

# WEC Technology Performance Levels (TPLs) - Metric for Successful Development of Economic WEC Technology

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**Abstract**— The paper discusses the importance of the Technology Performance Levels (TPLs) as an essential metric for the assessment and quantification of the techno-economic performance at all stages of the wave energy converter (WEC) technology development and its significance to the successful development of economic technology. TPLs provide an integral technology assessment of all cost and performance drivers grouped into the five high level categories of acceptability, power conversion efficiency, availability, capital expenditure (CapEx) and lifecycle operational expenditure (OpEx), while broadly inversely related to cost of energy (CoE).

Following previous introduction of the TPLs in [1], used alongside the Technology Readiness Levels (TRLs) in form of the TRL–TPL–Matrix visualisation providing a useful means for the evaluation, comparison and discussion of different research technology development trajectories over the technology readiness and performance levels plane, this paper recaps on the motivation for introduction and use of TPLs and extends their description through their fundamental principles. TPLs are applicable at all development stages over all TRLs and the associated techno-economical WEC technology assessments are described over a range of TPLs.

The value of technology is discussed with respect to investability while under development and marketability when at product stage. It is shown that the combined consideration of both TRL and TPL are of the essence in order to a) identify requirements of WEC technology for successful entry and survival in the electricity market and b) assess actual value technology under development when crucial investment and funding decisions are made.

**Keywords**— Wave energy converter, technology assessment, Technology Performance Level (TPL), Technology Readiness Level (TRL), TPL–TRL–matrix, WEC technology value map, techno-economic performance, marketability, investability.

## I. INTRODUCTION & MOTIVATION

Wave energy technology development as a whole has not delivered the desired progress and success hoped for. There remains a wide diversity of technology types with prototype implementations far from converged optima. Techno-

economic performance in terms of cost of energy (CoE) requires considerable improvement for profitable commercial application beyond the essential cost reductions associated with economies of scale. The situation can be characterised with the following key points:

- Widely diverse WEC technologies are being considered today – still
- No evidence of common convergence of technology implementation nor of underlying operational principles in key market segments
- High cost of energy (CoE) projections. Techno-economical performance still requires considerable improvement for profitable economical application even if the expected cost reductions associated with economies of scale and learning curves are taken into account
- Technology developments are mostly
  - Expensive – > € 100 m to get to TRL 9
  - High risk – Setbacks in prototype tests, too early focus on demonstration
  - Slow – up to 15 years from TRL 1 to 9
  - Rigid – retaining initial early concept idea

As a consequence the following key questions are justified.

- Are technology development paths well chosen?
- How good are the resulting technologies?
- How can process and results be improved?

Further to the analysis of the above questions and the discussion of how to find the best research technology development trajectory in [1], this paper considers the following questions.

- How can the techno-economic performance of a WEC technology be expressed and assessed at any stage of its development?
- How can technologies under development be characterised and compared with respect to their development status, value and investability?
- What are the requirements for a technology to be marketable as an energy production product?

In order to attempt an analysis of the problems above, suitable metrics to quantify technology development status and progress are required.

Progress in technology readiness is well quantified by Technology Readiness Levels (TRL). Originating in aviation, space and defence industries, TRLs have in recent years been established in wave energy technology development. In particular the TRL definitions by Fitzgerald [2] have been widely adopted and applied in the wave energy technology development, project development and end user industries.

Further definitions and formulations of TRLs along with recommended technology development roadmaps have for instance been presented in [3] and [4]. In [3] clear distinction is made between TRLs of WEC devices and TRLs of wave farms. In [4] the TRL series are extended by a range of Commercial Readiness Levels (CRLs).

The use of TRLs has proven to be extremely valuable and definitely applicable in assessing and quantifying technology development status with respect to technology readiness for specific project goals, whether it be prototype demonstration at a particular scale or pre-commercial full scale integrated system demonstration or a phased commercial utility project. In [5] discussion and full definition of technology readiness for wave energy projects under the ESB and Vattenfall classification system in 9 TRL categories is provided.

The focus here clearly is on readiness towards commercial operation of WEC technology. However, in order to fully describe and quantify the status of WEC technology, a further metric is required which focuses on the level of techno-economic performance of the WEC system. Further to previous presentation [6], the Technology Performance Levels (TPLs) have been introduced in [1]. In analogy with the TRL categories the TPLs are categorised into 9 levels quantifying both techno-economic functional and lifecycle performance of the WEC system.

The fundamental understanding of the TRL and TPL metrics are juxtaposed in Table 1.

TABLE I  
FUNDAMENTAL UNDERSTANDING AND DEFINITION OF TRL AND TPL

Metric	Defines	Directly associated with
TRL	how ready a technology is	commercial ability of the technology
TPL	how well a technology performs	economic ability of the technology

Essentially, the technology performance levels quantify the techno-economic performance of a WEC system by describing the level of economic functional and lifecycle performance. At a high level this includes

- Acceptability
- Power absorption, conversion and delivery capability
- System availability
- Capital Expenditure (CapEx)
- Operational Expenditure (OpEx) over complete lifecycle

At a lower level these performance criteria are made up of a multitude of sub-criteria and cost drivers of the system to

define the technology performance level. At the highest level the TPL categories 1 to 9 of the WEC system are inversely related to Cost of Energy (CoE) of the system.

The TPL concept has been introduced [1], development is progressing and wide application in technology evaluation and development is being encouraged.

The description of the TPL metric and accurate definition of the 9 levels requiring detailed specification with respect to the multiple performance sub-criteria and cost drivers are under advanced development. The assessment process and methods for the quantification of the TPLs at the different TRL development stages have been described and are being refined for effective and wide application.

## II. TECHNOLOGY PERFORMANCE LEVELS (TPLS)

Reflecting on the purpose of the TPLs, fundamental principles are considered prior to the description of the overall assessment process, relevant assessment criteria and performance level categories. Subsequently, appropriate depth of assessment and expectable confidence levels of the TPL metric statements over the range of TRL stages are discussed.

### A. Fundamental Principles

In the context of techno-economic wave energy performance assessment, clear distinctions must to be made between WEC technology assessment, wave farm project assessment, marine renewable energy competitive analysis and especially, site, resource or market assessments. The aim of the TPLs is to provide a techno-economic performance metric applicable to all wave energy technologies when considered in their commercial configuration, for instance, but not exclusively, as a wave farm operation plant for energy delivery to the electricity grid. In support of this general approach the following guiding principles for the purpose, application and characteristics of technology assessment via TPLs are stated.

- TPL is to be understood as a metric to describe and quantify technology inherent performance properties not dependent on particularities of specific wave farm development projects, specific site conditions, legal frameworks or market conditions of specific jurisdictions.
- TPL assessments are applied at the level of commercial configurations considering full concepts of operation, e.g. wave farm operation and concentrate on the techno-economic performance evaluation of the underlying WEC technology.
- TPL assessments shall be applicable to all wave energy technologies and support technology comparison.
- TPL assessments shall be applicable at all technology development stages i.e. at all TRLs and their assessment depth and resulting confidence levels are dependent on the TRL.
- TPL assessments aim to provide a holistic integral performance measure of the technology. This is targeted by consideration of all cost and performance drivers even at the lowest TRLs, with preference for

completeness while accepting low certainty and confidence levels.

### B. Assessment Process

The WEC system performance criteria and score associated with the different TPLs are based on an integrated techno-economic WEC performance assessment framework composed of an engineering analysis of the WEC device and lifecycle analysis of the wavefarm, as specified by Weber et al. [7] and schematically depicted in Fig. 1.

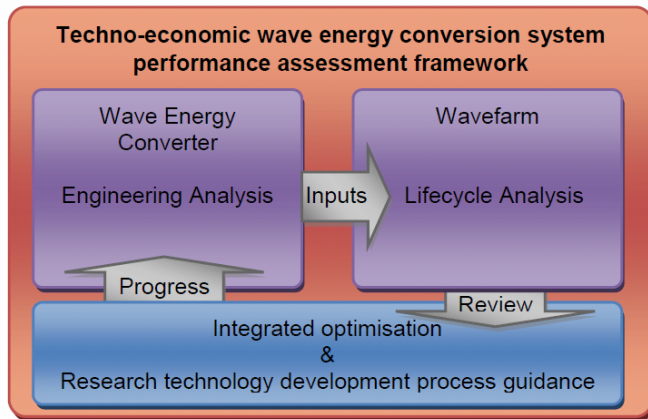


Fig. 1 Schematic of the techno-economic wave energy converter performance assessment framework [7].

The WEC engineering analysis comprises hydrodynamic absorption, system dynamics, power conversion as well as design, construction, assembly, operation, failure and maintenance analyses along with other subsystem performance aspects. The outputs of this analysis include information on power production, reliability and CapEx and OpEx drivers which are passed on to the wavefarm lifecycle analysis. The wavefarm lifecycle analysis comprises model representations of manufacturing, deployment, operations, maintenance and productivity, subjected to marine operations environment models. In combination these models deliver in-situ estimates of CapEx, OpEx and annual energy yield which are then analysed to determine discounted cash flow and economic performance characteristics including CoE.

The feedback of the economic performance resulting from the wavefarm lifecycle analysis under commercial application conditions on the WEC technology design parameters facilitates both guidance for an effective, focused and objective research technology development process, and implementation of an integrated techno-economic WEC system optimisation.

A significant share of the techno-economic WEC performance assessment framework can be implemented in form of numerical simulation models, combining WEC system simulation (solving over each occurring sea state class with a time domain resolution of milliseconds) and wavefarm lifecycle simulation (solving over the construction, installation, operation and recovery lifecycle with a time domain resolution of minutes up to an hour). Both [8] and [7] describe

the structure of the techno-economic WEC software tool and give application examples.

However, at the same time a considerable range of WEC performance assessment processes cannot be simply implemented in a straightforward way as numerical tools as they require expert judgement and evaluation, such as design, safety, failure and maintenance analyses and those outlined in [9].

### C. Performance Assessment Criteria

The criteria for assessing TPLs are diverse and include both WEC system functional performance criteria and wavefarm lifecycle performance criteria. Based on the five high level criteria groups given in Section I, associated sub-criteria and cost drivers are outlined below.

- **Acceptability:**  
Lifecycle environmental acceptability, social acceptability, socio-economic impact and/or benefit, market acceptability, legal acceptability, insurability, compliance with regulations and standards, safety during build, transport, deployment and operation, risk mitigation, insurability, ...
- **Power absorption, conversion and delivery:**  
Hydrodynamic wave power absorption, wave radiation, internal power conversion, power output conditioning, compliance to point of sale, capacity factor of power conversion subsystems, power balancing, short-term energy storage, controllability, ...
- **System availability:**  
Reliability, durability, redundancy and system and subsystem level, failure mode effect analysis (FMEA), survivability in large waves, survivability in large forces, system adaptability to resource and environmental condition variations, state and mode variability, load acceptance, criticality of load paths and power paths, fatigue loading, wear loading, ...
- **Capital Expenditure (CapEx):**  
Supply chain availability and security, material selection and quantity requirements, design effort for manufacturability, design effort for ease of mass production, construction, assembly, transport, deployment, installation, commissioning, accessibility, maintainability, modularity, external and internal peak load management, fatigue and wear load reduction, effort for structural integrity, ...
- **Lifecycle operational Expenditure (OpEx):**  
Maintainability, accessibility, modularity, ease of monitoring and exchange at system, subsystem and component level, spare part and replacement subsystem supply chain, graceful degradation, ease of partial operation, maintenance infrastructural and equipment and human resource requirements, ...

The above listing is not exhaustive and the allocation of the sub-criteria to the group is by no means a biunique relationship. Several of the individual criteria influence more than one of the five high level performance criteria. Further development of assessment criteria and process is underway

and in total in the order of 100 performance and cost drivers are expected to be employed in the assessment method.

#### D. TPL Characteristics and Categories

TPLs are ranked into nine categories with the lowest TPL at rank 1 and the highest at rank 9, following the nine categories of the TRLs. The nine TPL ranks are broadly grouped into three high level categories.

The low-performance category with TPL 1 to 3 characterises technologies that are not economically viable. The medium-performance category with TPL 4 to 6 characterises technologies that features some characteristics for potential economic viability under distinctive market and operational conditions. The high-performance category with TPL 7 to 9 characterises technologies that are economically viable and competitive as a renewable energy form. An overview of the nine TPL ranks along with their primary characteristics and high level category allocation are displayed in Table 2.

TABLE II  
TECHNOLOGY PERFORMANCE LEVEL CATEGORIES & CHARACTERISTICS

TPL	Category		TPL Characteristics
		Characterist.	
9	high	Technology is economically viable and competitive as a renewable energy form	Competitive with other energy sources without special support mechanism
8			Competitive with other energy sources given sustainable support mechanism
7			Competitive with other renewable energy sources given favourable support mechanism
6	medium	Technology features some characteristics for potential economic viability under distinctive market and operational conditions. Technological or conceptual improvements may be required.	Majority of key performance characteristics & cost drivers satisfy potential economical viability under distinctive and favourable market and operational conditions
5			In order to achieve economical viability under distinctive and favourable market and operational conditions some key technology implementation improvements are required.
4			In order to achieve economical viability under distinctive and favourable market and operational conditions some key technology implementation and fundamental conceptual improvements are required.
3	low	Technology is not economically viable	Minority of key performance characteristics & cost drivers do not satisfy potential economic viability
2			Some of key performance characteristics & cost drivers do not satisfy potential economic viability
1			Majority of key performance characteristics & cost drivers do not satisfy and present a barrier to potential economic viability

A detailed definition of the individual characteristics based on the performance criteria listed in section II C and their quantitative specification for each of the 9 TPLs will be the

subject of a separate publication. It is important to notice that during a technology performance assessment the plethora of individual assessment criteria will inevitably not lead to identical and consistent TPL scoring.

Thus, in order to identify an integral overall TPL score of a technology, non-linear weighted averaging method with the consideration of a range of minimum threshold criteria for individual or combined criteria or criteria subsets is applied. Embedded in the integration of all assessment criteria is an overall system simulation comprising a WEC engineering analysis & simulation and a wave farm operational simulation as described in [8] and [7].

#### E. Assessment Depth and Confidence Levels

Following the fundamental principles outlined above, the TPL assessment is applicable at all TRLs and a holistic integral consideration of all cost and performance drivers even at the lowest TRLs is desired. While the knowledge of the system specifications including overall and detailed designs as well as system properties and behaviour differs considerably over the different development stages, the possible depth of assessment and associated confidence levels of the assessment differs over the 9 TRLs. Evidently, at low TRL the possible assessment depth is lower and the achievable confidence level of the TPL evaluation result is lower than at higher TRLs. However, even though there are several unknowns of the WEC system at low TRL, reasonable consideration and estimation of all cost and performance drivers is undertaken even from TRL 1 on. Thus, a minimum detailed level WEC system and operational descriptions is required to conduct a TPL assessment. Hereafter, the TPL assessment content and depth with associated confidence levels are outlined for a selection TRL ranges.

##### 1) TPL Assessment at TRL 1

- Fundamental WEC device configuration descriptions need to be enhanced to the level of overall conceptual detailed system descriptions of the WEC and its Concept of Operations (ConOps) including functional and lifecycle aspects.
- All cost and performance drivers i.e. the relevant TPL assessment criteria are evaluated for the detailed system description through expert assessment and individual TPL scores are allocated for each criterion.
- Confidence levels of each individual TPL assessment score is considered and documented.
- The integration of the individual TPL scores to determine an overall TPL, to be allocated to the WEC system under assessment, is conducted via a non-linear weighted averaging method with the consideration of a range of minimum threshold criteria for individual or combined criteria or criteria subsets.
- The confidence level of the integrated TPL score is determined from the confidence levels of the entirety of the individual TPL scores and the functional relationship of the associated assessment criteria.

- Expected confidence levels are low with high error bars associated with the TPL score. However, valuable and detailed insight into the WEC system and its functional and lifecycle performance considerations are made at a very early stage of the development highlighting key weaknesses and strengths of the WEC system and concept and technology level.

## 2) TPL Assessment at TRL 2 and higher

- Detailed overall WEC system descriptions of the WEC and its Concept of Operations (ConOps) including functional and lifecycle aspects based on overall and critical subsystem design information.
- Large subset of cost and performance drivers i.e. the relevant TPL assessment criteria are evaluated for the detailed system description through expert assessment and individual TPL scores are allocated for each associated criterion.
- Confidence levels of each individual TPL assessment score is considered and documented.
- The integration of the individual TPL scores and the remaining cost and performance drivers to determine an overall TPL, to be allocated to the WEC system under assessment, is conducted via integrate system simulation comprising a WEC engineering analysis & simulation and a wave farm operational simulation as described in [8] [7]. Hereby the detailed overall WEC system descriptions provide the required inputs to the WEC and wave farm simulation models. This integrated system simulation determines key technical (e.g. power, availability) and economic (e.g. Capex, OpEx, CoE, NPV, IRR) performance indicators. These comprehensive performance indicators resulting from the simulation carry highly relevant contributions to the integration to determine the overall system TPL score. Hereby, a subset of cost and performance drivers that lies outside the system simulation are integrated via non-linear weighted averaging methods with the consideration of a range of minimum threshold criteria for individual or combined criteria or criteria subsets.
- The confidence level of the integrated TPL score is determined from the confidence levels of the entirety of the individual TPL scores and the simulation inputs and the overall functional relationship of the associated assessment criteria.
- Improved (over TRL assessment at TRL 1), acceptable confidence levels with reduced error bars associated with the TPL score are achievable. Valuable and detailed insight into the WEC system and its functional and lifecycle performance while considering complex system representations are made at an early stage of the development highlighting key weaknesses and strengths of the WEC system and concept and technology level.
- The numerical integration of the overall system TPL score comprising the embedded WEC engineering

analysis & simulation and wave farm operational simulation facilitates a good representation of the diverse assessment criteria interactions and delivers valuable insight through sensitivity analysis.

3) *TPL Assessment at TRL 3 and higher* The TPL assessment methodology at TRL 3 and higher is fundamentally identical to the one performed at TRL 2. However, with increasing TRL the content, detail and depth of information on the WEC system specification, overall and detailed designs as well as system properties and behaviour increases leading to associated improvement in the confidence levels of the TRL assessment.

The following short and incomplete list outlines only but a few examples of additional content, detail and depth of information considered during the TPL assessment at higher TRLs.

- Hydrodynamic power absorption performance, fatigue and production load case measurements, etc. from wave basin testing at reduced model scales.
- Hydrodynamic survival behaviour under extreme wave conditions from wave basin testing at reduced model scales.
- Mooring performance from dedicated mooring analysis.
- Subsystem performance from laboratory testing.
- Detailed engineering assessment from detailed system and subsystem designs.
- Thorough reliability performance from detailed FMEA.
- Detailed OpEx models from O&M strategy and detailed planning.
- Detailed dry CapEx models from part lists, supply chain, manufacture, construction and assembly planning.
- At sea performance results and system experience from reduced scale and full scale at-sea demonstrations.

## III. VALUE OF TECHNOLOGY

In the context of considerations of the requirements for successful development of economic WEC technology perceived and actual values of WEC technology is a central and important quantity both during and at the end of the technology development. As a wide spectrum of technologies compete during development for funding and aim to operate in competitive energy markets, it is essential to reflect on appropriate high level requirements and marketability, investability and market opportunity associated with a technology.

The TRL-TPL-Matrix, as introduced in [1] is used here, both in its function as technology value map, for the comparison of technology during development and as two-dimensional visualisation of technology development trajectories to consider cost of past and future development paths and expected technology development outcome.

### A. Marketability

Marketability is a measure for the likelihood that a product can be sold and will be bought in a product relevant market.

Assuming the important market of electricity generation, sales and trading, it is important to ask for minimum requirements for WEC technology to enter into this market and for conditions likely to give prospects for WEC technology to succeed in this market.

It is generally recognised as being mandatory for WEC technology to be technologically and commercially ready for market operation and the technology is required to have proven its readiness by having achieved TRL 9 with significant prototype operational time on record. This constitutes the technology being producible, that it can be ordered, delivered, commissioned and made available ready for operation. However, it is important to emphasise that the level of techno-economic performance capability of the WEC technology is crucial for the technology to actually enter, survive and potentially succeed in the electricity market. This requirement results from three levels of competition including:

- Competition with other WEC technologies under equal wave energy market conditions.
- Competition with other renewable energy technologies under potentially favourable relevant renewable energy type market conditions and/or at higher levels of technological maturity.
- Competition with other general energy technologies (including fossil and non-renewable sources) under potentially favourable relevant energy type market conditions and/or at higher levels of technological maturity.

Thus, it is apparent that a further requirement for marketability is the achievement of sufficient techno-economic performance expressed by high TPL comprising low CoE. Reflecting on the TPL definitions in section 2, a minimum requirement of techno-economic performance for market entry is TPL 7+ with WEC technology at least performing economically under favourable market conditions and being competitive with other renewable energy forms. Consequently, the minimal requirements for market entry are TRL 9 and TPL 7+. These circumstances are summarised in Table 3 and visualised in Fig. 2 by use of the TRL-TPL-Matrix.

TABLE III  
MINIMAL REQUIREMENTS ON TRL AND TPL FOR MARKET ENTRY

Metric	Level	Characteristics
TRL	9	Functional and lifecycle commercial project technology readiness proven
TPL	7+	Functional and lifecycle performance proven economic under favourable market conditions and competitive with other renewable energy forms

Technology should not leave the TRL-TPL-Matrix below the blue market entry line in Fig. 2. Furthermore, technology development trajectories that have low likelihood of achieving TPL 7+ at TRL 9 should be identified at an as early as possible stage in the development process to intervene in the development either by fundamental technology improvement at low TRL or by redirecting funding and investment to higher

quality technologies. Consideration on the possibilities, advantages and disadvantages of different technology development trajectories and criteria for best possible development paths with respect to development cost, time, risk and most importantly outcome have been discussed in [1].

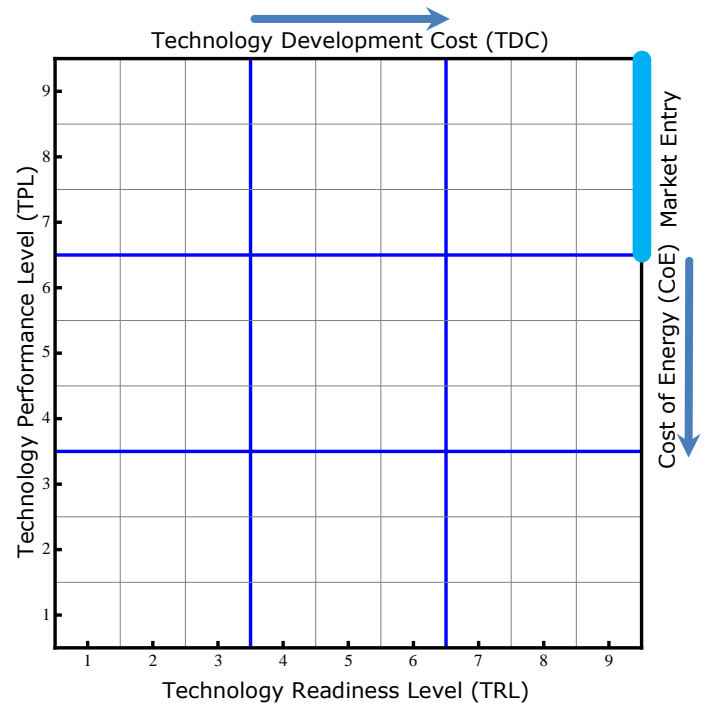


Fig. 2 Market entry requirements displayed over the TRL-TPL-Matrix for WEC technology development.

### B. Investability

While technologies are under development typically a multitude of funding stages and funding sources, both public and private, are required to support the technology development process, potentially taking up to 15 years involving total investment in the order of €100 m. Again, perceived and actual values of WEC technology are central to the success of these fundraising efforts. The relevance of TRL is widely accepted and recognised in this context and developers as well as funders and investors refer to the TRL of a technology when assessing its maturity and readiness for commercial operation. While CoE projections feature as one of many criteria during fundraising and investment rounds, much less established in the decision making are agreed, widely recognised considerations of metrics for the overall techno-economic performance capabilities of technologies. These circumstances may lead to major discrepancies between perceived and actual values of WEC technology under development with the consequence of poor investment and funding decisions both by private entities and public bodies. Thus, it is important to consider the required information and interpretation to estimate the value of technology with sufficient accuracy in order to arrive at reliable investability criteria.

In order to highlight the relevance of both TRL and TPL with respect to investability, two cases of technologies under



development are assumed. These cases are summarised in Table 4 and visualised in Fig. 3 by use of the TRL-TPL-Matrix.

TABLE IV  
CASES OF WEC TECHNOLOGIES UNDER DEVELOPMENT FOR CONSIDERATION OF VALUE OF TECHNOLOGY AND INVESTABILITY

Criterion	WEC-I	WEC-II
TRL	3	7
TPL	6	3

In case WEC-I the technology has achieved a high TRL of 7 at a low TPL of 3. Conversely, in case WEC-II the technology has achieved a TPL of 6 while still at TRL of 3.

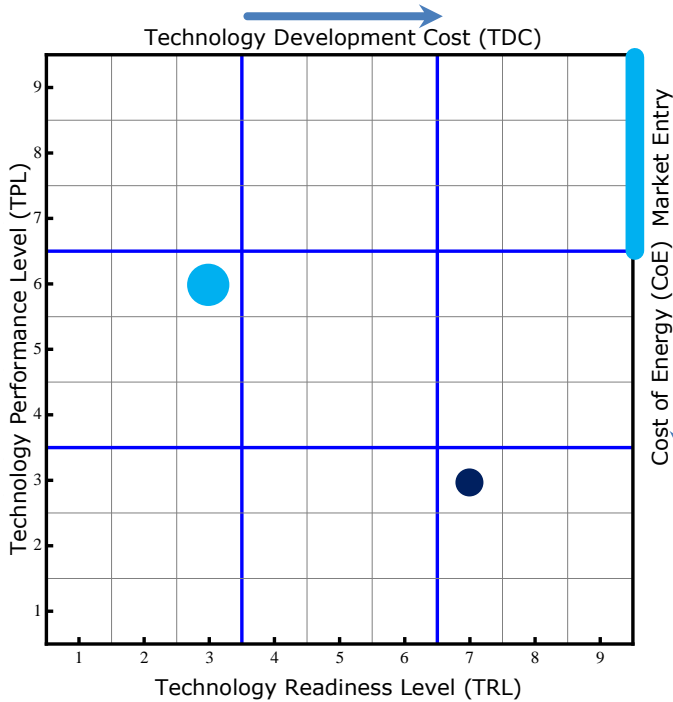


Fig. 3 Two cases of WEC technologies under development for considerations on value of technology and investability.

When contemplating the value of technology under development past development and future development need to be considered. As each TRL is associated with a technology development cost for any one development project or activity at a given TRL stage, the accumulative total cost of past development is associated with the development trajectory and somewhat related to the TRL status of the technology. Thus, WEC-I at TRL7 can be expected to have incurred significantly higher development cost in comparison to WEC-II at TRL3. The level of past development cost strongly influences vendor expectations. This may however not be reflected in the actual value of stage and quality of the technology under development.

More detailed consideration with regard to the value of technology is required for the evaluation of future development cost that will be incurred by the investor prior to reaching returns and subsequently profits based on technology sales and/or electricity sales. Effects of multiple investment

scenarios and intermediate exit strategies are common but are not considered here, as the focus and the concern of this analysis is on the valid assessment of the value of a technology under development with respect to achieving its final application of commercial and economic operation and electricity production rather than any intermediate monetary value. Beyond the pure direct development cost of technology development, the time and risk of further development also need to be taken into account when assessing the value of technology.

Recalling the minimal requirements for market entry from the previous section, i.e. TRL 9 and TPL 7+, the reasons for required future cost are twofold.

- Future required development cost, time and risk to achieve TRL 9.
- Future required development cost, time and risk to achieve TPL 7+.

Considering required future development trajectories for both considered technology cases WEC-I and WEC-II, the following observations can be made.

In case WEC-I the technology is already at TPL 6 and requires modest techno-economic performance improvement to achieve the minimal performance criterion of TPL 7+. Reflecting on the analysis of best technology development trajectories in [1], this required TPL increase is best achieved at low TRL while even fundamental technology improvements may be implementable at affordable cost time and risk. Following a performance improvement to TPL 7 or higher the technology requires refinement, maturing and proving-out of the performance while increasing the TRL through to TRL 9. Continued techno-economic performance assessment is required to ensure both, maintenance of the high TPL during this development path toward TRL 9 and reduction of the number of individual technology development projects to ideally one single instance per technology development stage, i.e. per TRL stage.

In case WEC-II the technology has already been matured and refined to TRL 7 and has incurred associated past development cost. Apparently, only two further stages of technology maturing refinement and proving-out are required. However, as the techno-economic performance of the technology is only at TPL 3, significant performance improvements are required in order to achieve TPL 7+.

Considering the definition of the low TPL category, economic viability even under favourable market conditions is not possible or (from TPL 4) fundamental changes to the key performance features of the technology are required. Again, reflection on the analysis of best technology development trajectories in [1] development activities in the range of TRL 5 to TRL 9 are in the domain of technology refinement and demonstration where it is strongly recommended that system fundamentals be maintained, as highly structured, legally binding as well as cost, time and risk intensive engineering procurement construction installation (EPCI) type projects are severely disrupted and likely to be damaged or fail if system fundamentals are changed at this stage. As a consequence the required technology development trajectory of WEC-II to

attain TPL 7+ is likely to lead back to considerable activities at lower TRLs of TRL 4 and less where fundamental system variation and large performance improvements are achievable at much reduced cost, time and risk. These fundamental system improvements are likely to come with a requirement for innovation and a need to commercially secure this innovation through an increased portfolio of intellectual property (IP). This requirement clearly leads to an undertaking of poor predictability and high risk with respect to the required time for secured innovation results. Furthermore, the need for change of fundamental WEC system features may significantly de-value the IP of the original technology in case WEC-II. As an alternative to the returning to low TRL development activities in order to achieve significant TPL improvements, developers may be tempted to consider trying to achieve significant TPL improvements while remaining in the high TRL domain of technology demonstration. Such attempts would require multiple iterations of technology demonstration at high TRL leading to substantial development cost, development time and unwarranted development risk, with any of the later factors potentially leading to final commercial failure of the undertaking.

In summary, it is expected that a detailed analysis of the development cost, time and risk to achieve the minimum requirements for market entry of TRL 9 & TPL 7+ and the associated actual value of the technologies considered in the two example cases, will lead to a clear preference for WEC-I (TRL 3& TPL 6) over WEC-II (TRL 7 & TPL 3).

### C. Market opportunity

Finally, a further criterion to be taken into account when assessing the value of technology either under development or close to market entry is the type and size of the market opportunity. A range of factors influence the market opportunity potentially available to a particular WEC technology. Some prominent examples are listed here.

- WEC type clarification of on-shore, near-shore and off-shore technologies with large differences in associated wave resource and global site availability.
- Technology suitability for niche markets with improved market conditions e.g. power offshore marine assets.
- Technology suitability to markets with particular regulatory requirements.

All though the criterion of market opportunity is outside the remit of the TPL or TRL metrics, it is relevant to the value of technology. This is accounted for when comparing WEC technologies over the TRL-TPL-Matrix and the relative market opportunity is represented via the size of the circle marker, as displayed in Fig.3 with e.g. market opportunity of WEC-I larger than the market opportunity of WEC-II.

## IV. CONCLUSIONS

Following previous introduction in [1] the Technology Performance Levels (TPLs) have been established and identified as an effective metric for the quantification of techno-economic performance of WEC systems. In

combination with the Technology Readiness Levels the TRL–TPL–Matrix is employed as a means of visualisation, evaluation and comparison of WEC technology development status and trajectories. Furthermore, the matrix serves as a WEC value map for visualisation, quantification and comparison of the technology development status with respect to overall commercial readiness and economic performance.

The fundamental principles underlying the TPL definition were outlined, showing the focus of the TPL purpose as a technology-inherent performance metric for techno-economic assessment and comparison of WEC technologies, applicable at all TRL development stages. The depth of assessment and associated confidence levels of the performance statement in terms of TPL are discussed and outlined for a selection TRL ranges. Throughout all TRLs, even at TRL 1 a preference is made for completeness with consideration of the complete set of cost and performance drivers while accepting low certainty and confidence levels.

The value of technology is discussed with respect to investability while under development and marketability when at product stage. It has been shown that the combined consideration of both TRL and TPL are required to a) identify requirements of WEC technology for successful entry and survival in the electricity market and b) for identification of actual value of technology under development when investment and funding decisions are made.

In an admittedly simplistic and figurative analogy to the consumer market the following statement can be made. TRL 9 expresses technological and commercial market readiness and ensures the availability of a product for the market – i.e. the product is available on the shelf. Whereas, high TPL (7 to 9) expresses the ability of the technology to perform economically and to be competitive as a wave energy technology (TPL7), potentially to compete with other renewable energy forms (TPL8) and potentially to compete with the general energy market (TPL9) – i.e. the product will be bought and picked up from the shelf.

To date, the TPL metric alongside the TRL metric has proven very valuable in the description, visualisation and discussion of different technology development trajectories, as well as in the assessment and comparison of technologies under development.

Many stakeholders of the WEC development industry have been invited to contribute to the refinement of the TPL assessment metric and process; they are engaging and the process is enjoying positive feedback and benefiting from a variety of collaborations and inputs from a range of contributors. These include government agencies, research institutions, standardisation bodies, technology developers, technology users, strategic investors and financiers. It is intended and hoped that the TPLs in combination with the TRLs will be widely utilised in the

- Management, support and improvement of technology development processes,
- assessment and comparison of technologies under development during vendor and buyer technical due diligence,



- decision making process of public funding bodies and
- considerations of technology value, investability and marketability by private, institutional and strategic investors.

The author hopes that this valuable and much appreciated engagement of WEC technology development stakeholders and the continued work on TPLs and techno-economic WEC assessment will bear fruit in providing a contribution to improving WEC research technology development processes, supporting developments to be funded and bridging the valley of death on the basis of the merits, quality and techno-economic performance of their technologies, and in delivering higher performance WEC technology outcomes for economic renewable energy production; an imperative for sustainable societies.

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