WEC Technology Readiness and Performance Matrix – finding the best research technology development trajectory

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WEC Technology Readiness and Performance Matrix – finding the best research technology development trajectory

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Abstract

The paper identifies and discusses the need for techno-economic performance improvements at early stages of the wave energy converter (WEC) technology development process. Technology Readiness Levels (TRLs) for wave energy projects provide a valuable metric of technology readiness and deliver useful guidance for the development process. This paper describes the complementary metric of Technology Performance Levels (TPLs) characterised by a set of quantified performance criteria aimed at identifying and classifying the techno-economic performance of wave energy technology. These TPLs are broadly inversely related to cost of energy (CoE) and provide a combined measure for capital expenditure (CapEx), lifecycle operational expenditure (OpEx), energy conversion efficiency and technology availability. Less quantifiable performance aspects such as acceptability and safety are also considered in the definition of the TPLs.

A 2-dimensional representation of technology readiness and performance levels is introduced. This TRL–TPL–Matrix visualisation provides a useful means for the evaluation, comparison and discussion of different research technology development trajectories over the technology readiness and performance levels plane. The paper identifies the need for technology performance trajectories with high technology performance levels at low readiness levels and gives valuable advice on the development strategy and tools required to achieve successful WEC technology development outcome at reduced development time, total development cost and encountered risk.

Keywords: Wave energy converter, technology development, technology performance level, technology readiness level, TPL–TRL–matrix, WEC technology value map.

1. 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-economical 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 on 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 central questions are justified.

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

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 [1] have been widely adopted and applied in the wave energy technology development, project development and end user industries.

The use of these 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. Fitzgerald & Bolund [2] provide discussion and full definition of technology readiness for wave energy projects under the ESB and Vattenfall classification system in 9 TRL categories.

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 by Weber [3], the Technology Performance Levels (TPLs) are being introduced here. 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**.

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

Table 1: Fundamental understanding and definition of TRL and TPL.

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.

To date, the TPL concept has been initiated and encouraged for application in technology evaluation and development. The TPL metrics and accurate definition of the 9 levels require some further development and completion of detailed specification with respect to the multiple performance sub-criteria for effective, comparable and wider application.

Nonetheless, the TPL metric alongside the TRL metric has proven very valuable in the description, visualisation and discussion of different technology development trajectories even at the current, not fully developed stage.

2. Technology Performance Levels (TPL)

An integrated techno-economic WEC performance assessment process is employed to extract relevant technology performance assessment criteria. Subsequently, an overview of the high level TPL characteristics and categories is presented.

2.1 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. [4] and schematically depicted in Fig. 1.

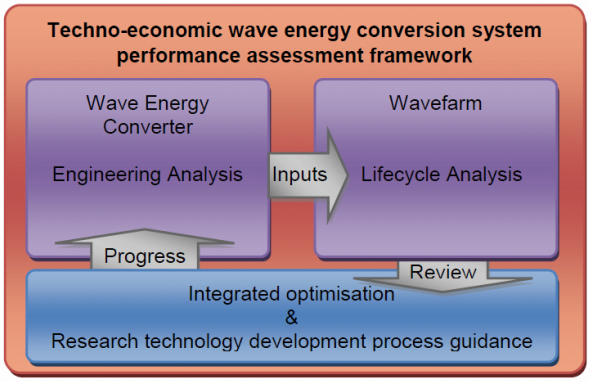

Figure 1: Schematic of the techno-economic wave energy converter performance assessment framework [4].

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 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 economical 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). Teillant et al. [4] and Weber et al. [4] 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 [6].

2.2 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 1, associated sub-criteria and cost drivers are outlined below.

- Acceptability:
  Lifecycle environmental acceptability, social acceptability, safety during build, transport, deployment and operation, risk mitigation,
- Power absorption, conversion and delivery:
  Hydrodynamic wave power absorption, wave radiation, internal power conversion, power output conditioning, compliance to point of sale, controllability,
- System availability:
  Reliability, durability, redundancy, failure mode effect analysis (FMEA), survivability in large waves, survivability in large forces, sea condition and mode adaptability,
- Capital Expenditure (CapEx):
  Supply chain, material selection and quantity requirements, manufacturability, ease of mass production, construction, assembly, transport, deployment, installation and commissioning, maintainability, accessibility, modularity, external and internal load management of peak, fatigue and wear loads,
- Lifecycle operational Expenditure (OpEx):
  Maintainability, accessibility, modularity, ease of subsystem and component exchange, graceful degradation, ease of monitoring, ease of partial operation, insurability,

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.

2.3 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**.

TPL	Category		TPL Characteristics
	L	Characteristics	
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

Table 2: Technology Performance Level characteristics.

A detailed definition of the individual characteristics based on the performance criteria listed in Section 2.2 and their quantitative specification for each of the 9 TPLs will be 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 the overall TPL status of a technology, a minimum score method for 90% of the performance criteria is applied in combination with the overall cost of energy prediction for the technology.

3. TRL–TPL–Matrix – WEC technology value map

For a comparison of the development status of different technologies and for the visualisation and discussion of different technology development trajectories, it is convenient to display TRL and TPL values in the form of a matrix diagram as depicted in Fig. 2. The abscissa is used to display the TRL. With reference to the indicative development costs presented by Fitzgerald it follows that the abscissa of the TRL–TPL–matrix i.e. the TRL scale, is strongly related to the required development funding. The ordinate is used to display the TPL. Consequently, the ordinate is inversely related to the cost of energy performance achieved by the displayed technology. Rough orders of magnitude of required funding and cost of energy are accordingly displayed alongside the vertical top and horizontal right border of the TRL–TPL–matrix (see Fig. 2). The desired technology development goal is to reach the top-right corner of the matrix characterising a technology of high TRL, ready for commercial operation, and of high TPL, delivering economic performance objectives.

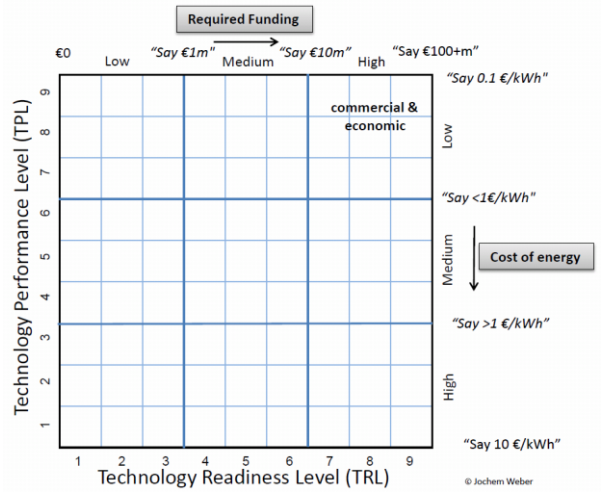

Figure 2:.TPL–TRL–matrix – WEC technology value map.

Through the display of the development status of a number of different technologies over the TRL–TPL–matrix, this representation can serve as an absolute and comparative WEC technology value map. Regarding detailed, thoroughly conducted technology readiness and technology performance assessment procedures as a prerequisite for an entry into the WEC value map, this display delivers powerful representations of technology status and value.

Furthermore, the TRL–TPL–matrix can be utilised for the visualisation of development trajectories when the development status of a particular technology is displayed for different stages of the development process over time. This visualisation is constructive for the identification and evaluation of the effectiveness of development steps performed in the past and for the consideration of alternative development options in the future. In combination with sensitivity analysis for the impact of different system parameter changes and performance criteria improvements, such as those presented by Teillant et al. [5], objectively established and effectiveness based research technology development decisions can be undertaken. As described in Weber et al. [4], this application of the underlying technology assessment framework delivers beneficial guidance for technology research & development programmes and it informs human, time and financial resource allocation as well as strategic management and investment decisions. This approach ensures high value for money development processes and the TRL–TPL–matrix facilitates the visualisation of these circumstances.

4. Discussion of technology development trajectories

With the goal of finding the best technology development trajectory, a number of generic and realistic fundamental scenarios are discussed. Subsequently, the required tools for the implementation of the desired research technology development trajectory are identified.

4.1 Generic technology development trajectories

In order to set the outer boundaries for development trajectories, initially generic, extreme and identifiably unrealistic development trajectories are considered and briefly discussed.

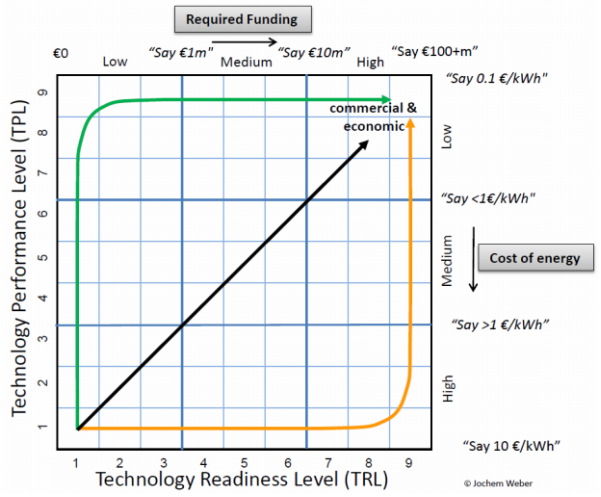

Figure 3: Generic WEC technology development trajectories.

Three such generic development trajectories are displayed in Fig. 3 over the TRL–TPL–matrix, each setting out from (TRL, TPL) = (1,1) and leading towards (TRL, TPL) = (9,9).

Readiness before performance – extreme case

The yellow trajectory assumes initial pure technology maturing along the TRL scale and subsequently aiming to accomplish the complete performance improvement at TRL 9. Such a performance improvement path would require several technology steps at full technology readiness. Given the high development cost and time for each of the development steps at high TRL, the total technology duration and time would be unacceptably high.

Furthermore, WEC system improvements within a high maturity technology status are extremely unlikely to deliver the performance increase of the kind required on the yellow trajectory. More fundamental system improvements are required to move from TPL 1 to TPL 9. Such fundamental improvements would be extremely risky when conducted at full scale prototype small array level of TRL 9 and would imply breach of the basic principles of available WEC technology development protocols. Additionally, the funding of such an extremely costly, long and parlous development process, only delivering performance levels of interest at the very end of the process, is unworkable. It can therefore be assumed that such an extreme approach would lead to significantly lower technology performance outcomes than TPL9 or potentially into a cul-de-sac development path.

Following technology development through the TRL–TPL–matrix, post TRL 9 maturity, technologies will enter commercial mass production if regarded as economically viable. From then on and with increasing installed capacity the cost reduction and performance improvement effects of learning curves will take effect. Within a certain variance this can be expected to be the case for all technology types. From experience aggressive learning curves may achieve cost reductions and thus associated technology performance improvements of 15%. Consequently, the economic success of a technology should not be reliant to an excessive degree on the beneficial effect of learning curves. Furthermore, competitiveness requires entering the commercial mass production stage at the highest TPL and lowest CoE possible.

Performance before readiness– extreme case

Reflecting on the green development trajectory in Fig. 3 a pure technology performance improvement process for TPL 1 to TPL 9 is initially assumed. This is followed by technology maturing with increasing readiness levels up to TRL 9.

A key challenge in such an approach lies in the uncertainties associated with the determination of the TPL value of a technology that is only defined at the level of detail and empirical evidence available at TRL 1. Reflecting on the diverse technology performance assessment criteria outlined in section 2, a reasonably detailed understanding of the WEC system design and its operation at high maturity and commercial status is to be attained already at low TRL in order to conduct a TPL determination as a basis for TPL increase on a controlled development trajectory. Such an early insight and rational anticipation of the system performance characteristic requires both realistic, comprehensive formulation of assumptions describing the WEC system at high TRL, and sophisticated modelling of the overall WEC system techno-economic system performance. The validity and certainty of the development along the green development trajectory entirely depends upon the expertise and objective foresight in describing the system as of mature level and the capacity of integrated modelling tools and the expert judgement in reliably evaluating their TPL.

The drastic increase in TPL in the first half of the green development trajectory in Fig. 3 is most likely only achievable under the consideration of significant changes and improvements to system fundamentals. However, at the same time it is important to emphasise that fundamental system changes are possible and affordable at low TRLs. Furthermore, the performance assessment process with detailed description of the mature system and application of sophisticated simulation and assessment tools, such as those described in section 1, can facilitate the early detection of poor fundamental concept features, delivering valuable feedback for early concept definition and reducing development risk.

Reflecting on the cost associated with development activities at the different TRLs, the total financial requirement for the green development trajectory can be assumed to be low by comparison, as the engagement into costly technology prototype demonstration is delayed until after accomplishment of high TRLs and the number of capital intensive large scale sea-going demonstration efforts are reduced to a viable minimum. Corresponding assumptions can be made on the total duration of the development process along the green trajectory.

Limitations in the implementability of the green development trajectory are directly associated with the uncertainties in the foresight of the mature system characteristics and limitations of the simulation and modelling capabilities. A range of system properties are extremely difficult to simulate accurately and in order to increase the reliability of the TPL assessment, empirical evidence and experience from focused subsystem testing at appropriate scale will be required.

In their totality both the yellow and the green generic development trajectory in Fig. 3 are unworkable or somewhat unrealistic and challenging. Viable and practical development trajectories will therefore turn out as combined moderations between both discussed extremes. However, it is questionable if a straight line development path, as indicated by the black trajectory in Fig. 3, is the most beneficial with respect to development cost, time, risk and deliverable technology success.

4.2 Generic technology development domains

These considerations of generic development trajectories lead to the recognition of two principally different generic technology development domains as displayed in Fig. 4.

In the region of low to intermediate TRLs, dominated by research activities, changes of conceptual and technological system fundamentals are possible as they entail moderate and acceptable impact on development time, cost and risk. Regarding the significant performance improvements that are required for advancing to a TPL 9 technology, many initial concept approaches do require changes to the system fundamentals. Thus, within the research dominated domain of low TRLs, advantageous alterations to conceptual and technological system fundamentals are not only practical but should also be encouraged in order to achieve the desired high TPL.

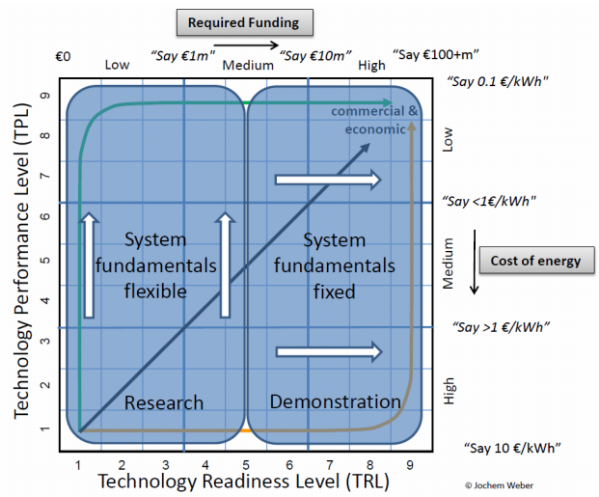

Figure 4: Generic WEC technology development domains.

Contrary to this, in the region of intermediate to high TRLs, dominated by demonstration activities, changes of conceptual and technological system fundamentals are difficult to implement, risky and often counterproductive to achieving distinctly defined demonstration project goals. Thus, at high technology maturity and readiness, changes to system fundamentals should as far as possible be avoided, particularly within a running project. Development methods should be put in place to identify the need for fundamental system amendments at lower TRLs.

Furthermore, it is important to acknowledge that on the one hand the research and on the other hand the demonstration dominated domains are significantly different in relation to required work methods, development tools, skill sets, development partners, human resource needs, management structure, time lines, capital expenditure, overall budgets, liabilities and corporate risk exposure. This emphasises their distinction with respect to ease and complexity of changes to system fundamentals during the development process and indicates strong recommendations for the choice of the technology development trajectory.

It is to be emphasised again that the above generic and extreme development trajectories are hypothetical. However, their contemplation delivers insight with respect to the limits of realistic development trajectories, leads to the identification of the characteristics of the two main generic development domains and furthermore gives strong indication for the track region of the best development trajectory with regard to development cost, time, risk and achievable outcome.

4.3 Realistic technology development trajectories

Prior to considering realistic, workable technology development trajectories, the current status of the WEC technology development industry is schematically reflected in Fig. 5. The current development status of a characteristic subset of anonymous WEC technologies is presented in form of blue circles over the TRL–TPL–matrix in Fig. 5. The position of a circle in the matrix is in accordance with the achieved TRL and TPL values of a considered technology. In this form the TRL–TPL–matrix serves well in its function as a value map, reflecting on absolute and comparative commercial and economic status and value of a technology under development. The representative sample of WEC technologies displayed includes

- Technologies at low and intermediate readiness level with low and intermediate performance prospects
- Technologies of high readiness however, at low performance level, having demonstrated at large prototype scale poor technology performance
- Technologies of high readiness and intermediate performance levels, representing current front runners of technologies under development in the international WEC industry.

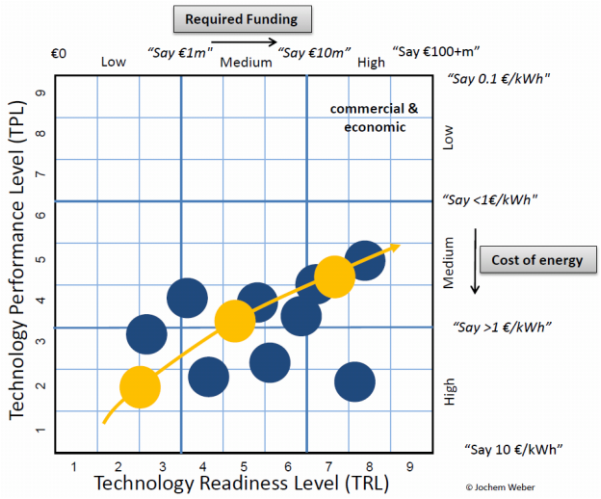

Figure 5: Characteristic subset of WEC technologies and their development status in the value map with corresponding realistic WEC technology development trajectory example.

The joined yellow set of circles represents a realistic development trajectory example of a technology at different stages of the development over time. The circles refer to key development projects and milestones along the technology development path when an evaluation of TRL and TPL is undertaken. It is noted that TPL estimates may well be higher at the onset of a development at TRL levels 1 and 2 due to initially low confidence levels.

This concentrated and compacted representation in Fig. 5 of the technology development status is clearly incomplete yet representative and does outline the region in the TRL–TPL–value map that has to date been reached by the WEC technology developing industry.

Without further representation of the analysis of the current industry status in this paper, however reflecting on the technology developments activities of the last decades, it is strongly felt that the following statements on the limitations and deficiencies of the state of the art WEC technology development status and approach can be made.

- Technologies do not achieve high economic performance levels TPL i.e. low CoE
- Development paths are rigid and retaining initial early concept idea
- Technology improvements by change of system fundamentals are largely avoided
- Developments concentrate on advancement of technology readiness
- Focus and drive on demonstration of often underdeveloped technology
- Techno-economical system performance is considered too late in the process
- Reduction of CoE is limited, too expensive and risky when pursued at high TRL

In conclusion, it is argued that in order to arrive at high economically performing technologies in the region of TPL 7 to 9, the above deficiencies and limitations must be overcome and a different development approach is required.

Reflecting upon:

- the observations made on the overall character and status of WEC technology development (sections 1 and 3),
- the consideration of the pros and cons as well as the imponderables and limits to practicability of the extreme generic development trajectories
- and the characteristics of the generic development domains in relation to ease and complexity of changes to system fundamentals during the development

leads to the recommendation for the guiding principle to pursue development trajectories that firstly strive to primarily increase technology performance as far as practically possible and secondly to engage in increasing technology readiness in order to arrive at commercially ready and economically performing WEC technology. The pursuit of this general premise of "performance before readiness" has the potential to deliver significant benefit with respect to development cost, time, risk and deliverable technology success.

Fig. 6 displays a corresponding improved realistic technology development trajectory (in green) in comparison with the state-of-the-art technology development path and resulting technology status. Again, the green circles in Fig. 6 correspond to key development project stages and milestones along the improved technology development trajectory.

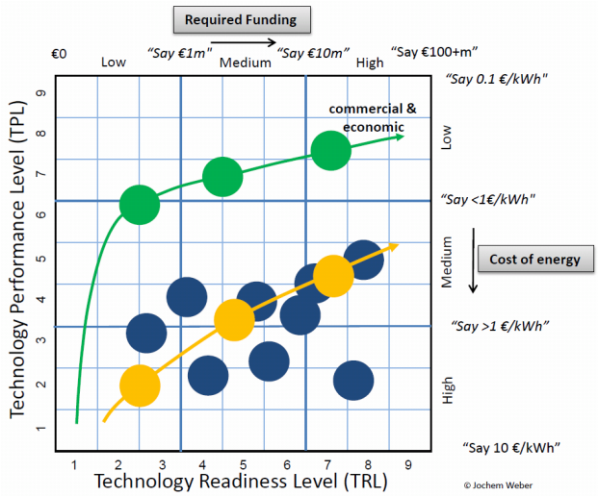

Figure 6: Comparison of development trajectories. Improved realistic development trajectory (in green) following the guiding principle of "performance before readiness".

In the development along the green trajectory, costly technology prototype demonstration is delayed until the system configuration with the highest possible predicted TPL at high TRL is identified and the highest level of confidence is reached in achieving this performance level prior to engaging in such capital and time intensive activities with high technical and particularly corporate risk.

This approach is particularly favourable as the technology development of WECs is fundamentally different from other technology developments such as wind energy converters. This becomes clear when reflecting on principal differences with regard to early technology concept conversion, market opportunity at reduced scales, availability and reliability requirements and ease of maintenance, as outlined by Weber et al. [7]. There, it is concluded that an "intelligent design" approach is required in wave energy technology development as opposed to the "technology evolution" approach that was possible in wind energy technology development.

Considering the yellow development trajectory in Fig. 6, at least one further substantial technology development iteration would be required to arrive at high TRLs of equivalent economic performance to those achieved by the yellow trajectory. Estimating the line integrals of required development time, consumed development expenditure and encountered technology

and corporate risk along these two considered development trajectories, the superiority of the green trajectory become evident.

The identified improved development trajectory leads to the requirement of early consideration of all relevant techno-economic performance and cost drivers as previously suggested by Weber et al. [8]. The following section will consider the associated necessary tools and methods in order to implement the green improved development trajectory displayed in Fig. 6.

4.3 Required Development Tools

Addressing the challenges associated with the realisation of the green development trajectory in Fig. 6, the required development tools and methods can be identified.

As outlined in section 4.1 key challenges rest in the uncertainties associated with the determination of the TPL of a technology only typically defined at the level of detail and empirical evidence available at TRL. This relates to both realistic assumptions describing the WEC system at high TRL, and sophisticated modelling and assessment techniques to determine the system TPL.

A detailed account of the system under commercial operation in the form of the Concepts of operation (ConOps) as outlined by Weber et al. [7, 8] as part of a sound system engineering approach, provides a good methodology of formulating assumptions describing the WEC system at high TRL. This understanding of the assumed system of (TRL, TPL) = (9, 9) is to be employed in and made subject to the performance assessment and the techno-economic simulation of the system. These circumstances are illustrated in form of two blue arrows in Fig. 7.

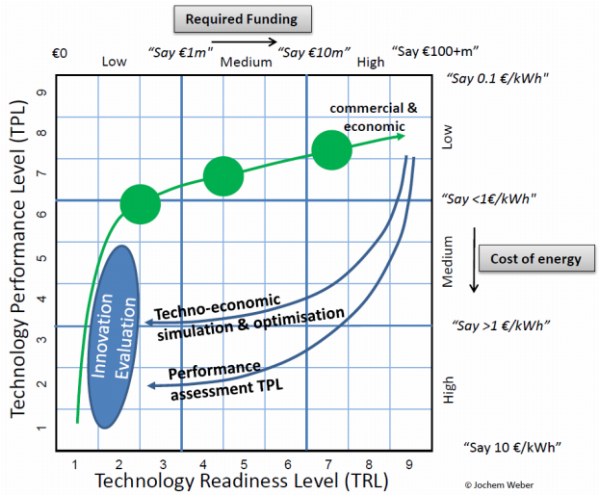

Figure 7: Required WEC technology development tools (blue) for improved realistic development trajectory (green).

Evidently, it is crucial that as outlined in section 2, an objective assessment process, performance assessment criteria and characteristics of the TPL performance metrics are fully developed and available for use. Central to the TPL determination and the overall system evaluation process is the integrated techno-economic WEC system simulation as described by Teillant et al. [5] and Weber et al. [4] delivering combined WEC technology and wavefarm lifecycle performance criteria and overall economical metrics, as pointed out in section 2.

It is important to account for the fact that, when a WEC technology concept developed just to low TRL is refined and described in the detail of a high TRL system in form of the ConOps, in order to apply the TRL assessment, the magnitudes of system design, control and operation parameters are still to be defined and are variable. These circumstances require the inclusion of parameter variations, sensitivity analysis and overall integrated system optimisation into the assessment process of a technology, as included in the schematic visualisation in Fig. 7. A detailed example of such an integrated techno-economical system optimisation using the described tools is presented by Costello & Ringwood [9].

It is furthermore important to recognise that several of the detailed system description processes required for the TPL assessment are associated with TRL determination processes and criteria, as described in detail by Fitzgerald [1] and Fitzgerald & Bolund [2]. Thus, increasingly detailed TPL assessment processes will inevitably lead to a rise in TRL with respect to some of the TRL criteria.

Furthermore, as pointed out previously, a range of system properties are extremely difficult to simulate accurately and in order to increase the reliability of the TPL assessment, empirical evidence and experience from focused subsystem testing at appropriate scale will be required, when the level of confidence in the system properties is brought to a maximum.

Both of the above circumstances will bend the generic development trajectory in green in Fig. 3 to the realistic development trajectory in green in Figs. 6 and 7. In accordance with these observations Fitzgerald & Bolund [2] describe the TRL level as ”a measure of confidence that the required functionality can be successfully delivered”. At the same time these circumstances again emphasise the crucial importance and high quality of the integrated techno-economic simulation tools and the expert assessment methods to increase confidence and accuracy in the determination of the TPL at low TRL in order to postpone particularly the capital intensive components associated with high TRL levels.

The management, reduction and to a certain degree acceptance of uncertainty at low TPL levels is important and the initially low and moderate confidence levels at low TRL levels are no justification for not engaging into and advanced consideration and determination of integrated technology, economic and lifecycle system performance, as emphasised by Weber et al. [7]. It is acknowledged that due to the uncertainties encountered in the TPL determination at low TRLs the development trajectory may peak at particularly low, possibly up to intermediate TRLs and may reduce again when higher levels of confidence are

achieved at higher TRLs. It is therefore important to apply highest possible objectivity and a strictly diligent and conservative approach in the description, modelling and performance assessment of the projected mature high readiness system while still at the low TRL stage.

One essential aspect pointed out in the illustration in Fig.7 is the process of innovation alongside the evaluation (blue ellipse) in a development process targeting high TPL system solutions at low TRL levels.

Flexibility of system fundamentals at low TPL is a valuable and important ingredient to successful high TPL development and this flexibility must be reflected and capitalised in the development process.

Thus it is central to set up a concept and technology development approach that is originally concept independent covering a multitude of fundamental WEC hypotheses and technology implementations.

Such multi-, inter- or cross-conceptual development approaches must be applied not just to the system evaluation process but decisively also to the concept and technology innovation process.

A number of innovation techniques, such as morphologic analysis, are available and have traditionally been applied in design engineering. An overview of such design, invention and innovation methods is described by Pahl & Beitz [10] and Zwicky [11] and an engineering design application example of morphologic analysis is provided by Weber [12]. These techniques fall under the wider concept and Theory of Inventive Problem Solving (TIPS, also known as TRIZ) and have become increasingly established and embedded in industrial innovation processes and are supported by a variety of software packages. Gundlach & Nähler [13] provide an overview of concepts, tools and application examples including the one by B. Denne [14].

Such multi-conceptual problem solving techniques can make effective use of the diverse and multiple techno-economic performance criteria in their sub-function solution process. These multi-conceptual techniques are the counterpart on the innovation side to the multi-objective (MO) techniques on the system optimisation side. The circumstances around Pareto-optimality are discussed by Weber [8]. In this way the innovation process, the performance assessment process and the integrated system optimisation process all have the capability of delivering multiple (Pareto) optimal sets of solutions.

The application of innovative problem solving techniques to WEC innovation and development will be covered in a separate publication.

5. Conclusions

Technology Performance Levels have been established and identified as an effective metric for the quantification of economic performance of WEC systems. In combination with the Technology Readiness Levels the TRL–TPL–Matrix has been introduced and employed as a means for visualisation, evaluation and comparison of WEC technology development 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 viability of generic development trajectories has been discussed and two generic development domains, namely Research and Demonstration have been identified. These strongly distinguish themselves with respect to the ease and complexity of changes to system fundamentals. Based on a characterisation of the current WEC technology status worldwide and the consideration of alternative realistic development trajectories, a development approach following the guiding principle of "performance before readiness" has been proposed and found to deliver significant benefit over the state-of-the-art in relation to development time, cost, risk and resulting technology performance. Required tools and methods key to the implementation of such an improved development path have been identified; these primarily include:

- Technology performance assessment tools and related quantification metric TPL
- Integrated techno-economic system simulation and optimisation tools
- inter-conceptual technology development and innovation techniques

In summary and at the highest level, it is concluded that the key ingredients for successful and winning WEC technology development are:

- Mastery of objective, effective, sophisticated WEC performance assessment tools
- Effective value-for-money research technology development (RTD) with flexible system fundamentals at TRL 1 to 4
- Focused technology refinement, subsystem and integrated system demonstration with fixed system fundamentals at TRL 5 to 9
- Interactive, yet parallel and separate process threads and capability structures of research technology development (RTD) and engineering, procurement, construction (EPC)
- In RTD question fundamentals. Innovate and capitalise on knowledge gain
- In EPC rely on fundamentals. Implement and deliver

It is strongly felt that the described development approach, with the support of the relevant development and assessment tools, has the potential to deliver significant benefits to system development time, development cost and development risk as well as to the resulting development success in form of WEC systems attaining high Technology Performance Levels (TPL) at high Technology Readiness Levels (TRL), delivering economic performance at commercial readiness.

Independent of the number of wave energy development players the diversity in the wave energy technology is likely to reduce and focus around a multiple of high performance technology families. Thus, a consolidation of the industry can be expected. Additionally to the increasing competitiveness amongst wave energy technologies, competitiveness of wave energy technologies with other renewable energy technologies and energy technologies as a whole will become more relevant. It is hoped that an objective performance metric will be beneficial in guiding this consolidation and competition process.

Finally, finding the best research technology development trajectory clearly is an undeniably challenging optimisation problem in its own right.

Within the development process it is not always evident where the highest TPL gradient is pointing to when making crucial decisions on technology direction, engineering design implementation, operational strategy, development budget allocation, HR and expertise development, funding opportunity pursuit, corporate and strategic partnering and many more.

Furthermore, the ostensibly apparent local gradients of the achievement and opportunity planes spanned over the TRL-TPL coordinates may point towards rather different progression headings than the best research technology development trajectory to arrive at high economic performance commercial technology.

Indeed, depending on the fundamental definition of the objectives development trajectories can diverge considerably subject to the prioritisation of technology development or company development goals.

The author hopes that this paper will provide a contribution to improving WEC research technology development processes towards delivering higher performance technology outcomes.

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