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Existing Ocean Energy Performance Metrics

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PREAMBLE

This document was produced by the Department of Energy Water Power Technologies Office (WPTO) with the support of the National Laboratories. WPTO released an earlier version of this document as part of a Request for Information (RFI), DE-FOA-0001903. The results of the Request for Information (RFI) may be used to inform the WPTO's strategic planning in future years, contribute to evaluation criteria for potential future funding opportunities, and provide a baseline for U.S. input into international efforts related to Marine Renewable Energy (MRE) metrics. In addition, feedback from the RFI was used to update this document. Although not all feedback is directly included in this document, it was considered.

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1. INTRODUCTION

This document summarizes existing Marine and Hydrokinetic (MHK) performance metrics known to the United States Department of Energy and national laboratories. This document was updated based on feedback from the MHK Energy community, however, this summary still may not be exhaustive.

There are a wide variety of needs and uses for metrics. All stakeholders, such as developers, funding agencies, investors, and researchers, have a need for metrics and their many uses. It is evident that the sector will benefit from clear techno economic performance metrics to guide development towards success.

There are international efforts underway to bring the community together to (1) understand what metrics/approaches are being used currently and (2) reach a global framework on the approach to the measurement of success. This document serves to list existing metrics known to the U.S. at the present, and is not meant to represent international efforts or consensus.

Further, it should be noted that the International Energy Commission (IEC) Technical Committee on Marine Energy – Wave, Tidal and Other Water Current Converters is developing standards for this field. To date, eleven technical specifications have been published, including guidelines for calculating power production of wave (IEC TS 62600-100), tidal (IEC TS 62600-200), and river (IEC TS 62600-300) energy converters, as well as resource assessment (IEC TS 62600-101, -201, -301). Whenever possible, these technical specifications and standards should be considered in calculating performance metrics.

2. OVERVIEW OF MHK PERFORMANCE METRICS

Performance metrics are necessary for evaluating techno-economic potential, tracking the value of an innovation or improvement, and making stage gate decisions in R&D programs. Metrics are needed at all stages of development, and it is acknowledged that uncertainties in evaluations are high at low Technology Readiness Levels (TRLs). Input to metrics are typically based on measurements or validated models.

Within a specific resource (wave/current, etc.), and within each market application of the technology, the metrics should ideally be technology agnostic. However, at a lower level, metrics specific to device archetypes exist and may be used. For example, to calculate power absorption, experimental measured quantities such as flow rate and pressure are specific to an oscillating water column. This document and most existing performance metrics are geared towards the utility scale electricity generation. For the most part, it is expected that metrics will be similar or the same for different market applications, except with different thresholds of acceptability; however there will be a need for market specific metrics as well. This document focuses on wave energy converter (WEC) metrics, however each metric notes the applicability to the specific resource (e.g., wave, tidal, or ocean current energy converter technologies).

The techno-economic viability of a technology ultimately depends on the deployment of a full farm of energy conversion devices at a given resource location, with a given sale price, over a given lifetime. The type of energy output may also vary, ranging from electricity, mechanical power, pressurized fluids, and clean water. In most cases it is assumed an array of devices will be deployed, whether it is for utility scale electricity generation, distributed generation, or for alternative markets such as desalination. Perhaps in specific markets with lower energy needs, such as underwater sensor recharging, a single device would suffice. In any case, the total power or electricity to be delivered to a given market will be the driver of the farm design, even if the farm consists of a single device. Therefore, the metrics to assess a technology should start at the farm level, to ensure important balance of plant costs as well as operations and maintenance (O&M) costs are considered. From there, metrics can be considered at the device and subsystem levels. The document is arranged from that framework, starting with the energy converter farm level, then addressing the device, and finally the device subsystems.

A brief summary table of the metrics is provided in Table 1, and further details are in the respective sections.

Table 1. Performance metrics summary.

Energy Converter Farm	Technology Performance Levels (TPL)
	Levelized Cost of Energy (LCOE)
	Levelized Cost of Water (LCOW)
Energy Converter Device	TPL and LCOE drivers
	ACE
	Annual absorbed energy per wetted surface area
	Annual absorbed energy per characteristic mass
	Power to Weight Ratio (PWR)
	Annual absorbed energy per RMS PTO force
	Capture Width Ratio
Energy Converter Device Subsystem - General	TPL and LCOE drivers
	Failure Rate
Energy Converter Device Subsystem - Controls	Optimal Cost Criteria
	Sensitivity
	Signal to Noise Ratio (SNR)
	Performance Uncertainty via Numerical Simulation
Energy Converter Device Subsystem – Power Take-Off	Capacity Factor
	Peak to Average Power
	Energy Conversion Efficiency

3. ENERGY CONVERTER FARM

The energy converter farm is the highest level of consideration for metrics, as the total system needs to achieve cost competitiveness. For the purpose of this document a 'farm' can be understood as any of the following: utility grid scale electricity generation, or a small set of or single device(s) with its balance of plant included in a distributed generation scenario.

In some cases, electricity may not be the product, and the mechanical power (or a combination of mechanical and electrical power generated) will be used directly to operate a desired system such as a desalination plant. This case requires a metric that considers the specific product, e.g., levelized cost of water (LCOW).

The following tables include metrics for the farm level. These include TPL, LCOE, and LCOW. Note that availability is inherently included within TPL and LCOE, and therefore is not described as a separate metric.

Table 2. Energy converter farm metric: TPL.

Technology Performance Levels (TPL)	
Description: TPL is composed of a set of metrics that aim to holistically assess and quantify the techno-economic performance potential of the wave energy farm system and the included devices and subsystems by considering all cost and performance drivers. Building on the assessment with respect to a large number (90) of individual criteria and their individual scores (TPL 1 to TPL 9), group scores and the overall system score are also determined. The highest-level score is the TPL for the system. The TPL assessment methodology and tool considers all the capabilities of a successful wave energy farm. These capabilities were identified through a complete Systems Engineering analysis including a detailed lifecycle and cross-referenced stakeholder assessment. Seven capability topics are defined with sub- and sub-sub-capabilities. Each capability receives a score, and the overall score is determined by weighting them in a manner that reflects the LCOE calculation. The capabilities and second level sub-capabilities are: 1. Have market competitive cost of energy 1.1. Have as low a CAPEX as possible 1.2. Have as low an OPEX as possible 1.3. Be able to generate large amounts of electricity from wave energy 1.4. Have high availability 1.5. Have a low financing rate 1.6. Have a low insurance rate 2. Provide a secure investment opportunity 2.1. Low uncertainty on costs and revenues 2.2. Survivable	**Notes:** • The TPL questionnaire sheet is being refined based on evaluations of existing devices • Variations on the developed TPL methodology may be useful for considering other markets beyond utility scale electricity generation • Variations on the developed TPL methodology could also be developed specifically for tidal and/or ocean current energy • Documentation, the scoring tool (spreadsheet), and contact information can be found at: http://energy.sandia.gov/energy/renewable-energy/water-power/technology-development/wave-sparc/ • TPLs are a large set of individual metrics but also provide a combination of scores into an overall score; therefore individual metrics from TPL such as survivability are not explicitly defined as a

3. Be reliable for grid operations 3.1. Be forecastable 3.2. Have high correlation of power production to demand 3.3. Be useful to the grid 3.4. Be grid compliant 4. Be beneficial to society 4.1. Be beneficial to local communities 4.2. Be a low greenhouse gas (GHG) emission energy source 4.3. Be a low polluting energy source 4.4. Have minimal impact on taxpayers 4.5. Contribute significantly to energy security 5. Be acceptable for permitting and certification 5.1. Be environmentally acceptable 5.2. Be acceptable to other users of the area 6. Be acceptable with respect to safety 7. Be deployable globally Most capabilities include several sub-capabilities as listed above, and each sub-capability has one or more sub-sub-capabilities with specific questions used for scoring. In total 90 assessment criteria (i.e., individual metrics) are considered. There is quantitative guidance of low/med/high scoring values in the TPL framework for each criterion. Where possible, quantitative *and* numerical guidance values (for low, medium, high TPL ranges) with relevant physical units are given. Questions supporting the assessment with respect to the criteria depend on the Technology Readiness Level (TRL, described in Appendix A). The methodology provides questions of appropriate levels of detail at different TRL levels, broken out to TRL 1-2, TRL 3-4, TRL >=5. Certainty of TPL score increases as TRL increases. See references for full evaluation methodology.	separate metric in this document. • TPL is a single metric for a complete system, where the system value is supported by the underlying, complete details of cost and performance information
Applicability: wave energy farms intended for utility scale electricity generation **Assumptions:** extensive information is needed to evaluate TPL, and therefore certainty of TPL scoring becomes more certain at higher TRLs	**References:** • Weber 2012 • Weber 2013 • Bull et al 2017 • Bull et al 2017

Table 3. Energy converter farm metric: LCOE.

<table>
<tr><th colspan="2">Levelized Cost of Energy (LCOE)</th></tr>
<tr><td>

Description: LCOE is the total system cost per energy output based on annual average values, lifetime of the technology, and financing assumptions. It is a standard cost metric used to evaluate all electricity producing technologies in a market. It can be used for utility scale, or distributed markets, with the competitive thresholds varying based on market conditions.

$$LCOE = \frac{ICC \text{ x } FCR\ +\ O\&M}{AEP}$$

where

LCOE Levelized cost of energy ($/MWh)

ICC Initial capital cost per installed capacity ($/MW)

AEP Annual energy production per installed capacity (MWh/MW/year=hours/year); $AEP = CFxAFx365x24$

FCR Fixed charge rate is the annual return, represented as a fraction of installed capital costs, needed to meet investor revenue requirements, FCR=10.8%/yr in DOE guidance. The FCR is a lumped financing term that includes an assumed discount rate, inflation, federal and state taxes, depreciation schedule, and the period of economic life.

O&M Annualized operations and maintenance costs, including all routine maintenance, operations, and monitoring activity (i.e., non-depreciable) ($/MW/year)

CF Capacity factor, averaged over typical year (%). Note: must be consistent with the estimated ICC

AF Availability factor, percentage of time a device is operational throughout the year. Typically includes downtime due to expected and unexpected maintenance (%)

</td><td>

Notes:

- LCOE is defined the same way for tidal and current energy conversion technologies; both the reference wave and tidal resources are provided in the U.S. Department of Energy (DOE) Water Power Technologies Office (WPTO) LCOE guidance
- LCOE is a single metric for a complete system, where the system value is supported by underlying cost and performance information

</td></tr>
<tr><td>

Applicability: Marine and hydrokinetic energy farms intended for electricity generation (utility scale or distributed)

Assumptions:

- Extensive information is needed to calculate LCOE (becomes more accurate at higher TRLs); probabilistic analyses and sensitivity studies are useful, particularly at low TRLs.
- LCOE depends on the resource, and therefore tracking or comparing values should use a consistent and technology suitable resource (a joint probability distribution of sea states for wave, and a probability distribution of velocities for tidal).
- LCOE depends on the FCR, which as described in the LCOE description section above, includes more variables than only

</td><td>

References:

- DOE WPTO LCOE reporting guidance
- Bull et al. 2017

</td></tr>
</table>

interest rate, and for the DOE WPTO guidance is set to 10.8%/yr. See DOE WPTO guidance for more details. • LCOE depends on the project economic life, which is set to 20 years in the DOE WPTO guidance. • The IEC TC114 wave (62600-100) and tidal power (62600-200) performance technical specifications assume that AEP is calculated with 100% availability. However, the DOE WPTO guidance on LCOE calculation includes transmission losses and availability be included in the AEP calculation.	

Table 4. Energy converter farm metric: LCOW.

Levelized Cost of Water (LCOW)	
Description: LCOW is the total system cost per water output. Similar to LCOE, LCOW is meant to be a standard cost metric used to evaluate all clean water producing technologies in a market. Can be used for utility scale, or distributed markets, with the competitive thresholds varying based on market conditions. $$LCOW = \frac{ICC \text{ x } FCR + O\&M}{AWP}$$ Where *LCOW* Levelized cost of water ($/m^3/yr) *ICC* Initial capital cost ($) *AWP* Average annual water production (m^3/yr) *FCR* Fixed charge rate *O&M* Operations and maintenance costs, including all routine maintenance, operations, and monitoring activity (i.e., non-depreciable) over the lifetime of the farm ($)	**Notes:** • LCOW is defined the same way for tidal and current energy conversion technologies • Fixed charge rate can be assumed to be the same as in DOE LCOE guidance • LCOW is a single metric for a complete system, where the system value is supported by underlying, detailed cost and performance information
Applicability: Marine and hydrokinetic energy farms intended for generating clean water (utility scale or distributed) **Assumptions:** • Extensive information is needed to calculate LCOW (becomes more accurate at higher TRLs). • In the context of desalination using power from MHK, LCOW depends on the resource, and therefore tracking or comparing values should use a consistent resource (a joint probability distribution of sea states for wave, and a probability distribution of velocities for tidal). • LCOW depends on the FCR, following the DOE MHK LCOE guidance, it is set to 10.8%. • It is assumed the required water quality is determined prior to assessing LCOW.	**References:** • Yu & Jenne 2017

4. ENERGY CONVERTER DEVICE

The energy converter device is often assessed (rather than the farm) particularly when at a TRL that does not easily allow for a full LCOE calculation. In addition, for focusing on technology development, it is useful to consider metrics that concentrate on the device level rather than the system. TPL was developed to holistically cover the whole farm system, but can be applied at the device and subsystem level using the relevant system criteria (e.g., at the device level, cable failure or maintenance vessel availability would not be considered in the TPL device score). In addition, LCOE drivers can be applied at the device and subsystem level.

The following tables include additional metrics for the energy converter device. These include ACE, annual absorbed energy per wetted surface area, annual absorbed energy per characteristic mass, power to weight ratio, annual absorbed energy per RMS PTO force, and capture width ratio.

Table 5. Energy converter device metric: ACE.

ACE	
Description: The ACE metric is regarded as a low TRL proxy for the levelized cost of energy and was specifically developed for the U.S. DOE Wave Energy Prize. ACE is a benefit-to-cost proxy ratio. The two components that comprise the ratio ACE are $$ACE = \frac{ACCW}{CCE}$$ Where $ACCW$ Average Climate Capture Width is a measure of the effectiveness of a WEC at absorbing power from the incident wave energy field in units of meters [m] CCE Characteristic Capital Expenditure is a measure of the capital expenditure in commercial production of the load bearing device structure in units of millions of dollars [$M]	**Notes:** • Details of how to calculate ACE are given in references below. Specific sea states and manufactured material costs are given. • This metric and Hydrodynamic Performance Quality (HPQ) were developed within the requirements of the WEPrize, and were intended to utilize the maximum amount of information out of a short tank test.
Applicability: This metric is specific to wave energy. In order to account for additional techno-economic considerations, the Wave Energy Prize also used HPQ (see references), but it is not generally applicable outside of the Prize because the values were based on ranking among a set of teams. **Assumptions:** The ACE metric assumes the structure is the largest portion of CapEx. It equally weights energy production with a portion of capital costs, whereas LCOE weights all costs to energy production, so it is not a one-to-one comparison. ACE needs additional techno-economic factors (e.g., as was attempted with HPQ), and perhaps extensions of ACE would include additional costs such as of moorings, PTO, etc. Without these additional factors, it is recommended that ACE only be used to compare structural efficiency of a device and to quickly assess low TRL devices. However, it should not be used alone to compare techno-	**References:** • Driscoll et al. 2017 • Wave Energy Prize rules, 2016 • Jenne et al. 2017 • Dallman & Bull 2017 • Dallman et al. 2018

economic potential across device types without additional considerations.	

Table 6. Energy converter device metric: annual absorbed energy per wetted surface area.

<table>
<tr><th colspan="2">Annual absorbed energy per wetted surface area</th></tr>
<tr><td>Description: The next several metrics are cost-performance metrics introduced by Babarit et al. 2012. They are benefit to cost proxy ratios.

$$\frac{Annual\ absorbed\ energy}{Wetted\ surface\ area}$$

$Annual\ absorbed\ energy$ — total energy absorbed in a year [MWh]
$Wetted\ surface\ area$ — Wetted surface area [m^2] is the surface area of the device below the waterline, and is a cost indicator for the capital costs of the WEC structure</td><td>Notes:
• N/A</td></tr>
<tr><td>Applicability: This metric was introduced for wave energy. However, it could be applied to tidal and/or ocean current energy.

Assumptions:
• The absorbed energy is dependent on the resource (site) selected. Babarit et al. 2012 presented values at several European sites, while Dallman et al. 2018 presented values at the Wave Energy Prize climates. When comparing values, a consistent resource should be used.
• The structure and the foundations are included in wetted surface area in Babarit et al. 2012, but only the structure is considered in Dallman et al. 2018. The choice to include foundations should be consistent when comparing values of this metric.
• In addition, the surface area does not consider cost of material types and manufacturing, and therefore only similar material types should be compared using this metric.
• This metric focuses on the efficiency of the absorber body, but neglects additional surface area (and therefore cost) above the water line that does not contribute to energy absorption.</td><td>References:
• Babarit et al. 2012</td></tr>
</table>

Table 7. Energy converter device metric: annual absorbed energy per characteristic mass.

<table>
<tr><th colspan="2">Annual absorbed energy per characteristic mass</th></tr>
<tr><td>Description: As in Table 6, this is a cost-performance metrics introduced by Babarit et al. 2012. It is a benefit to cost proxy ratio. Characteristic mass is a cost indicator for the capital costs of the WEC structure.

$$\frac{Annual\ absorbed\ energy}{Characteristic\ mass}$$
$Annual\ absorbed\ energy$ — total energy absorbed in a year [kWh]
$Characteristic\ mass$ — Characteristic mass [kg] is the mass of the energy absorber, and is a cost indicator for the capital costs of the WEC structure</td><td>Notes:
• N/A</td></tr>
<tr><td>Applicability: This metric was introduced for wave energy. However, it could be applied to tidal and/or ocean current energy.

Assumptions:
• The absorbed energy is dependent on the resource (site) selected. Babarit et al. 2012 presented values at several European sites, while Dallman et al. 2018 presented values at the Wave Energy Prize climates. When comparing values, a consistent resource should be used.
• The structure and the foundations are included in characteristic mass in Babarit et al. 2012 for devices that utilize the sea bottom as the force-reference, but only the structure is considered in Dallman et al. 2018. In Babarit et al. 2012, a factor was added to account for the mooring system without calculating it explicitly. The choice to include foundations and/or moorings should be consistent when comparing values of this metric.
• The metric does not consider cost of material types and manufacturing. In addition, using the mass as a cost indicator may be misleading because some very light materials such as fiberglass are more expensive than heavier materials such as steel.</td><td>References:
• Babarit et al. 2012</td></tr>
</table>

Table 8. Energy converter device metric: power to weight ratio.

<table>
<tr><th colspan="2">Power to Weight Ratio (PWR)</th></tr>
<tr><td>Description: This metric is a benefit to cost proxy ratio, and is very similar to annual absorbed energy per characteristic mass. Weight is a cost indicator for the capital costs of the device structure.

$$\frac{Rated\ Capacity\ x\ Capacity\ Factor}{Weight\ in\ Air}$$
$Rated\ Capacity$ — expected power that the system is designed to produce [kW]</td><td>Notes:
• This is the definition DOE has used historically (SPA I/II FOAs)</td></tr>
</table>

$Capacity\ Factor$ $Weight\ in\ Air$	ratio of the actual power produced at a site to the power produced by the device if operating at rated capacity, over a given time (typically one year) [kg]	
Applicability: This metric is applicable for wave, tidal and ocean current energy. This metric is used in other industries such as wind energy. Similarly to other metrics above focusing on the structure, it is assumed that the structural costs make up the majority of the capital expenditure. **Assumptions:** • The capacity factor is dependent on the resource (site) selected. When comparing values, a consistent resource should be used. • The metric does not consider cost of material types and manufacturing. In addition, using the weight as a cost indicator may be misleading because some very light materials such as fiberglass are more expensive than heavier materials such as steel. Therefore, this metric should not be used to compare devices of different material types.		**References:** • SPA I/II FOAs (DE-FOA-0000848 and DE-FOA-0001182)

Table 9. Energy converter device metric: annual absorbed energy per RMS PTO force.

Annual absorbed energy per RMS PTO force		
Description: As in Table 6, this is a cost-performance metrics introduced by Babarit et al. 2012. It is a benefit to cost proxy ratio. $\frac{Annual\ absorbed\ energy}{RMS\ PTO\ force}$		**Notes:** • N/A
$Annual\ absorbed\ energy$ $RMS\ PTO\ force$	total energy absorbed in a year [kWh] Root Mean Square (RMS) of Power Take-Off root mean square (RMS) of PTO force over a year [N]; the higher forces, the more expensive the PTO system will be, and therefore this is a cost indicator of the PTO	
Applicability: This metric was introduced for wave energy. However, it could be applied to tidal and/or ocean current energy. **Assumptions:** • The absorbed energy is dependent on the resource (site) selected. Babarit et al. 2012 presented values at several European sites, while Dallman et al. 2018 presented values at the Wave Energy Prize climates. When comparing values, a consistent resource should be used. • It is assumed that linear force is measured or modeled. Rotary PTOs that transform absorbed power as the product of torque and angular velocity will have different force units, and therefore should be compared separately from linear force values. It is recommended not to		**References:** • Babarit et al. 2012

convert rotary force to linear force due to the number of assumptions needed (including uncertainty in interpreting the distance), and the fact that the way a material carries torque is different from forces or bending moments.	

Table 10. Energy converter device metric: capture width ratio.

Capture Width Ratio	
Description: This is a hydrodynamic performance metric widely used in the literature. It is a measure of the hydrodynamic efficiency. $$\frac{CW}{B}$$ CW — Capture width, $CW = P/J$ [m] P — absorbed wave power [kW] J — wave resource [kW/m] B — characteristic dimension of the device [m];	**Notes:** • 'Capture width' is meant to represent the characteristic dimension as defined in the equation; often a length is used
Applicability: This metric is specific to wave energy. **Assumptions:** • The absorbed energy is dependent on the resource (site) selected. Babarit 2015 presented values at several European sites, while Dallman et al. 2018 presented values at the Wave Energy Prize climates. When comparing values, a consistent resource should be used. • The selection of the characteristic dimension, B, usually taken as width, is critical to ensure CWR is comparable between different archetypes of WECs. See Babarit 2015 for details on defining width; for heaving WEC devices, the characteristic diameter is defined in Babarit 2015. • This is not an economical performance metric, it only considers hydrodynamic efficiency.	**References:** • Babarit 2015

5. ENERGY CONVERTER DEVICE SUBSYSTEMS

Changes or improvements to the energy device subsystems, as well as the impacts of the subsystem characteristics on overall techno economic performance, are important to quantify as well.

Many of the sub criteria in previous metrics listed under farm and device level are applicable at the subsystem level including TPL and LCOE drivers. For many subsystems, metrics at the device level are often used to assess the impact of an improvement or innovation to a specific subsystem (assuming the rest of the system does not change) due to the limitations of full system knowledge and the specifics of development activities (e.g., utilizing power absorption from tank testing). However, the strongest consideration would be to assess its influence on all the cost and performance drivers (e.g., impact on TPL).

The following tables include metrics for the MHK device subsystems. The subsystems considered are general (failure rate of subsystems), structure, controls, power take-off (PTO), and moorings.

5.1. General

Failure rates apply to all subsystems, and sub-subsystems (components). These feed into an overall operations and maintenance (O&M) model which will determine O&M costs.

Table 11. Energy converter subsystem metric: failure rate.

Failure Rate	
Description: The failure rate of a component is defined in many different ways. Mean time between failure is a commonly misunderstood phrase, as illustrated here: http://www.weibull.com/hotwire/issue80/relbasics80.htm. Failure can signify complete failure or degradation, and the reliability definition should be specified with a confidence level. The L-50 life, used in the Reference Model Project (Neary et al. 2014), is assumed to be the mean life of a component, where 50% of the components will fail (and need replacement). The replacement cost of parts can then be determined using the L50 life as the replacement interval.	**Notes:** • N/A
Applicability: This metric applies to any MHK system, and expresses the reliability of a component, which affects operations and maintenance schedules and costs, as well as availability of the entire system. **Assumptions:** • The failure rate should be defined carefully with consideration of the operating environment, within a time window, with a clear definition of failure (complete or degradation), and with a confidence interval.	**References:** • Neary et al 2014 • http://www.weibull.com/hotwire/issue80/relbasics80.htm

5.2. Structure

Metrics that are relevant to consider for improvements or innovations to the structure include some of the same metrics as the system:

- ACE
- Absorbed energy per wetted surface area
- Absorbed energy per characteristic mass
- PWR
- CWR

In addition, evident metrics that could be considered for the structure include manufacturability, and transportability, which are sub-sub-capabilities in TPL under '1. Have market competitive cost of energy,' '1.1 Have as low CAPEX as possible.'

5.3. Controls

Metrics that are relevant to consider for improvements or innovations to control systems include some of the same metrics as the system:

- ACE
- Absorbed energy per wetted surface area
- Absorbed energy per characteristic mass
- PWR
- CWR
- Failure rate (in terms of allowing survival mechanisms to be employed or more generally, avoiding high loads on the device or PTO by using controls)

In addition, specific descriptions of optimal cost criteria, sensitivity, signal to noise ratio, and performance uncertainty via numerical simulation are given below. Note that these four metrics specific to controls are useful for evaluating performance within a project or development process of a control system for a specific device. However, they are not helpful for comparing technologies.

Table 12. Energy converter controls subsystem metric: optimal cost criteria.

<table>
<tr><th colspan="2">Optimal Cost Criteria</th></tr>
<tr><td>Description: Optimal cost criteria are often used as a figure of merit for evaluating the performance of a control system. Usually, these cost criteria are expressed as some combination of control effort needed to minimize tracking error of the system response. This figure of merit can be as simple as the total amount of control effort to maintain the tracking error at zero over some time interval. This is more formally expressed as the integral (or summation in the case of a discrete-time system) of quadratic tracking error plus control energy over a time interval (or a number of sampling points) of interest.

Given a linear system in state space format
$$\dot{x} = Ax + Bu$$
The standard quadratic optimal cost criteria is expressed as
$$Cost = \int_{t_0}^{t_f} (x^T Qx + u^T Ru)dt$$</td><td>Notes:
• N/A</td></tr>
</table>

where x is the system states, u is the controller input, A and B are the linear system matrices, Q is a weighting matrix for the tracking error and must be positive semi-definite, and R is a weighting matrix of the control effort and must be strictly positive definite.	
Applicability: This metric is used to see how well a given controller (for any energy technology, e.g., wave, tidal, current, etc.) can improve its performance (as measure by the cost criteria) compared to a baseline controller design. Examples of this comparison approach can be found in Coe et al. 2017. **Assumptions:** • The cost criteria adopted need to be applied consistently to all controllers being compared. • Not all control designs are based on an explicit optimization criterion, therefore this metric won't work across the board.	**References:** • Coe et al. 2017

Table 13. Energy converter controls subsystem metric: sensitivity.

Sensitivity	
Description: The generic definition of sensitivity is the percentage change of some quantity of interest with respect to the percentage change of a different quantity of interest. For controls, sensitivity represents the robustness of the controller to uncertainties in the system. Generally, one wants these sensitivities to be as small as possible. How well the controller reduces these sensitivities is a key metric for evaluating the performance of the controller. The uncertainties include process noise (more commonly referred to as disturbances), measurement noise, and model uncertainty. Given a parameter of interest, α, and the MHK power output, P, the sensitivity of the power output to the parameter of interest for a given controller design, say controller N, can be expressed as $${}^{N}S_{\alpha}^{P} = \frac{\partial P}{\partial \alpha}$$ Then, given a baseline controller design, say controller M, the metric of interest is the improvement of controller N over controller M in reducing the sensitivity of the power output to the parameter of interest, denoted by R: $$R = {}^{N}S_{\alpha}^{P} / {}^{M}S_{\alpha}^{P}$$ The reference by Coe et al (2017) provides an example of assessing parameter uncertainty in WEC control performance using an empirical approach. The reference by Mathew (2015) is a good source of definitions and simple examples for the analytical approach to sensitivity analysis.	**Notes:** • N/A
Applicability: This metric is used to evaluate how well a control system (for any energy technology, e.g., wave, tidal, current, etc.) performs in the presence of uncertainty compared to a baseline controller performance or open-loop performance.	**References:** • Coe et al. 2017

Assumptions: • For a system that is not easily modeled as a linear system, empirical analysis is probably the better way to evaluate sensitivity rather than an analytical approach with a nonlinear model. The empirical approach would also be preferable for high order systems or when a large number of parameters are of interest. • In the empirical case, the Monte Carlo method is well known and usually sufficient for a small number of parameters. For a larger set of parameters of interest, there are more advanced methods (e.g. Taguchi analysis) to help in reducing the number of simulations needed.	• Mathew 2015

Table 14. Energy converter controls subsystem metric: signal to noise ratio.

Signal to Noise Ratio (SNR)	
Description: This is a measure of how well the control system rejects disturbances, such as measurement noise, unmodeled or poorly modeled component dynamics, and uncertainty in sea state estimation. SNR is the ratio of the output power magnitude to the spectral magnitude (or estimated variance magnitude) of the uncertainty quantity that one wishes to minimize (e.g., modeling errors, sensor noise) over the frequency range of interest. This means the SNR metric will result in a plot of magnitude (usually in dB) on the y-axis vs. frequency (in Hz or rad/sec) on the x axis. Often the frequency range of interest is very small and the SNR varies little in this range. In these cases, the SNR would be expressed as a single value in dB. $$SNR = 10\ log_{10}(Average\ Signal\ Power / Average\ Noise\ Power)$$ $Average\ Signal\ Power$ — the expected value of the variance of the output power $Average\ Noise\ Power$ — the expected value of the variance of the noise signal	**Notes:** • N/A
Applicability: This metric is applicable to the control system of any energy technology (e.g., wave, tidal, current, etc.). **Assumptions:** N/A	**References:** • N/A

Table 15. Energy converter controls subsystem metric: performance uncertainty via numerical simulation.

Performance Uncertainty via Numerical Simulation	
Description: This metric yields a table containing the performance of a controller given a certain level of uncertainty in a parameter of interest. Performance is measured by the output of interest (of the output power). Uncertainty in the parameter of interest can be characterized by the deviation from a nominal (known) value of the parameter. The deviation can be expressed as a relative value (in %) or as a certain number of standard deviations from the mean value of the	**Notes:** • N/A

parameter. Often, Monte Carlo techniques are employed in tabulating the performance uncertainty of a particular control design to various parameters of interest. The reference by Coe et al (2017) provides an example of assessing performance uncertainty in MHK control performance using the numerical simulation approach.	
Applicability: This metric can be used as a means of comparison between different controller designs with respect to their performance in mitigating uncertainty in parameters. It can also be used in tradeoff analysis in the case that performance uncertainty may be improved for one parameter but gets worse for another parameter. **Assumptions:** • This metric can be tedious to use if the simulation time is relatively long since 100s of simulations may be necessary. • To use the standard deviation as a means of parameter uncertainty, it is necessary to have a statistical profile of the parameter of interest. • Though this metric can be very effective in comparison and tradeoff analysis, it is not as useful in identifying means of improving the controller design compared to a model-based approach.	**References:** • Coe et al. 2017

5.4. Power Take-Off

A metric for improvements or innovations to power take-offs (PTOs) includes PWR, a system metric. As with the other subsystems, there are components from the TPL that would apply directly to the PTO, such as maintainability, reliability, and redundancy.

In addition, there is capacity factor, peak to average power, and energy conversion efficiency detailed in the tables below.

Table 16. Energy converter PTO subsystem metric: capacity factor.

Capacity Factor	
Description: The capacity factor is the average electrical power generated divided by the rated peak power (high capacity factor is favorable). $$CF = \frac{average\ electrical\ power}{rated\ peak\ power}$$ $average\ electrical\ power$ Average electrical power generated [kW] $rated\ peak\ power$ Rated peak power of the generator [kW]	**Notes:** • N/A
Applicability: This metric applies to any MHK system, and is a standard metric used in related power producing technologies (e.g., wind turbines). Note that capacity factor can be considered for either farm, device, or even individual PTO level (for devices with multiple PTO systems). **Assumptions:** • The average electrical power is dependent on the resource (site) selected. When comparing values, a consistent resource should be used.	**References:** • N/A

Table 17. Energy converter PTO subsystem metric: peak to average power.

Peak to Average Power		
Description: This is a proxy for capacity factor (see table above). Peak to average absorbed power is an inverse proxy (high capacity factor is favorable while low peak to average ratio is favorable). $$Peak\ to\ average\ power = \frac{peak\ absorbed\ power}{average\ absorbed\ power}$$		**Notes:** • The effect of limiting instantaneous power on the AEP was studied in Babarit et al. 2012. • In a theoretical scenario (with constant power input), 1.0 is the ideal value for both capacity factor and peak to average ratio
$peak\ absorbed\ power$	peak of mechanical power absorbed (before conversion to electrical power) [kW]; this can be the statistical measure of the peak power, fitted to a distribution rather than the absolute peak measured in testing	
$average\ absorbed\ power$	average mechanical power absorbed (before conversion to electrical power) [kW]	

Applicability: The peak absorbed power will drive the selection of the PTO (higher peaks will require a more expensive, higher rated PTO or loss of energy produced and higher forces on the selected PTO). The average absorbed power is tied to AEP. This metric could be extended to consider components of the power take-off system, such as peak to average force. **Assumptions:** • The peak to average power is dependent on the resource (site) selected. When comparing values, a consistent resource should be used. • When comparing values of peak to average power, it is important to consistently apply it at the same location in the PTO and consider whether or not controls are being used.	**References:** • WEPrize rules

Table 18. Energy converter PTO subsystem metric: energy conversion efficiency.

Energy Conversion Efficiency	
Description: The energy conversion efficiency is the ratio of electrical power output to power into the PTO. It can be measured either directly at the output of the PTO, or as grid compliant (including conditioning). $$\eta = \frac{electrical\ power\ out}{power\ into\ PTO}$$ η — energy conversion efficiency $electrical\ power\ out$ — electrical power out either immediately from the PTO (not necessarily grid compliant) or at the point of grid connection (including conditioning) [kW] $power\ into\ PTO$ — power into the PTO [kW]	**Notes:** • N/A
Applicability: This metric applies to any MHK system, and is a standard metric used in related power producing technologies (e.g., wind turbines) **Assumptions:** • It is useful to consider the efficiency both before conditioning and after conditioning. • This metric can exclude transmission losses if a subsea cable is needed to transmit electricity to the grid connection (in order to make a site agnostic assessment). • The average electrical power is dependent on the resource (site) selected. When comparing values, a consistent resource should be used.	**References:** • WES 2017 workshop report

5.5. Mooring / Foundation

Metrics for improvements or innovations to mooring systems include some of the same metrics as the system:

- Absorbed energy per wetted surface area (if moorings/foundations are included)
- Absorbed energy per characteristic mass (if moorings/foundations are included)

In addition, mooring force (e.g., statistical peak), and mooring force per installed MW could be considered but are not detailed here.

6. SUMMARY

This document, while not exhaustive, catalogs common, historical performance metrics used within the marine energy industry. The topic of which performance metrics are most appropriate at various stages of maturity in the technology development process is an ongoing discussion which needs to be revisited as technologies mature and more data becomes available. A comparison summary of the previously described ocean energy performance metrics is provided in the following table.

Table 19. Detailed summary table of performance metrics.

	PERFORMANCE METRIC	APPLICABILITY - RESOURCE	APPLICABILITY - SYSTEM	STRENGTHS	LIMITATIONS
ENERGY CONVERTER FARM	**Technology Performance Levels (TPL)**	**Wave -** yes **Tidal** – N/A **Current** – N/A	**Farm -** yes **Device** – possibly (TPL drivers) **Component** – possibly (TPL drivers)	• More certainty at higher TRLs • Most holistic assessment of performance	• Extensive data required for calculation
	Levelized Cost of Energy (LCOE)	**Wave -** yes **Tidal** – yes **Current** – yes	**Farm -** yes **Device** – possibly (LCOE drivers) **Component** – possibly (LCOE drivers)	• More certainty at higher TRLs • Holistic assessment of performance	• Extensive data required for calculation • Use at lower TRLs requires multiple assumptions; results in large error bands around values • Resource specific
	Levelized Cost of Water (LCOW)	**Wave -** yes **Tidal** – yes **Current** – yes	**Farm -** yes **Device** – possibly (LCOW drivers) **Component** – possibly (LCOW drivers)	• More certainty at higher TRLs • Holistic assessment of performance	• Extensive data required for calculation • Use at lower TRLs requires multiple assumptions; results in large error bands around values • Resource specific

ENERGY CONVERTER DEVICE	**ACE**	**Wave** - yes **Tidal** – N/A **Current** – N/A	**Farm** – N/A **Device** – yes (prize use only) **Component** – N/A	• Simplistic estimate of LCOE structural cost & energy capture • More useful at lower TRLs	• Only applicable for evaluation of structural efficiency • Should not be used independently to assess techno-economic potential
	Annual Absorbed Energy per Wetted Surface Area	**Wave** - yes **Tidal** – possibly **Current** – possibly	**Farm** - possibly **Device** – yes **Component** – N/A	• Simplistic proxy for LCOE material cost & energy capture • More useful at lower TRLs	• Resource site specific • Surface area does not consider cost of material types and manufacturing (therefore device comparisons limited to like materials) • Does not account for material (cost) above the waterline
	Annual Absorbed Energy per Characteristic Mass	**Wave** - yes **Tidal** – possibly **Current** – possibly	**Farm** - possibly **Device** – yes **Component** – N/A	• Simplistic proxy for LCOE material cost & energy capture • More useful at lower TRLs	• Resource site specific • Mass alone as a cost indicator may be misleading; does not account for tradeoffs associated with other performance metrics
	Power to Weight Ratio (PWR)	**Wave** - yes **Tidal** – yes **Current** – yes	**Farm** - possibly **Device** – yes **Component** – N/A	• Simplistic proxy for LCOE material cost & energy capture • More useful at lower TRLs	• Resource site specific due to capacity factor • Mass alone as a cost indicator may be misleading; does not account for tradeoffs associated with other performance metrics
	Annual Absorbed Energy per RMS PTO Force	**Wave** - yes **Tidal** – possibly **Current** – possibly	**Farm** - possibly **Device** – yes **Component** – N/A	• Simplistic proxy for LCOE energy capture • More useful at lower TRLs	• Resource site specific • Comparison of linear and rotary PTOs is not recommended
	Capture Width Ratio	**Wave** - yes **Tidal** – N/A **Current** – N/A	**Farm** – N/A **Device** – yes **Component** – N/A	• Simplistic proxy for energy capture • More useful at lower TRLs	• Resource site specific • Only considers hydrodynamic efficiency

ENERGY CONVERTER DEVICE SUBSYSTEM - GENERAL	**Failure Rate**	**Wave** - yes **Tidal** – yes **Current** – yes	**Farm** – yes **Device** – yes **Component** – yes	• Contributor to maintenance planning • Indicator for availability of component/ device/ farm	• Requires significant data collection to minimize confidence interval
ENERGY CONVERTER DEVICE SUBSYSTEM - CONTROLS	**Optimal Cost Criteria**	**Wave** - yes **Tidal** – yes **Current** – yes	**Farm** – N/A **Device** – N/A **Component** – yes	• Tool to evaluate controller options	• Applies only to controllers and control systems • Does not apply to control design that are not based on an explicit optimization criterion
	Sensitivity	**Wave** - yes **Tidal** – yes **Current** – yes	**Farm** – N/A **Device** – N/A **Component** – yes	• Tool to assess parameters of interest most significantly affecting the design	• Not recommended for systems not easily modeled as linear or for systems with a large number of parameters of interest
	Signal to Noise Ratio (SNR)	**Wave** - yes **Tidal** – yes **Current** – yes	**Farm** – possibly **Device** – possibly **Component** – yes	• Tool to assess the efficiency of a control system	• Applies only to controllers and control systems
	Performance Uncertainty via Numerical Simulation	**Wave** - yes **Tidal** – yes **Current** – yes	**Farm** – possibly **Device** – possibly **Component** – yes	• Effective in comparison and tradeoff analyses	• Tedious if many simulations are required • Not as useful to identify controller design improvements
ENERGY CONVERTER DEVICE SUBSYSTEM – POWER TAKE-OFF	**Capacity Factor**	**Wave** - yes **Tidal** – yes **Current** – yes	**Farm** – yes **Device** – yes **Component** – possibly	• Indicator for PTO utilization efficiency within system	• Resource site specific
	Peak to Average Power	**Wave** - yes **Tidal** – yes **Current** – yes	**Farm** – yes **Device** – yes **Component** – possibly	• Indicator of system efficiency	• Resource site specific
	Energy Conversion Efficiency	**Wave** - yes **Tidal** – yes **Current** – yes	**Farm** – yes **Device** – yes **Component** – possibly	• Indicator of system efficiency	• Resource site specific • Multiple variables should be considered for consistent comparison, such as power conditioning and transmission losses

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APPENDIX A. TECHNOLOGY READINESS LEVEL (TRL)

Unlike the performance metrics in this document, TRL only describes the procedural implementation of technology development and the commercial readiness; it does not indicate quality of the technology or techno-economic potential. However, TRL may be used to identify appropriate performance metrics to be used, e.g., the TPL questions are tailored to TRL ranges.

This metric is used in many industries and research communities to define technology development stages, and several definitions exist. For use with all types of technologies, DOE, DOD, NASA, DHS, NATO all have slightly varying, but general definitions. For marine and hydrokinetic technologies, there are varying versions, for example, DOE WPTO's version (https://openei.org/wiki/Marine_and_Hydrokinetic_Technology_Readiness_Level) was modified from the NASA and DOD definitions, and focuses heavily on experimentation and prototype demonstration (Ruehl & Bull 2012). Wave energy specific definitions exist, with varying levels of specificity (consensus has not yet been reached). For example, Sandia National Laboratories produced a wave energy development roadmap with modeling and experimental expectations at the device and farm level for each TRL (Ruehl & Bull 2012), and Ireland has a detailed description of TRLs specifically for wave energy (ESBI 2011, 2012). TRLs are typically defined for the whole system but they can be applied at the farm, device, and subsystem level. Feedback is encouraged on the appropriate level of detail and existing definitions.

Extensions beyond TRL that focus on the readiness of the device also exist. For example, Manufacturing Readiness Level (DOD 2017), and Commercial Readiness Index (ARENA 2014) can be considered in a similar manner as TRL in terms of a readiness measure, but are not performance metrics.

APPENDIX B. COMMENTS ON CONTROLS METRICS

B.1. Optimal Cost Criteria as a controls metric:

Since many types of control design techniques involve some aspect of optimal control or optimization (as in model predictive control), this provides an obvious measure of comparison between different control systems. However, one needs to be careful in comparing "apples to apples." That is, there are many cost criteria in use, and even though the criteria may be structurally the same, the exact weighting of the tracking errors and control effort can vary. There are several ways of handling this. One can re-evaluate different controllers using a standard cost criterion. Another method is to look at the sensitivity of the cost criterion to specific parameters of interest and compare (on a normalized basis) how well the different controllers reduce this sensitivity. With model predictive control becoming more common in the WEC control literature, the ability to evaluate and compare controller performance on the basis of an optimal cost criterion should become more standard in the near future.

B.2. Sensitivity as a controls metric:

Model uncertainty includes uncertainty in the parameters used for the design of the controller as well as unmodeled dynamics. Parameter uncertainty is generally easier to calculate than uncertainty associated with unmodeled dynamics (e.g. higher order dynamics), and therefore it is much more commonly used in sensitivity analysis of control systems.

Parameter uncertainty can be evaluated analytically or empirically. To evaluate parameter uncertainty analytically, one needs a model containing the parameter(s) of interest. Generally, this will be a linear model. Then one can take the partial derivative of the transfer function (open or closed loop) with respect to the parameter of interest. In the empirical case, a numerical simulation of the system containing the parameter(s) of interest is carried out with a tabulation of how the response varies with variations in the parameter(s) of interest. For instance, one may vary the parameter by multiples of the standard deviation of the parameter and use Monte Carlo sampling (as in MATLAB) to evaluate how the controller response varies relative to the parameter variation.

B.3. Failure rates as they pertain to cont rol systems:

Failure rates for control systems do not have any generally accepted definitions, therefore one doesn't normally use failure rates as a metric of interest in evaluating controller performance. However, if this is of specific interest for a particular application, there are several ways to define failure rates. There is the failure rate of the control system itself. This would be how often (per month or per year or whatever time frame of interest) that the control system is not available or breaks down. There are also the failure rates of individual components of the control system which may or may not lead to the failure of the entire control system. These components can include sensors, processors, electrical logic circuits, motors, etc. If one has a baseline failure rate profile for a baseline controller or open loop control then one can evaluate how well a new controller design improves failure rates relative to the baseline design. The biggest issue in using failure rates as a metric for control systems is that most models and simulations do not model the mechanical/electrical failure of the control system very well. This means that some combination of experimental and numerical analysis will be needed to evaluate failure rates. Since this would involve extensive testing, one wouldn't normally expect much empirical evidence to be available for a new control design technique. Therefore, failure rates are usually limited as a metric of performance to well-established control designs with extensive field performance.

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