times until the failure of all the population, during a specified period (Hodges et al., 2021). As for the other metrics in Table 5, these entail a lower-level assessment, introducing aspects such as repair and maintenance operations, and establishment of degradation thresholds (Starling, 2009).

The reliability assessment in other industries continues to be an active field of research. This review identified the field of software engineering and IT services in general as one of the most active. As IT related reliability (excluding hardware) does not relate to material or physical component failures, the sector is in need for new metrics and procedures to assess reliability to depart from the traditional physical component reliability estimations listed in Table 5. For the same reason, it is difficult to relate those new metrics to the case of WECs.
A set of selected reliability metrics that can be of prospective use in WEC systems is listed in Table 6. These metrics deviate from Table 5 as they are not explicitly mentioned in WEC related standards, albeit some of them being of general use in reliability.

SURVIVABILITY

Events relevant for survivability assessment are those which result from environmental factors, e.g. wave and current induced forces, or specific design situations, e.g. occurrence of a fault, emergency shut-down, transport etc., that are beyond normal operating conditions for which the device was designed to operate in. For example, while reliability focuses on (cumulative) degradation of systems measuring the ability of those to fulfil their function fully or partially under operational conditions, one may consider here that survivability deals only with the ability for the systems to survive extreme conditions with the device in survival mode. Determination of the conditions at which a device should transition from operational mode to survival mode is critical to the ultimate reduction of the cost of power and increase of reliability and survivability of marine energy converters (Brown et al., 2010). Furthermore, historical analysis has shown that survivability is a key metric, which not only affects the economics and success of individual wave energy projects, but also play a large role in sector's confidence and *investability* (Guo and Ringwood, 2021).

From the above consideration, events like rogue waves, tsunamis, collisions, etc. are not considered in survivability analysis – as per its above stated definition. Note, however, that survivability also includes unexpected events such as these in some literature: e.g. (IEA-OES, 2016), although no formal formulations are presented therein. In fact, this is but an example of the difficulty to arrive at a formal definition of survivability, as different standards and publications refer to reliability and survivability without making a clear distinction between both and seldom present an exercise of its actual assessment, e.g., in (Starling, 2009). While reliability and survivability terms are occasionally used interchangeably, the recognition of two unique definitions is essential to the function of a more systematic WEC design process, as stated by (Coe and Neary, 2014). In any case, survivability analysis is mostly focused on extreme loads, with testing of systems and components under survival conditions also allowing to identify product-specific failure modes.

Survivability metrics identified in well-known guidelines for the Wave Energy sector are listed in Table 7.
The first of these metrics, Design Conditions Boundary, is somewhat straightforward where the limit states can be obtained from, e.g. (DNV, 2005; DNV GL, 2018). The last three, however, are of a more ambiguous nature.
The LEALD involves the identification of an "acceptable level" on a case-by-case basis for each technology or project, including environmental, financial or reputational risks factors (Hodges et al., 2021). With regard to the Safety and Functional Survivability, (Brown et

al., 2010) states: “The drawback of these definitions is that they appear nearly identical to the EMEC’s [(Starling, 2009)] definition of reliability [*the probability that an item can perform a required function under given conditions for a given time interval*]. The differences appear to lie in the magnitude of the repair, which remains ambiguous, and the time duration considered, which is left undefined for reliability, but set at the life of the system for survivability.” The definition of survivability implied in these two metrics therefore seems inadequate, as it does not provide a clear distinction between survivability and reliability.

Table 7. Survivability metrics.

Name and Reference	Remark
Design conditions boundary (Hodges et al., 2021)	Beyond which a component, subsystem or device behaviour is unknown, and damage or loss of functionality may occur. Linked to Ultimate Limit State (ULS).
LEALD (Hodges et al., 2021)	Likelihood of Exceeding an Acceptable Level of Damage or loss of functionality, with or without taking suitable protective action. Numerical value. Calculated probability or likelihood estimate based on best available information.
Safety Survivability (Starling, 2009)	Probability that the converter will stay on station over the stated operational life. It seems exclusive for mooring systems, or station keeping systems in general.
Functional Survivability (Starling, 2009)	Probability that the converter will produce its rated energy (or an allowed degraded energy rating) without damage leading to the need for major unplanned removal or repair over the stated operational life. It does not provide a clear distinction between survivability and reliability.

Table 8. Survivability metrics in (Brown et al., 2010).

Name	Short Description
Failure rate in survival mode per hour	Probability curve relating the chances of suffering a failure in a one-hour period of waves of a certain height outside the standard operating conditions.
Cumulative probability of 1-Year Survival	The survival distribution relative to the previous point, taking into account the wave climate on the deployment site.

Research literature on WEC survivability is mostly focused on review and novel works on frameworks for survivability and on calculation methods for assessing aspects that influence it, e.g., estimation of extreme loads (Madhi and Yeung, 2018). Studies which bridge both, i.e., that perform or present unambiguous methods for calculation of survivability, therefore exhibiting explicit metrics, are rare.

(Brown et al., 2010) is one that truly proposes a couple of new unambiguous metrics for survivability– listed in Table 8. These can easily be used by any device design to provide a location specific survivability cost estimate assuming an average cost of access and repair. In (Brown et al., 2010), it is assumed that all failures result in the same degradation of the device. In those circumstances, a binomial distribution can be used to model the number of yearly failures combined with the number of hours at each significant wave height bin in the wave scatter diagram at the location of deployment of the device. The cumulative probability of 1-Year Survival is then obtained from the complementary cumulative probability.

TECHNO-ECONOMICS

Techno-economic studies are used to analyse the economic performance of methods of energy provision and include metrics that assess the performance of these methods. Examples of metrices include: Time-based Availability, Energy-based availability, Capital Expenditure (CAPEX) (including development, commissioning and decommissioning), Operational Expenditure (OPEX) including fixed and variable Operation and Maintenance (O&M), Levelized Cost of Energy (LCOE) and inverse of LCOE.

A high-level descriptive summary of common metrics used for measuring the economic performance of Ocean Renewable Energy sectors is presented in Table 9. The list excludes metrics that constitute proxies for evaluation of, and comparison between, economic performance of WEC solutions that have already been presented in previous sections; namely: Capture Width Ratio, Energy per Device Mass, Energy per Wetted Surface, Failure Rate, Capacity Factor, Peak to Average Power, and Power Conversion Efficiency.

It is worth noting that in the LCOE assessment, transmission losses and availability ought to be included in the annual energy production, although a 100% availability is sometimes assumed, e.g., in (IEC, 2012) as pointed out by (Dallman et al., 2019). Likewise, regarding CAPEX and OPEX, when sufficient knowledge is not available at the low development stages, subsystems’ CAPEX and OPEX can be estimated as percentages of total system CAPEX and OPEX. Accurate OPEX assessment thus requires reliability modelling, e.g. by assessing expected operating condition load, Failure Modes, Effects and Criticality Analysis (FMECA), and MTBF.

Table 9. Metrics for measuring WECs economic performance.

Name	Short Description
LCOE (Hodges et al., 2021)	The Levelized Cost of Energy is the ratio between lifetime costs and the energy production (e.g., in €/MWh). Its calculations require extensive information, probabilistic analyses, and sensitivity studies, especially for low Technological Readiness Levels (TRLs).
CAPEX (Hodges et al., 2021)	The Capital Expenditure (e.g., in €, €/MW, €/MWh) is an indicator of the cost at both early and late-stage development phases.
OPEX (Hodges et al., 2021)	OPEX (fixed and variable O&M costs) and energy generation (taking into account lifetime O&M activities and device downtime affecting availability) feed directly into LCOE.
Average climate capture width and Characteristic capital Expenditure (ACE) (Sergiienko et al., 2018)	A proxy to LCOE for evaluating and comparing WEC devices with different working principles where information is insufficient to calculate LCOE. It is specific to a particular site and its energy climate.

ENVIRONMENTAL IMPACT

Most studies have investigated impacts of Marine Renewable Energy (MRE) devices such as underwater noise, collisions, electromagnetic disturbances, habitat change, wave or tidal modifications and water quality. Wave and tidal devices show a similar pattern in terms of the impacts of interest, with noise being the dominant impact (Martínez et al., 2021).

There are currently no standards or established test-derived metrics for environmental impacts of WECs and MRE devices in general. However, there are some recommendations and guidelines relating to the environmental impact of MRE devices both at a national and European level. The most relevant of these are summarised in Table 10.

Table 10. Selected guidelines relevant to WEC environmental impacts.

Geographic level, legislative context and year	Guidance Reference
Europe, EIA, 2012	(Commission expert group of EIA/SEA, 2012)
Europe, EIA, 2013	(EC, 2013b) (EC, 2013a)
Europe, EIA, 2015	(EC, 2015)
Europe, EIA, 2017	(EC, 2017b) (EC, 2017a) (EC, 2017c)
Europe, EIA, 2020	(EC, 2020)
Europe, Natura 2000 (Habitats and Birds Directives), 2021	(EC, 2021) (EC, 2010)
Ireland, National Legislation and European Directives (EIA, Natura 2000), 2017	(Barnes, 2017)
Scotland, National Legislation, 2018	(Marine Scotland Directorate, 2018)
Spain, National Legislation and European Directives (EIA, Natura 2000), 2010	(Bald et al., 2010)
Portugal, National Legislation and European Directives (EIA, Natura 2000), 2010	(de Jesus et al., 2016)

CONCLUSIONS

A review of existing metrics that are, or can be, applied to monitor the development of WECs was presented in this paper. The starting point was what the IMPACT participants agreed to be the main reference on established / broadly accepted metrics for the sector: IEA-OES's Evaluation and Guidance Framework for Ocean Energy Technology (Hodges et al., 2021). Then, the objective was to expand considerably the metrics in (Hodges et al., 2021) considering other sources.

Summary of Identified Metrics

A summary of the number of metrics in each of the evaluation areas is listed in Table 11. A total of 58 metrics were identified, where 48 are not listed in (Hodges et al., 2021) and are denoted "additional".

Under the power capture category, a significant number of additional metrics were reviewed, mainly from research projects such as the Wave Energy Prize (Bull and Dallman, 2017a, 2017b; Dallman et al., 2018) and the NUMWEC project (Babarit et al., 2011). Standard metrics used in other industries, namely in the wind sector, appear to have their equivalent in wave energy already established.

Metrics under the power conversion category are intrinsically related to the power capture through the influence of the PTO damping on the dynamics of the device. However, their implementation at a different point in the wave-to-wire pipeline compared to the power capture ones does result in different values for some of the metrics which are otherwise equivalent between both categories. A total of 17 additional metrics were identified, where 11 of these are related to grid code requirements that are not specific to wave energy.

Table 11. Summary of the number of identified metrics.

Category	A	B	C	D
Performance: Power Capture	2	3	8	4
Performance: Power Conversion	1	2	4	11
Reliability	2	4	0	7
Survivability	2	2	2	0
Techno-Economics*	3	0	1	0
All	10	11	15	22

A: metrics in (Hodges et al., 2021); B: additional metrics in standards, guidelines, and recommendations specific to wave energy conversion; C: additional proposed metrics in other publications specific to wave energy conversion; D: additional metrics from relatable industries or sectors; * 7 metrics already listed in other criteria are not listed here.

With regard to reliability, only 2 metrics are listed in (Hodges et al., 2021), while 11 additional ones were identified. Several of these additional metrics introduce alternative formulations for calculating MTTF, e.g., in terms of cycles, or derivations of MTTF considering aspects such as maintenance free periods. Metrics aiming at quantifying degradation of items, and its acceptability in terms of performance, were also identified.

Regarding survivability, 4 additional metrics were identified to expand the two listed in (Hodges et al., 2021), where the failure rate in survival mode per hour metric is worth highlighting given its unambiguity.

Most metrics can be seen as contributing to an assessment of the Technological Performance Level (TPL), converging to a techno-economic evaluation of the current state of the project; then typically, and ultimately, reduced to an LCOE assessment. Those metrics are thus proxies for economic assessments, and it is why 7 out of 11 of the techno-economics metrics identified (in addition to the 3 classic ones present in (Hodges et al., 2021): LCOE, CAPEX, and OPEX) are also part of other evaluation criteria.

Finally, in terms of Environmental Impact, no standards or test-derived metrics were identified. However, several recommendations and guidelines on the environmental impact at both national and European level were identified.

Salient Gaps and Proposed Next Steps

Arriving at a clear set of metrics to monitor the development of WEC projects is naturally challenging. Whatever set being proposed, including the one herein presented, it will likely be subject to criticism as it cannot contemplate all situations and particularities of the different projects. Despite this, it is possible to identify salient gaps and propose next steps towards filling them from the current status expressed by the present review.

These gaps can be divided into four categories: 1) *Formulation*, where relevant results are not reflected in existing metrics and a new metric should be formulated; 2) *Procedural*, where a metric is established/proposed, but no clear implementation details are given; 3) *Ambiguity*, where a metric is not clear in terms of what it assesses or what it takes into account. 4) *Targets and Thresholds*, where no indication is given of what is indicative of a good result.

On the *Formulation* aspect, although the considerable number of proposed metrics, one can argue that a more complete characterisation of the development of WECs, particularly by proposing different ways to assess data which is typically available at different design stages, is in order. New metrics should then be formulated focusing on specific TRLs to aid the monitoring of the development process, and the development itself, to complement the already established ones. This is in contrast with the current status, where several metrics are to be assessed across all development stages, thus bringing doubts on its ability to characterize a solution in lower TRLs where uncertainty is very high. An example of this is the difficulty of arriving at a credible LCOE in e.g. TRL 4, while at the same time such a metric is predominately used to compare between competing solutions irrespective of the TRL.

There also seems to be a systemic lack of interdisciplinarity in the existing metrics, with few notable exceptions. New interdisciplinary metrics could then be proposed by analysing results of holistic approaches to design and identifying relevant ratios and relations, or even through fundamental deduction. Novel metrics relating performance with reliability or survivability would be particularly attractive, as these are typically conflicting attributes in wave energy conversion.

Still within the *Formulation* category, the absence of established metrics related to Environmental Impact is worthy of additional comment. Although the efforts at the European level in the form of guidelines and recommendations, there is still not a common set of clear metrics to be assessed. In this respect, the EU taxonomy classification system (European Parliament and the Council, 2020) appears to be a promising framework from which such a set could be formulated.

It is also worth stressing that any novel metric should be properly assessed in terms of its capability to properly characterise different attributes which can in practice be used for decision support of design choices together with other results.

On the *Procedural* aspect, the standards and guidelines published by the IEC outline the procedures to assess the metrics. Most literature references identified in this review are typically high-level, where frameworks are proposed, or low-level, where components of the reliability assessment process are described at the same time the full procedure to quantify reliability is absent. Furthermore, procedural aspects relating to the establishment of Ultimate Limit States and corresponding sea states, and actual quantification of survivability are typically not presented.

Given the myriad of theoretical models and approaches to quantify reliability and survivability, it would be of great added value that specific procedures to attain them be listed by default in related publications to at least serve as a reference for developers who may otherwise tend to neglect it leading to serious consequences upon the prototype testing phase. Such step would also likely contribute to the reduction of the uncertainty in quantifying key metrics.

Regarding *Ambiguity*, this gap is particularly affecting the Reliability and Survivability evaluation areas and is tightly connected to the Procedural aspect mentioned above. It became clear early in the present review work that the definition of Survivability was far from established, not only in the wave energy sector but across other industries. Typically, the concept of survivability and reliability are interchanged and / or merged, often resulting in unclear metrics in terms of their actual implementation. The outcome is that publicized values for indicators of a given project need to be thoroughly examined in terms of their actual calculations to determine if they can be compared with others.

Such a discussion is not new, and has been addressed in, e.g., (IEA-OES, 2016; WES, 2016). Moreover, it is fair to say that the very reduced number of metrics listed in (Hodges et al., 2021) is a consequence of this. On the other hand, one can argue that all metrics should draw from a common understanding of what they are actually targeting, as is typically the case for performance related metrics.

Addressing the *Targets and Thresholds* type of gap, although design optimization across evaluation areas (converging to an economic assessment) is to be sought, it would be of much interest to developers to have clear indications of how their solution qualifies along the development process in key metrics against a reasonable expectation level, therefore raising red flags as early as possible and prioritizing addressing them. This naturally relates to the concept of TPL. However, here it is proposed that one should seek, despite its obvious difficulty, an indicative TPL threshold system which is expanded for targets related to key technical sub-indicators (metrics) not directly related to cost.

Testing methodologies for metrics evaluation

Lastly, it should be mentioned that monitoring the development of a WEC project through the application of a broad set of metrics is only possible by following a structured development and assessment process. Frameworks such as (Hodges et al., 2021), with its stage-gated development approach can be adopted. Likewise, especially for evaluating metrics within the reliability and survivability evaluation areas to which pre-prototype testing is required, a (currently unavailable) framework is needed to guide the establishment of test plans specific to the wave energy sector.

For wave energy applications, laboratory testing is an important activity as it typically forms the last development stage prior to open sea demonstration. However, a significant gap may exist between laboratory and open sea testing as conducting experiments in an uncontrolled environment has proved to be extremely challenging in previous wave energy developments, often leading to unexpected early failures or performance levels below expectations – see e.g., (Guo and Ringwood, 2021). The technical difficulties associated with the transition from laboratory testing to open sea demonstration are compounded by a lack of adequate design and test guidance specific to wave energy applications. The conceptualisation of a novel testing methodology aiming to create a framework that integrates the testing to be performed in rigs in a standard WEC design process, linking the assessment of key sub-systems / components that affect a variety of evaluation areas, in turn related to a range of design situations and specific design load conditions, should therefore be considered a crucial next step.

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