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Requirements for Realistic and Effective Wave Energy Technology Performance Assessment Criteria and Metrics

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***Abstract*—Assessment of wave energy converter (WEC) technology, commercial readiness and promise of economic competitiveness and monitoring of development progress are of crucial importance during and at all stages of the development. The assessment process requires employment of problem-relevant, fit-for-purpose, practical assessment criteria. The identification and the use of appropriate assessment criteria and methods has been an important issue since the beginning of WEC technology development. However, the investment into both the determination of assessment criteria and their application has not been adequate, given their crucial importance in guiding the technology development process to success in the most effective way. In recent years, the effort in determining assessment criteria and metrics have increased globally.**

This paper highlights a breadth of vital considerations supporting the specification of problem-relevant, realistic, effective assessment criteria. Following reflection on motivation, impact and benefits of technology assessment, a list of idealized expectations of assessment criteria and methods is provided and, subsequently, the significance of "realistic and effective" is defined. The core contribution of this paper is the collection of aspects that need to be considered to specify the requirements for problem-relevant, realistic and effective assessment criteria, methodologies and tools. These assessment criteria considerations are formulated in the form of questions to show possible choices that can be made in the requirement specification for assessment criteria. Finally, some overall conclusions of the above considerations are drawn.

***Keywords*—Wave energy, technology development, assessment criteria, metrics, Technology Readiness Levels (TRL), Technology Performance Levels (TPL).**

I. Introduction

The consideration, identification and formulation of performance requirements and related assessment criteria for WEC technology is as old as wave energy converter concept invention, research & technology development activities themselves, with the first patent registered by Pierre-Simon Girard 1799 [1]. Key metrics for wave energy conversion were used in the early 1970s and include efficiency in 2-D flow fields and capture width ratio in 3-D flow fields [2].

Between 2004 and 2007 during the "Co-ordinated Action on Ocean Energy" [3], performance metrics suitable for comparison across the many WEC device types, were evaluated under the "Performance Monitoring of Ocean Energy Systems" work package. Suggestions included the use of the cube route of the displaced volume of a WEC as the characteristic length in the, now referred to, capture length ratio. Clearly, the levelised cost of energy (LCOE) has always played a key role as a high-level system metric in wave energy and in renewables generally.

This paper reflects on the recent significantly enhanced activity in providing adequate technology assessment metrics, methods and tools, their crucial role in and impact on the success in the wave energy domain, as well as, the increased global awareness thereof.

It considers the widespread desire for idealised metrics and assessment criteria properties and proceeds to discuss the meaning of realistic and effective technology assessment criteria and methods that serve the purpose and stand up to the wave energy technology challenge.

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Subsequently, the paper elaborates on a number of fundamental considerations of the requirements for high-quality assessment criteria, methods and tools. These considerations are formulated in terms of questions posed, that need to be answered and accurately resolved within the various requirements specification response options, in order to specify the desired assessment criteria, methods and tools, in sufficient detail and ample clarity.

Design philosophy, reasoning and requirement choice, driving the development for the Technology Performance Levels (TPL), are outside of the scope of this paper and will be published separately. However, TPL and LCOE feature here as examples in the landscape of metric systems.

II. Motivation, Impact and Benefits

With the technology development setbacks encountered in the 2000s and the somewhat shifting yet persevering diversity of wave energy technology concepts, the importance of technology assessment has become increasingly significant and triggered many activities in the development of metrics, criteria, systems, methods and tools for the assessment of wave energy technology at different stages of the research and technology development. A sample of these includes:

- Development of TPL assessment criteria, methods and tools (first introduced in [4], further developed in [5]).
- Enhancement and application of TPL assessment system, since 2014, through detailed systems engineering approach, in Structured Innovation – Wave-SPARC project [6], [7], [8], [9].
- Ocean Energy Metrics project with request for information and metrics status report [10].
- DTOceanPlus project developing concept selection and assessment tools [11].
- Development of stage-gate metrics and tools for funding allocation and process evaluation [12].
- IEA-OES: Task 12: Stage Gate Metrics International Framework For Ocean Energy [13].

The breadth and intensity of these activities are testament to the fact that the crucial role for high-quality wave energy concept and technology assessment, which is unconditional for the successful development, commercial and economic operation, is now globally recognised.

The work presented in this paper is a contribution to identification of the fundamental requirements and specifications for WEC technology performance assessment criteria, methods and tool with imbedded metrics fit-for-purpose, realistic and effective while fully embracing the WEC technology problem statement.

III. Idealized Wishlist

In the spirit of ideality, a wish list of desired attributes of assessment criteria, methods and tools to be satisfied would include, but is not limited to, the following:

- *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 & 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

IV. Realistic & Effective Applications

The purpose of this work is to contribute to the successful development of wave energy technology. As proven on numerous occasions, technology success may not be achieved when the development methodology is not appropriate for the challenge, even when the technology concept carries the potential to do so.

Technology development cost, time and risk are strongly dependent on the development trajectory [14]. In turn, control over the development trajectory and the quality of choices, made along the path are significantly dependent on the knowledge of the technology status and the projected, and subsequently, the actual development progress made over an RD&D activity. These require adequate assessment criteria, methods and tools for both commercial readiness and projected economic or other purpose-relevant performance while the technology is under development. Finally, the achievability of the technological implementation and of the projected performance under commercial operation is equally based on the quality of the assessment.

Evidently, the capability and the quality of technology assessment, under development, are at the core of the development outcome.

An implicit necessity for high quality assessment capability is a profound understanding of all stakeholder requirements, throughout the lifecycle of the systems, expressed as system capabilities, and all the associated functional requirements to realize these capabilities; i.e. for the system to "do" so it is what it's intended to "be" [15]. This provides clarity about the problem statement, reflecting challenging multi-parametric dependencies and trade-offs and the targeted development goal, expressed by multi-objectivity.

In this context, the terms "realistic" and "effective" refer to the necessities of the technology assessment criteria, methods and tools to deliver the technology development goals. Unambiguously, the terms "realistic" & "effective" here do not refer to the ease of the “realization” and its simplicity, and thus is not about the “effectiveness” of the assessment process. The latter approach, as experience has proven, may represent a gross simplification of the challenge and may lead to development failure. With an assessment process, that realistically captures the technological challenges to be overcome in their entirety and complexity, the development is significantly more likely to be effective and successful and deliver commercially ready and high-performance technology.

V. Requirement Options

This section provides a range of aspects that need to be considered in the development of assessment criteria, methods and tools [15]. For increased clarity, the aspects “in question” are formulated as questions that need to be answered in order to specify the requirements for the assessment criteria, methodology and resulting tools. This process will deliver specific scope, purpose detail to arrive at assessment criteria, embedded metrics, methodology and resulting tools, that will serve the technology development process, in the best possible way.

A. Targeted system

Targeted assessment object

- What system level are the criteria applicable to?
  - Wave energy plant as an investment product
  - Wave farm including site conditions
  - Wave farm site independent
  - WEC device
  - Balance of plant
  - Device sub-systems
  - Component assemblies and single component
- Should the assessment be applicable at a range of different levels of the system’s hierarchy?
- Assuming applicability to a range of system levels, should the assessment criteria at lower system levels be an exact subset of criteria within the higher-level assessment criteria set? Further, should there be consistency in the assessment criteria from higher to lower level system assessments, regarding the criteria set and the assessment method?

B. Target technology maturity

Targeted technology development stage

- What development stage should the technology performance be assessed for? Options for targeted technology development status include:
  - Technology at the given development stage/TRL
  - Projected technology development status at market readiness defined by TRL 9
  - Projected technology development status, after having surpassed market entry [5] requirements of TRL 9 & TPL 7+ or LCOE below 0.2 €/kWh with the technology designed, manufactured, built, deployed under first small polit farm conditions
  - Projected technology status, after having surpassed market entry requirements, after full commercial rollout and into largescale deployment with the technology design, manufacturing, deployment and operation with full benefit from learning curves

C. Technological universality

Applicability across system types at a given system level

- Should the assessment criteria, method and metrics be technology agnostic? Across different:
  - Energy types
  - Renewable energy types
  - Marine renewable energy types
  - Wave energy archetypes
  - Archetype subsystems
  - Subsystem assemblies, components
- Assuming assessment criteria, method and embedded metrics are technology agnostic at a given system level, should the tool assessment facilitate comparison and hereafter down-select?

D. Conditional universality

Applicability across external operational conditions

- Should the assessment be agnostic to jurisdiction, local, regional, national requirements and conditions? Possible conditions include:
  - Regulatory – Certification – Environmental – Social – Political – Energy market – Energy price – Grid access – Point of sale – Project risk – Insurance costs – Interest rates – Inflation rates – Investor expectations

E. Observability

Observability and measurability of criteria & metrics

For the assessment of systems of the same system type and system level, however, functioning based on different physical effects and/or realised through different concepts, embodiments and designs, it is important to consider the distinction and connection of assessment criteria, metrics, observables and measurables physical quantities. Amongst others the following question arises:

- Should the same criteria and metrics be determinable from the different observables and measurables, across different technical solutions of the same type at the same level?

Table I lists a small set of WEC technology concepts or archetypes, considers the assessment criterion Power Absorption with the metric Absorbed Power and the related observable and, by different means, measurable quantities.

F. Assessment throughout development process

Assessment long the technology development path

The technology development activities over the technology development process are specified in the TRL.

A number of TRL definitions, either technology agnostic or specific to wave energy, have been specified over time. Examples for wave energy specific TRL definitions, at all development stages (typically 9 levels), include [16], [17].

More general and universally applicable TRL definitions, at all development stages (typically 9), have been widely developed. These Readiness Levels (RL) may be aimed at covering different renewable energy types, different energy technologies, technology development in general, non-technological e.g. software, service or process developments, either type specific and purpose built or agnostic. An overview of the significant number of TRL definitions and other RL definitions across a wide range of domains, including non-technical and non-physical systems, is presented in [18].

RLs that are related to TRLs include Market Readiness/Maturity Levels (MRL), Commercial Readiness Levels (CRL), Commercial Readiness Index (CRI) and specific to wave energy; Farm Readiness Levels [19].

In the majority of cases, RL are related to the maturity within the development process, as in the wave energy cases the maturity of a technology under development i.e. its development stage, rather than to its quality, technical or economic performance.

Clearly, it ought to be important to assess the potential technology promise for techno-economic performance of the fully developed commercial product during the development. This, in turn, means that the technology performance may not be a function of the technology readiness, but independent of it and can be regarded as orthogonal to it [4], [20].

In relation to technology assessment over the development process at all its stages of technology readiness, the following questions need to be considered:

- At what stages of the technology development is technology assessment important and should be conducted?
- Should the same set of assessment criteria be applied at all technology development stages, i.e. TRLs?
- What is the lowest development stage of TRL and conceptual technology development status at which technology assessment is possible?
- Is any kind of assessment; quantitative, qualitative or notional statement possible, meaningful below TRL1?
- Should the available information at and up to a given TRL that is based on the R&D activities as defined in the currently available TRL definitions determine, define and potentially be allowed to limit the selection of assessment criteria for that given TRL?
- Or, on the contrary, should the requirements for the technology assessment at any TRL define the required R&D activities at and up to a given TRL?
- What are the desired and what are the achievable levels and values of important qualifying properties of the range of assessment criteria at the different development stages? Considered properties include:
  - Completeness – Accuracy – Certainty – Detail – Objectiveness – Accountability – Supporting Info.
- Should the level of performance of a technology, at a given technology development stage, be suitable to influence the decisions on the most valuable and effective research and technology development steps? Options for subsequent R&D activities/goals include:
  - Concentration on technology weaknesses identified in the assessment
  - Focus on potentially highly performance-relevant unknown criteria
  - Improvement of technology performance, while maintaining technology readiness
  - Progressing to higher technology readiness, while maintaining technology performance
  - Progressing to higher technology readiness, and improving technology performance

TABLE I
EXAMPLES FOR CRITERION/METRIC & OBSERVABLES/MEASURABLE

WEC Concept	Criterion/Metric	Observable/Measurable
Oscillating Water Column	Power Absorption Absorbed Power	Air pressure on & volume flux of internal free surface
Vertical Axed Eccentric Mass	Power Absorption Absorbed Power	Torque & angular velocity around shaft axis
Hinged Barge Attenuator	Power Absorption Absorbed Power	Torque & angular velocity around hinge axis
Heaving Buoy Point Absorber	Power Absorption Absorbed Power	Force & translational velocity along motion axis

WEC archetype examples with different observables/measurables supporting the identification of the same assessment criteria/metrics

G. *Purpose and scope*

Purpose and/or justification assessment criterion

For the identification and selection of assessment criteria regarding the purpose and intent of the assessment, the following questions need to be considered:

- Is a criterion justified solely for the purpose of ensuring awareness?
  - Known unknown vs unknown unknown
- Is a criterion justified and fit for purpose, when it is difficult to quantify but important for the overall system performance?
  - Pointer towards high risk and high impact technology properties
  - Guidance to allocate effort to better quantify high impact metrics
- What level of accuracy of criteria metrics is acceptable and realistic?
  - Consider compound uncertainty at system level based on multiple level combined sub-system criteria metrics

- Should the assessment criteria and metrics serve the purpose of multi-parametric analysis? This could support:
  - Implementation of sensitivity analysis to identify most effective and/or efficient development effort and investment
  - Systematic parameter variation and multi-objective potential optimization

H. *Markets and applications*

From continental grid to blue economy

Besides the significant, but also most competitive continental grid electricity markets, a wide variety of alternative, current and future markets have been identified [21], such as "Maritime or Blue Economy Markets". In this context, the following questions arise:

- To what degree should the development of a technology assessment method, designed for wave energy delivery to the continental grid market, be transferable and what is the expected effort and drawback in doing so?
- What level of consistency and similarity of the assessment criteria is desired and possible across different markets, such as, but not limited to, continental grid, off grid remote communities, floating aquaculture, marine sensing?
- Could the adaptation of the assessment to different markets be achieved through use of the identical fundamental assessment criteria and metrics?
- If so, could the adaptation be implemented through an adapted combination of criteria and metrics, such as differing and market-specific weightings?
- Should grid market criteria be considered for those alternative markets that are suitable for technologies that are also applicable in grid markets at a later development stage? This may facilitate consideration of technology upscaling in size or numbers, following application in early adopter markets.
- Are there alternative markets for which the wave energy technologies and, as a consequence, the assessment criteria and tools need to satisfy significantly different requirements, requiring individual formulation and development of assessment criteria, methods and tools?

I. *Systems of criteria*

Individual, combined and overarching criteria

Regarding the level of detail, granularity, amount, hierarchy and relationship the following considerations are beneficial.

- Should assessment criteria and metrics be formulated at high or at low level of detail captured by in large or small amounts of criteria and metrics, respectively? For example: Maintenance frequency and time at sub-function or component assembly level
- Should assessment criteria and metrics just be formulated as multiple individual entities? This may amount to 100+ quantities and related bars in a chart for visualisation
- Should multiple individual assessment criteria and metrics be combined to meaningful group criteria and metrics? For example: Combination of all power conversion aspects along the power absorption and conversion chain expressed as an overall power conversion efficiency
- Should multiple group metrics be combined to an overall system metric? Examples include the system TPL or LCOE
- Are all of the above aspects to be satisfied to for a coherent assessment criteria system?

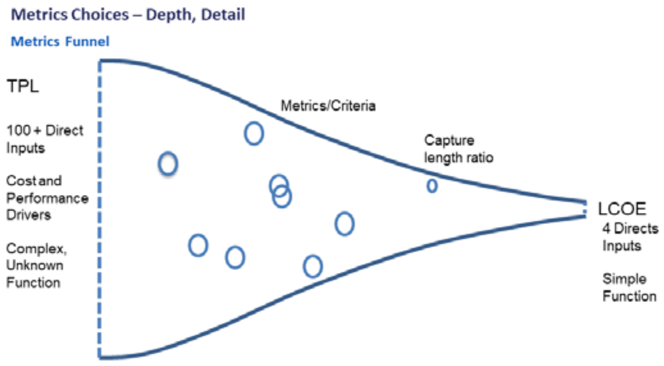


Fig. 1. Metrics funnel, simplistically illustrating the spectrum of assessment criteria and metrics choices regarding detail, amount and hierarchy of criteria.

A visualization of the above considerations is provided in Fig. 1, in form of a "metrics funnel". The width of the funnel to the left represents the breadth of detail, covered by the large amount of assessment criteria. As an example, the TPL assessment is considered with over 100 criteria in form of cost and performance drivers. These represent direct inputs to the technology assessment method, whereby, their functional relationship, in forming an overall systems assessment, is complex and practically unknown. On the other hand, to the right of the funnel, its width is narrow, representing a very small number of criteria and metrics, with low resolution of details. As an example, the levelized cost of energy, at its highest hierarchy level of just four input metrics (capital expenditure, operational expenditure, power and availability), is provided. Here, the functional relationship is known, precise and objective. However, the root causes of the overall systems performance, in form of cost and performance drivers, may not be obvious or identifiable. Fig. 1, also indicates a variety of other assessment criteria and metrics, depicted as ovals. The characteristics of these metrics regarding level of detail and resolution varies and lie in between the cases of TPL and LCOE.

J. *Criteria consistency*

Systematic criteria selection to achieve consistency.

For the selection of technology assessment criteria at any level of depth and detail, it is important to consider a number a requirement options for the criteria set,

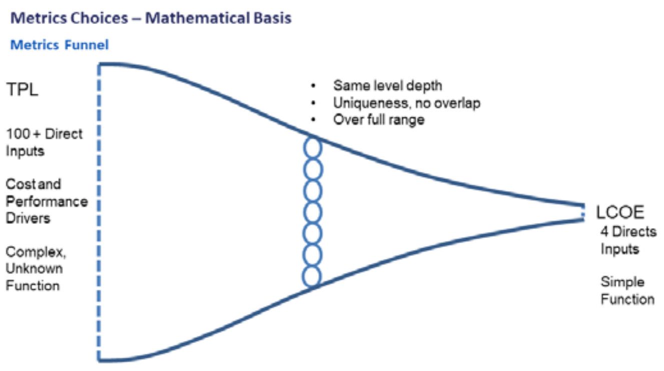


Fig. 2. Metrics funnel, simplistically illustrating the principles of consistency of criteria at all levels of the hierarchy of criteria.

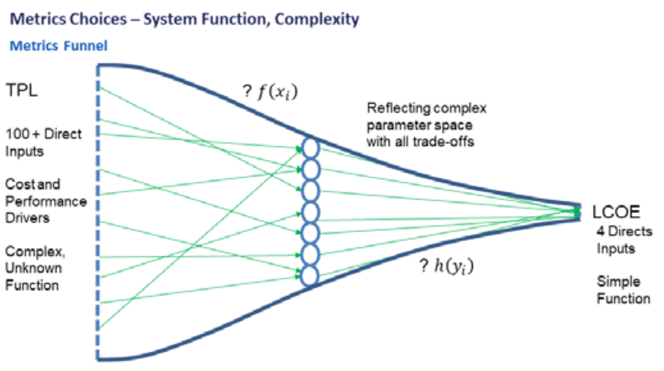


Fig. 3. Metrics funnel, simplistically illustrating the complex functional relationship of criteria between different hierarchy levels.

including the following questions:

- Should the criteria be chosen so that all criteria are of the same level of detail and depth of information required for the assessment?
- Should the criteria be chosen so that they cover the entirety of technology characteristics? What level of holisticness is desired?
- Should the criteria be chosen so that the criteria are unique and avoid overlay?
- Should the criteria set cover all trade-offs and how can this be achieved?

Fig. 2 depicts an intermediate criterion set within the metrics funnel, that satisfies the following requirements:

- Consistent, identical level of detail and depth of information – position in the funnel
- Holistic, complete coverage of technology characteristics – covering the width of the funnel
- Uniqueness, no overlap or double accounting of criteria – no intersection of the oval criteria symbols

In a simplistic and symbolic way, these characteristics could be considered similar to those of a mathematical basis, as labelled in Fig. 2.

K. *Functional relationship*

Logic, connection of criteria at different levels of detail.

In order to formulate the functional relationship between the assessment criteria at different levels (individual, group and system values), the following considerations are relevant:

- What degree of knowledge and accuracy of the relationship between criteria at different levels is required to formulate such relationships?
- What level of effort is appropriate to achieve the desired validity and accuracy of the relationship?
- How can all critical design contradictions and multi-parametric performance trade-offs be captured through the functional relationship?

Fig. 3 provides a simplistic visualization of the functional relationships between the three example levels of depth and detail i.e. in this example: TPL, intermediate criteria and LCOE. The green arrows represent just a fraction of the many interconnections and the complexity of the dependencies. Most crucial, for the validity and quality of an assessment criteria system, is the consideration of relative importance and the representation of the many trade-offs.

L. *Quantitative and qualitative criteria*

Combination of quantitative and qualitative criteria

Given the need to combine a large number of individual assessment criteria of a variety of types in order to also arrive at aggregate higher-level system performance statements and to express trade-offs in the assessment methodology, it is important to consider the following question:

- How can assessment criteria of different types be combined in assessment systems?

Assessment criteria types that require amalgamation may include but are not limited to the following:

- Criteria that are purely justified to raise the awareness of this performance aspect
- Qualitative criteria and characteristics, not directly associated with physical or other units and values
- Quantitative criteria expressed by a variety of physical units and orders of dimension e.g. scalar, vector and higher order tensors
- Quantitative criteria determined:
  - Through observation, measurement, simulation, analysis, estimation
  - At high or low levels of certainty and accuracy

M. *Reference values and characteristics*

Base or benchmark characteristics and criteria values

In order to calibrate an assessment method and the related assessment criteria values at all levels, it is essential to consider the following questions:

- Should reference or benchmark values be provided for the criteria within the assessment tool?
- Should reference values be provided for all criteria within and at all criteria levels (individual, group and system values)?
- What should the reference values be based on? Possible options include:
  - State of the art values reflecting best technology

performance values of past and at present either with all criteria values from the same technology or with each criterion value chosen as best value across the leading technologies
  - Average values of the technologies, currently under development in the industry
  - Values extracted of publicly available open source technology descriptions and investigation, as for example the DOE Reference Models with preference of transparency over high performance values
  - Values determined in a number of different studies, over a range of or across the entire technology spectrum such as [22], [23]
- Depending on the above options, how is the complete set of reference values determined as the sources many be incomplete, unspecific or unreliable?
- How can multiple qualitative reference characteristics be specified, validated and synthesised if multiple reference sources?

N. Minimum and target values and characteristics

Minimum thresholds and top target values

Regarding the identification of the fundamental performance qualification of a technology, and of desired development targets, in the context of an assessment method and the related assessment criteria at all levels of the assessment system, the following questions arise:

- Should threshold and/or target values at all be provided for the assessment criteria alongside the assessment methodology and tool?
- Should overall system, high level criteria and metrics be subject to thresholds and target values? Potentially to express competitiveness with other marine renewables: System TPL 8+, LCOE = 0.1 €/kWh
- Should group criteria and metrics be subject to thresholds and target values? For example Availability = 90%, capture length ratio = 1
- Should fundamental individual criteria and metrics be subject to thresholds and target values? For example: Subsystem component lifetime longer than 50 years, noise peaks level below regulatory limit
- What are the appropriate approaches and methods to determine these thresholds and target values? Possible options include:
  - Reverse [24] or inverse LCOE or inverse TPL analysis based on extremely low or high system values and related high or low groups and individual low-level criteria values in order to identify corresponding thresholds and target values, respectively.
  - Based on theoretical physical maxima. For example: linear wave theory point absorber limit dependent on degrees for freedom
  - Based on relationships to best practice high performance values for related mature technology applications. For example: Fatigue life of highly tested commercial components
- How should these thresholds and target values relate to the reference values?
- Should any thresholds and target values be expressed at all below the high-level system value? Thus, all limitations and expectations are only expressed for the combined integrated systems considering all imbedded complex trade-offs thereby allowing for the possibility of balancing of low and high criteria values at intermediate group and individual criteria level.

Beyond the questions listed here, similar questions as those stated under the previous sub-section are to be considered here as well.

O. Technology showstoppers

Identifying fundamental realisation impediments

Where unsatisfactory assessment results of specific assessment criteria (either at individual, group or system levels) breach of minimum threshold values and the related technology attributes cannot be improved to satisfy the minimum threshold values, not to mention achieve the target values, the technology may not be viable. In such cases, a fundamental wave energy technology conceptual change might be required.

Examples include, but are not limited to:

- Theoretical hydrodynamic absorption limits in relation to required technology mass and material type do not allow to satisfy minimal system criteria threshold values even with otherwise optimal assessment criteria values and under ideal conditions
- Survival cannot be achieved within technology concepts archetype and related threshold values are not satisfied
- The fundamental physics of the technology require the use of environmentally unacceptable materials or substances whereby with any level of likelihood the acceptable level of risk is exceeded for example electromagnetic substance of working fluid in power conversion chain
- Characteristics of the technology concept or its implementation prohibit certification and/or insurance. Related threshold values are breached
- Technology material type requirements may by far exceed the material resources

Considering these examples, the key question arises:

- Should the assessment method identify showstoppers in if so how is this capability implemented?

P. Use cases

Users and application purposes

- Given the characteristics and purpose of different use cases, should assessment method be specifically tailored to serve these and how are these requirements implemented? Use cases include:
  - Technology development guidance considering

cost, time and risk of development steps
- Innovation of entire novel WEC systems
- Investment into technology developers

Q. Effort and relevance

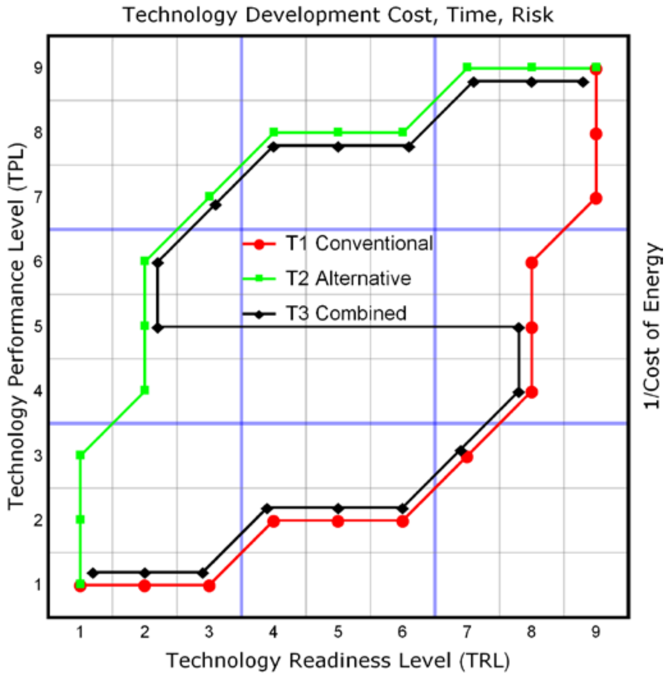
Cost & time investment vs payback of assessment

The importance and the impact of technology assessment, throughout the technology development process, is considered in different ways and with respect to different criteria by different stakeholders. These may be funding bodies, investors, certifying bodies system operators, energy clients, academia, research bodies and clearly the technology developers themselves. In common practice and for different purposes, the degree of effort in time and cost for the assessment may vary from funding proposal evaluations, through preliminary to detailed technical due diligence, to funding and subject matter expert support of strategic investor in a first phase of close, fully integrated collaboration with the developer.

Regarding the relevance and impact of the knowledge of technology performance during the development, it is revealing to consider the cost, time and risk of technology development for different development trajectories. This insight can support the determination of the appropriate effort in terms of cost and time for the technology assessment process. With reference to the estimation of cost, time and risk of three different technology development trajectories (T) T1, T2 and T3 in [14] Fig. 4 displays the considered trajectories and Table II display the key results of this evaluation.

Importance and impact of technology development focus, objectives, value, cost, time, risk, and subsequently success of navigation along the best possible development trajectory highlight the relevance of these key questions:

- What is the appropriate financial investment for the technology assessment, in relation to the technology development cost: 1%, 5%, 10%, 20%? For Example:
  - €200k for technical due diligence at TRL 6
  - €10k for funding proposal evaluation at any TRL
- What is the appropriate time investment for the technology assessment, in relation to the technology development time: 1%, 5%, 10%, 20%? For Example:
  - 2000 subject matter expert (SME) full time equivalent (FTE) hours technical due diligence at TRL 6
  - 100 SME FTE hours, proposal evaluation, any TRL
- How does the available depth, detail, certainty and accuracy of the information regarding the technology and its properties at the different development stages/TRL relate to the possible and/or desired depth, detail, certainty and accuracy of the assessment?
- How does the desired depth, detail, certainty and accuracy of the assessment relate to the effort of performing the assessment?



. 4. Three generic and distinctly different technology development trajectories: T1 – Conventional, T2 – Alternative, and T3 – Combined are shown over the TRL-TPL Matrix; T3 – Combined is slightly shifted to provide a better visualization. [14]

TABLE II
TOTAL TECHNOLOGY DEVELOPMENT COST, TIME AND RISK FOR DIFFERENT TECHNOLOGY DEVELOPMENT TRAJECTORIES [14]

Trajectory	Cost [$ m]	Time [yr]	Risk [$ m yr]
T1 – Conventional	155	22	165
T2 – Alternative	65	13	9
T1 – Combined	114	23	39

R. Technological achievability

Technical implementation and realisation

Technological achievability considers challenges on the remainder of the required trajectory of the technology development process to achieve market entry. These may include prior achievement of fundamental material science advancement, or full development of as yet unavailable manufacturing techniques. Such considerations are distinctly different those of technology performance at the market entry stage of development. Key questions include:

- Should technological feasibility and challenges of reaching full technology maturity and market entry be captured in the assessment?
- How can technological achievability be best combined performance assessment criteria?

S. Commercial and economic achievability

Market and product implementation

Commercial and economic achievability considers challenges in achieving commercial, industrial rollout and mass production and economic competitiveness, following successful market entry. These may include circumstances around the supply chain; such as: Does a supply chain already exist for a different product? Is it supported by multiple suppliers reducing commodity prices or is it a high price market with difficulty for wave energy technology to gain access? Key questions include:

- Should commercial and economic achievability and challenges of reaching full technology maturity and market entry be captured in the assessment?
- How can commercial achievability be best combined with performance assessment criteria?

T. Tool implementation platform

Implementation platform requirements and capabilities

The choice of the software platform determines the capability of assessment toot. Thus, the following question is relevant:

- What are the key tool developer and tool user requirements that specify the capabilities of the platform to facilitate their implementation? Example included:
  - Flexibility in numerical implementation and dynamic input, system parameter and output data visualisation, multi-parametric and multi-objective sensitivity analysis and system optimization, user friendly graphic user interface, open source or licence, protectable

U. Deployment

Market range and penetration

- Should technological assessment consider criteria related to the possible total market opportunity? Aspect include:
  - Market size – Types of markets that can be accessed – Possible market penetration

V. Validation

Validation and adaptation of criteria, method and tool

- How can the assessment methodology and the tool implementation be validated and as required improved? Considerations include:
  - Comparison of assessments of projected performance of same technology from the perspective of different development stages.
  - Comparison of assessment by different users
  - Accuracy and uncertainty penetration through assessment methodology and tool
  - Relationship and alignment and alternative assessment metrics, criteria, methods, tools

W. Uptake

User community acceptance and uptake

- To what degree is the uptake of the assessment system and tool and related challenges a justified consideration for its specification and design?

VI. Conclusion

Experience of two decades of wave energy technology development and the analysis presented in previous work [14] has clearly shown that the implemented technology development path towards market entry has significant influence on the required technology development cost and time and the encountered risk.

The wave energy conversion problem statement, with the goal of developing technology that operates economically in a competitive commercial environment, on its own right, represent a significant engineering and business challenge. Under such circumstances, it is not acceptable, and can entail serious consequences, to employ inappropriate or inadequate methods and tools.

Thus, in order to implement an efficient and successful technology development path and to have control and make adjustments to the paths and consequently to the technology under development, sound methods and tools are required. At the core is the ability to assess the technology status and the progress of the development, with respect to both technology readiness and technology performance. These assessment systems, practically, serve as the “torch” to shed the light onto the technology development space, and in a simplified way projected on the two-dimensional TRL-TPL-Matrix [4], [20]. It is central to being able to navigating the best possible or any efficient and realistic technology development trajectory that leads to success. Without effective and realistic assessment tools and proper use thereof, critical performance aspects are likely to remain in the “dark” or be ignored till late in the development process, potentially leading to significant setbacks or, in the worst case, are only discovered at a mature project and commitment level, potentially causing technological and/or business failure.

The work described in this paper aims to provide guidance in the formulation and clear specification of technology assessment criteria, methods, tools and embedded metrics. Rather than pre-scribing and describing a specific criteria system choice, the relevant aspects, leading to the development of an assessment systems are provided as questions to motivate clear decisions, considering the formulation of assessment criteria and metrics. Alongside, several considerations, on the relevance of technology assessment, are shared and its importance on the technology development process and its success, are emphasized.

Clearly, the provided list of questions to guide the specification of wave energy technology assessment criteria and metrics is not complete, however, it represents a comprehensive selection of critical aspects, and is likely to extend the number of aspects usually considered when identifying wave energy assessment criteria and metrics.

Addressing and answering the provided assessment criteria specification questions does not require notable effort, in relation to the resulting effort and quality of the assessment process and significantly more so in relation to the magnitude of the consequences on the technology development process and outcome. Thus, it is critical to make conscious choices, define scope and purpose of the assessment criteria and specify accordingly to obtain the desired assessment criteria and, subsequently, the desired development outcome of a WEC successful technology.

The art of technology development naturally embraces innovation, variation, diversity, comparison, selection, synergy and iteration. The technology assessment is at the core of this process and is itself subject to the same improvement processes as the assessment enabling tools, equally under ongoing development. This is particularly so for long development processes as is the case in wave energy technology.

Given this interwoven nature of technology development and assessment, providing vital connection of progress and orientation as the vector to success, it is valuable and effective to have a direct link between the assessment results and the diverse technology conceptual decisions, design choices and assessment driving and systems specifying parameters, such as the range of cost and performance drivers. Direct feedback from assessment result to both, design and performance drivers throughout the continuous technology assessment that occurs throughout the development is far superior to infrequent post-mortem type assessments that don't provide causality nor directly link concept or design choices taken.

Finally, an important point shall be made regarding the necessary and sufficient condition for frequent and complete assessment of technology. Crucial, to the successful outcome of any development, is the discovering and uncovering of Unknown Unknowns and to transform these to Known Unknowns. This insight is widely recognized as it can lead to the identification and possibly alleviation or utter avoidance of potential showstoppers. However, it appears that more prevalent species of the Unknowns are Neglected and Ignored, namely Known Unknowns, as is reflected by the experience form many development efforts.

Hopefully, this paper will provide a useful contribution to the globally increasing efforts in identifying problem-relevant i.e. realistic as well as problem-solving i.e. effective wave energy technology assessment criteria, methods and tools with embedded metrics.

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