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Cost, Time, and Risk Assessment of Different Wave Energy Converter Technology Development Trajectories

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Abstract—**This paper presents a comparative assessment of three fundamentally different wave energy converter technology development trajectories. The three technology development trajectories are expressed and visualised as a function of technology readiness levels and technology performance levels. The assessment shows that development trajectories that initially prioritize technology readiness over technology performance are likely to require twice the development time, consume a threefold of the development cost, and are prone to a risk of technical or commercial failure of one order of magnitude higher than those development trajectories that initially prioritize technology performance over technology readiness.**

Keywords—**Wave energy converter, technology development trajectory, development cost, development time, development risk, technology performance level, technology readiness level**

I. Introduction

To date, wave energy converter (WEC) technology development as a whole has not yet delivered the desired commercial maturity nor, and more importantly, the techno-economic performance. Both are required for commercial readiness and economic viability, respectively.

WEC technology developments can typically be described by the following features. They mostly are:

- Expensive; costing on the order of $100 million or more to get to technology readiness level (TRL) 9
- High risk; there have been setbacks in prototype tests with a premature focus on open-ocean technology demonstration
- Slow; from the start of development to TRL 9, the process has taken up to15 years and sometimes beyond
- Rigid; the initial WEC technology concept idea and associated intellectual property has been retained, thereby significantly limiting the potential success of the technology development process.

Some characteristic values of total development cost and time for five leading WEC technologies up to varying TRL stage (6-8) are provided in [1]. These support the above rough statements for full technology development to TRL 9. The reasons for these circumstances are plentiful and associated with the central technology development and design challenges that are specific to WEC technology development and fundamentally different to those of wind energy converter technology development. WEC technology development is characterized by the following circumstances:

- A large spectrum of diverse converter functional system concepts with no evidence of convergence even within the different operational domains (onshore, nearshore, and offshore)
- Time and cost-intensive permitting or environmental study requirements
- Strongly reduced market opportunity at reduced scales, with scale referring to the size of the machine and the wave farm
- Limited transferability of the technological experience, design, production, and operation of seemingly related industrial applications
- Expensive, delayed, and difficult access to operating systems (offshore) for repair and maintenance activities, prohibiting high failure rates from the onset of commercial operations
- Key system design loads are one to two orders of magnitude higher than high-power operational loads
- The global average incident energy flux density is on the order of a 10- to 30-kW/m wave crest width
- Reciprocating irregular, multidirectional wave load characteristics.

These circumstances require the implementation of technology development paths that are the most effective in terms of cost-, time, and risk.

For the identification of the technology development status of the development progress, appropriate metrics are required. Progress in technology readiness is well quantified by TRLs. Originating in aviation, space and defence industries, TRLs have also been established in wave energy technology development. In particular the TRL definitions by Fitzgerald [2] provide a detailed description of the technology readiness at the different development stages and have been widely adopted and applied in wave energy technology development.

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. For this purpose, the Technology Performance Levels (TPLs) have been introduced in [3]. 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 I.

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

In [3] and [4], the various ways in which WEC technology is being developed were analysed. Deficiencies with these approaches were recognized and fundamental requirements for successful WEC technology development were recognized. The fundamental decisions, priorities, and intermediate goals of the chosen technology development paths were identified as being of crucial importance to the required effort in terms of cost and time and to the encountered risk; and thus to the likelihood of development success. For the description of the technology development trajectories, the TRL and TPL, in the form of the TRL-TPL Matrix, as introduced in [3], is used and shown in Fig. 1.

The superiority of technology development trajectories that initially prioritise technology performance over technology readiness over those that initially prioritise technology readiness over technology performance, has previously been identified in [3] and [4] on the basis of qualitative considerations. The investigation presented in this paper considers three generic technology development trajectories and quantifies the technology development cost and time required as well as the encountered development risk to support these findings.

II. TECHNOLOGY DEVELOPMENT TRAJECTORIES

Three technology development scenarios and their associated technology development trajectories are considered here.

A. Trajectory Assumptions and Visualization

The technology development trajectories are represented as a function of TRL and TPL and visualised over the TRL-TPL Matrix as depicted in Fig. 1. For each technology development trajectory, it is assumed that the development starts at the coordinates (TRL, TPL) = (1,1) and finishes at the coordinates (TRL, TPL) = (9,9). Start and finish points are shown in Fig. 1.

This approach was chosen to capture the most complete technology development processes. It is clear that the TPL value of an early-stage WEC technology concept description at TRL 1 is subject to high uncertainty, possibly in the range of plus 3 to minus 3 TPL points. Furthermore, an early-stage TRL 1 WEC technology concept can be assumed to be of higher techno-economic performance potential than TPL 1. These circumstances are further elaborated in [1]. In the investigation of technology development trajectories presented here, we made the following assumption with respect to the start point of the development. The TPL value assumed—resulting from a TPL assessment—must reflect the minimal value within the uncertainty band considered for the relevant development stage and associated TRL value. This approach ensures that the considered TPL values are attainable, with reasonable reliability by the considered WEC technology. Thus, because of the high uncertainty of the TPL at TRL 1, it is not justified to assume a higher TPL value than TPL 1.

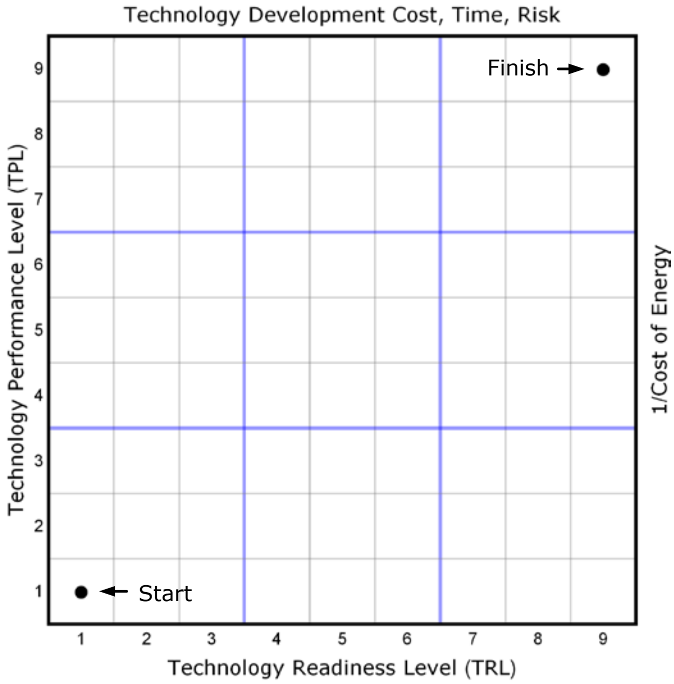

Fig. 1 Trajectory visualization over the TRL-TPL Matrix with the start and end point

With respect to the finish point of the technology development, the requirements for market entry are relevant. In [4], these requirements were defined as: attaining TRL 9 (i.e., full commercial readiness) and realizing a minimal value of TPL 7 to at least achieve economic competitiveness with other renewable energy sources operating under favourable market conditions. Again, in order to consider the most comprehensive and complete technology developments in this investigation, a TPL value of 9 (i.e., economic competitiveness with other energy sources without any support mechanisms) is assumed for the finish point of the WEC technology development process. The definitions and interpretations of the TPL values used in this work were first defined in [3] for the full TPL value range from 1 to 9.

To compose a complete technology development trajectory from (TRL, TPL) = (1,1) to (TRL, TPL) = (9,9), we assumed a continuous sequence of incremental integer steps of TRL and TPL along the technology development path. Each technology development stage is visualised with a marker in the TRL-TPL Matrix and a connecting line between the markers represents the considered technology development trajectory. For each technology development stage, we assumed the associated development activities and the related effort in the form of development cost and time. These development activities are a function of the maturity of the technology and thus of the attained TRL value. For this investigation, we assumed a slight variation of the technology development activities and related efforts in the form of cost and time as defined in [2].

In the following subsections, we present the three generic and fundamentally different technology development trajectories that are considered in this investigation.

B. Trajectory 1 – Conventional

The first technology development trajectory, depicted in Fig. 2, is characterised by a development that first concentrates on the maturation of the technology by increasing the TRL and subsequently thrives to improve the techno-economic performance by increasing the TPL at high TRL. This case reflects the circumstances that WEC technology developments have traditionally been driven principally by TRL, as increasing maturity has been associated with access to increased public and private funding. Furthermore, TRL was regarded as a suitable metric for identifying the value of a technology under development. This technology development trajectory is referred to as Trajectory 1 (T1) – Conventional. The challenges associated with this development approach are further discussed in [3], [4], and subsequently in [1].

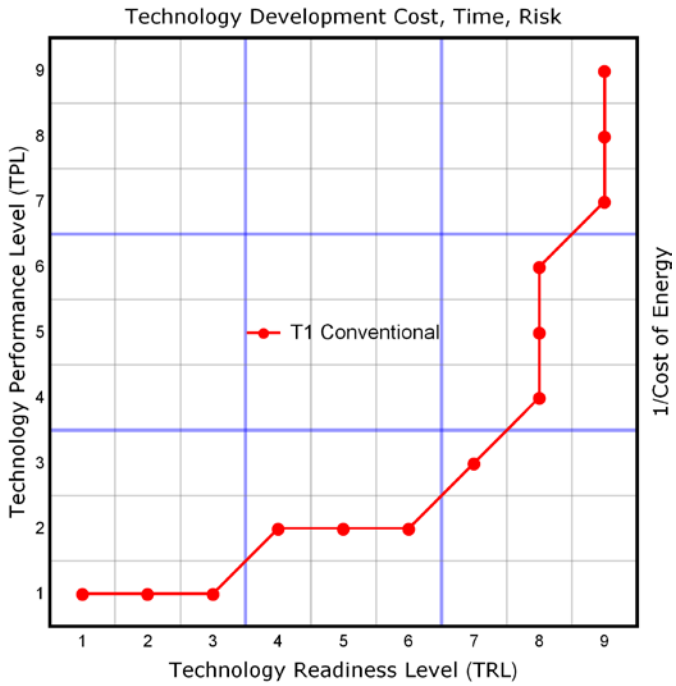

Fig. 2 Conventional development trajectory over the TRL-TPL Matrix

C. Trajectory 2 – Alternative

The technology development characterised by the second trajectory can be considered as an inverse approach to the technology development described by T1 – Conventional. Initially, the development focuses on a rise of the techno-economic performance potential by increasing the TPL. This process is followed by a maturation of the technology by increasing the TRL while maintaining high TPL values.

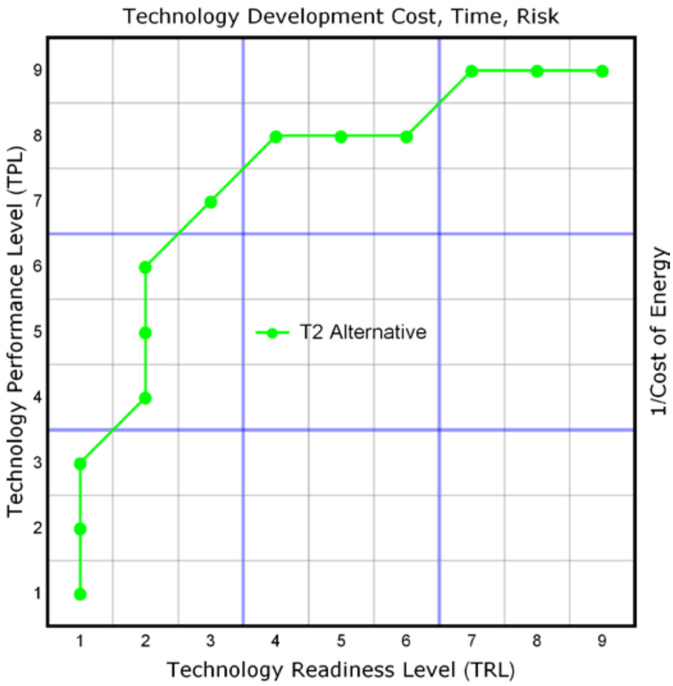

Fig. 3 Alternative development trajectory over the TRL-TPL Matrix

This trajectory is depicted in Fig. 3 and is referred to as Trajectory 2 (T2) – Alternative. In previous considerations alluded to in [3], [4], and subsequently in [1], the trajectory T2 – Alternative was identified as superior to trajectory T1 – Conventional, with respect to development cost, time, risk, and the associated development success or more likely technical, commercial, or corporate failure of trajectory T1 – Conventional. However, these differences between the two development approaches have yet to be quantified, which is the goal of this investigation.

D. Trajectory 3 – Combined

Finally, a technology development trajectory that is composed of portions of T1 – Conventional and T2 – Alternative is considered. In this approach, the development starts out with the maturation of the technology by increasing the TRL and subsequently aiming to grow the techno-economic performance by increasing the TPL; however, after reaching the development stage (TRL, TPL) = (8,5), further development progress towards a higher TPL is assumed as not possible with the considered WEC technology.

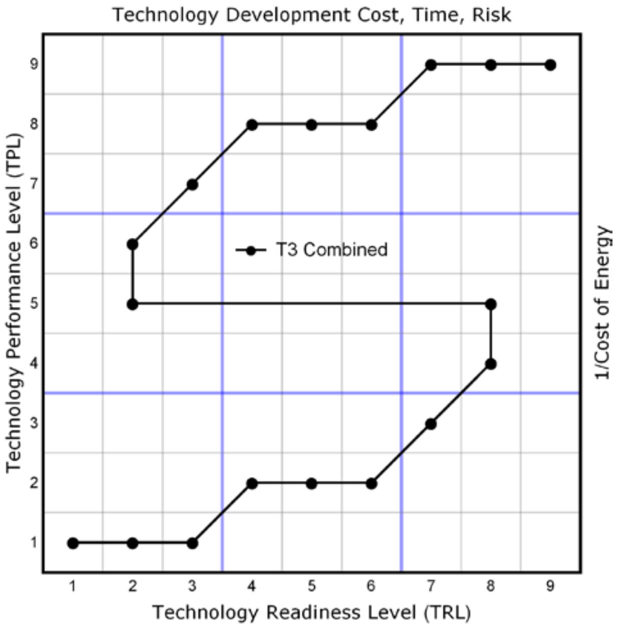

Fig. 4 Combined development trajectory over the TRL-TPL Matrix

This inability may be associated with the challenges of implementing the remaining "vertical" technology development path towards market entry (i.e., the required development cost, time, or risk), or may be a result of the fundamental limitations of the WEC technology concept. Thus, it is assumed that the WEC technology developer abandons this technology, and engages in the development of an alternative WEC technology concept that achieves the TPL value similar to the value at which the previous technology development ended. This alternative technology concept is assumed to be immature and at a TRL 2. Subsequently, this alternative technology concept is developed in accordance with trajectory T2 – Alternative, to achieve market entry requirements. This combined development trajectory is referred to as Trajectory (T3) – Combined, and is depicted in Fig. 4. In many cases, the technology developers, except in very few instances, have not been in a position to make fundamental changes to the WEC technology concept, or exchange the WEC technology concept entirely, as their business models have been too deeply committed to the original WEC concept idea and to the related intellectual property.

III. Technology Development Cost

The technology development cost is assumed to be a sole function of the TRL, as the techno-economic performance potential in terms of TPL is not directly related to the development cost. For each TRL development stage and associated development activity, a cost burden, ranging from $10,000 for the formulation and description of an early-stage technology concept at TRL 1 to $30 million for the design, build and operation of the precommercial WEC array of three devices, is allocated. The full range of cost estimates for the activities at each TRL is listed in Table II. These values are closely related to those specified in [2].

TABLE II
Technology development cost in $million for a given technology development activity as a function of TRL

TRL	Cost [$ m]
1	0.01
2	0.05
3	0.5
4	1.0
5	3.0
6	5.0
7	10.0
8	15.0
9	30.0

To determine the total cost of each technology development case, the individual cost contributions of all development stages are integrated along each of the development trajectories. Table III provides the total development costs for each of the three technology development trajectories.

TABLE III
Total technology development cost in $million for each technology development trajectory

Trajectory	Cost [$ m]
T1 – Conventional	155
T2 – Alternative	65
T3 – Combined	114

IV. Technology Development Time

Equally, the technology development time is assumed to be a sole function of the TRL, as the techno-economic performance potential in terms of TPL is not directly related to the development time. For each TRL development stage and the associated development activity, an expenditure of time, ranging from 0.05 years for the formulation and description of an early-stage technology concept at TRL 1 to 3 years for the design, build and operation of the precommercial WEC array of three devices at TRL 9, is allocated. The full range of time estimates for the activities at each TRL is provided in Table IV. Again, these values are closely related to those specified in [2].

TABLE IV
Technology development time in years for a given technology development activity as a function of TRL

TRL	Time [yr]
1	0.05
2	0.3
3	0.7
4	1.0
5	1.5
6	1.5
7	2.0
8	2.0
9	3.0

To determine the total development duration of each case, the individual time contributions of all development stages are integrated along each of the development trajectories. Table V juxtaposes the total development durations for each of the three technology development trajectories.

TABLE IV
TOTAL TECHNOLOGY DEVELOPMENT TIME IN YEARS FOR EACH TECHNOLOGY DEVELOPMENT TRAJECTORY

Trajectory	Time [yr]
T1 – Conventional	22
T2 – Alternative	13
T3 – Combined	23

V. TECHNOLOGY DEVELOPMENT RISK

The assessment of risk and its aggregation over a complete technology development trajectory is less obvious than the assessment of cost or time, as the risk of a particular development activity depends on the activity itself and the degree to which this risk has been retired because of previous and relevant development activities. Thus, the assessment of the development risk is conducted according to the following set of assumptions and rules:

- The risk of each development activity is regarded as the product of likelihood and severity.
- Both the development time and cost are quantities that are related to the risk severity. Here, we use the product of development time and cost as a measure for the risk severity.
- The likelihood of a certain development activity to be considered a failure depends on two factors. First, it depends on the likelihood of this activity to be considered a failure when conducted in isolation (i.e., no other related development activity was conducted prior to the considered activity). Second, it depends on the way in which previous, related, and relevant development activities have reduced or significantly retired the risk of the considered activity to be a failure when conducted in isolation.
- The likelihood of a certain development activity to be a failure when conducted in isolation is regarded to be a sole function of TRL, as the techno-economic performance potential in terms of TPL is not directly related to the development risk.
- Each previous development activity related to and relevant to a given development activity is assumed to reduce (by half) the likelihood of the considered development activity to be a failure, when conducted in isolation.
- Development activities that are conducted prior to the considered development activity and are for a similar system type and quality, with respect to TPL (that is of the same TPL, one TPL point lower, or one TPL point higher), to the system undergoing the considered development activity, are regarded as being related and relevant to the considered development activity, thereby reducing (by half) the likelihood of the considered development activity to be a failure, when conducted in isolation.

Table VI lists the quantities that are required for estimating the risk of isolated development activities as a function of the technology maturity in terms of TRL. These quantities include the development cost, time, risk severity (in $ million years [$ m yr]), likelihood of the risk of the considered development activity to be a failure when conducted in isolation (solo), and finally the risk (in $ million years ([$ m yr]) of the considered development activity to be a failure when conducted in isolation (solo).

TABLE VI
TECHNOLOGY DEVELOPMENT RISK-RELATED QUANTITIES FOR EACH TECHNOLOGY DEVELOPMENT ACTIVITY AS A FUNCTION OF TRL

TRL	Cost [$ m]	Time [yr]	Severity [$ m yr]	Likelihood (Solo) [-]	Risk (Solo) [$ m yr]
1	0.01	0.05	0.0005	0.9	0.0005
2	0.05	0.3	0.015	0.9	0.0135
3	0.5	0.7	0.35	0.9	0.315
4	1.0	1.0	1.0	0.9	0.90
5	3.0	1.5	4.5	0.9	4.05
6	5.0	1.5	7.5	0.9	6.75
7	10.0	2.0	20.0	0.9	18.0
8	15.0	2.0	30.0	0.9	27.0
9	30.0	3.0	90.0	0.9	81.0

In Tables VII–IX, the three technology development trajectories are analysed with respect to the occurrence of each development stage based on the TRL and number of risk reductions by a factor of ½ for each of the occurrences and for the entire development (i.e., for the complete range of TRL). The maximal occurrence of a given TRL in each of the development scenarios is three, thus the three columns (two, three, and four) are required in each of the three tables. Thus, the number in these three columns are the number of related and relevant previous development activities that each lead to a reduction by a factor of ½. The total encountered risk at each of the TRLs, considering the occurrence of the associated development stage and the relevant risk reductions by a factor of ½, is listed in column five.

TABLE VII
TECHNOLOGY DEVELOPMENT RISK REDUCTIONS BY FACTOR OF ½ AND RISK CONTRIBUTIONS AS A FUNCTION OF TRL FOR TECHNOLOGY DEVELOPMENT TRAJECTORY T1 – CONVENTIONAL

TRL	Risk Reductions [-]	Risk Reductions [-]	Risk Reductions [-]	Risk [$ m yr]
1	0	–	–	0.0005
2	1	–	–	0.0068
3	2	–	–	0.0788
4	3	–	–	0.1125
5	4	–	–	0.2531
6	5	–	–	0.2109
7	3	–	–	2.2500
8	1	1	1	40.500
9	1	1	1	121.50

TABLE VIII
TECHNOLOGY DEVELOPMENT RISK REDUCTIONS BY FACTOR OF ½ AND RISK CONTRIBUTIONS AS A FUNCTION OF TRL FOR TECHNOLOGY DEVELOPMENT TRAJECTORY T2 – ALTERNATIVE

TRL	Risk Reductions [-]	Risk Reductions [-]	Risk Reductions [-]	Risk [$ m yr]
1	0	1	1	0.0010
2	1	1	1	0.0203
3	1	–	–	0.1575
4	1	–	–	0.4500
5	2	–	–	1.0125
6	3	–	–	0.8438
7	3	–	–	2.2500
8	4	–	–	1.6875
9	5	–	–	2.5313

TABLE IX

TECHNOLOGY DEVELOPMENT RISK REDUCTIONS BY FACTOR OF ½ AND RISK CONTRIBUTIONS AS A FUNCTION OF TRL FOR TECHNOLOGY DEVELOPMENT TRAJECTORY T3 – COMBINED

TRL	Risk Reductions [-]	Risk Reductions [-]	Risk Reductions [-]	Risk [$ m yr]
1	0	–	–	0.0005
2	1	0	1	0.0270
3	2	1	–	0.2363
4	3	1	–	0.5625
5	4	2	–	1.2656
6	5	3	–	1.0547
7	3	3	–	4.5000
8	1	1	4	28.688
9	5	–	–	2.5313

Thus, the risk analysis for the development trajectories T1 – Conventional, T2 – Alternative, and T3 – Combined, are represented in Tables VII, VIII, and IX, respectively. Finally, the risk contributions at all TRLs (column five in Tables VII, VIII, and IX) are totalled to determine the overall encountered risk for each of the three technology development trajectories (listed in Table X).

TABLE X

TOTAL TECHNOLOGY DEVELOPMENT RISK IN $ MILLION YEARS FOR EACH TECHNOLOGY DEVELOPMENT TRAJECTORY

Trajectory	Risk [$ m yr]
T1 – Conventional	165
T2 – Alternative	9
T3 – Combined	39

VI. DISCUSSION AND CONCLUSION

To provide an overview of the three technology development scenarios, the associated three trajectories T1 – Conventional, T2 – Alternative, and T3 – Combined are displayed together over the TRL-TPL Matrix in Fig. 5. Trajectory T3 – Combined is displayed in a slightly shifted manner to provide a clear visualization.

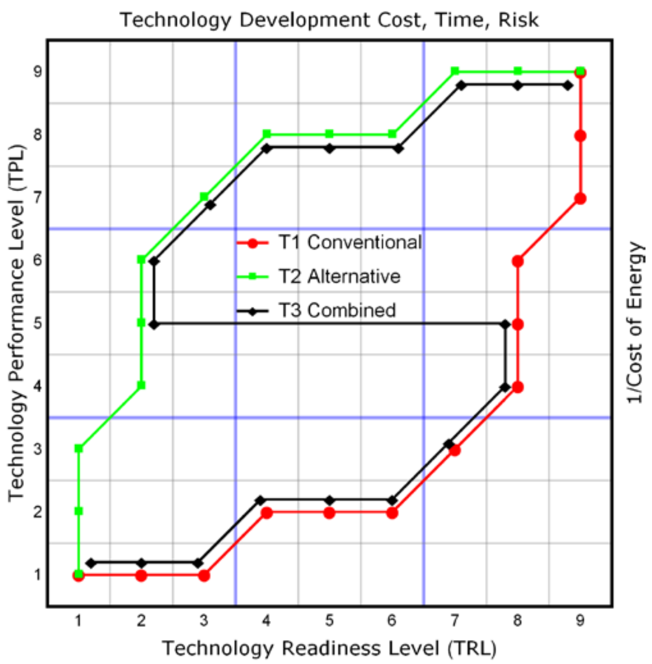

Fig. 5 All three technology development trajectories: T1 – Conventional, T2 – Alternative, and T3 – Combined are shown over the TRL-TPL Matrix; T3 – Combined is slightly shifted to provide a better visualization

TABLE XI

TOTAL TECHNOLOGY DEVELOPMENT COST, TIME, AND RISK FOR EACH TECHNOLOGY DEVELOPMENT TRAJECTORY

Trajectory	Cost [$ m]	Time [yr]	Risk [$ m yr]
T1 – Conventional	155	22	165
T2 – Alternative	65	13	9
T3 – Combined	114	23	39

Table XI combines the final results of the analysis of development cost, time, and risk for T1 – Conventional, T2 – Alternative, and T3 – Combined.

A. Technology Development Cost

The total technology development costs of each of the three technology development scenarios differ significantly, ranging between $65 and $155 million. T2 – Alternative is superior and requires just 42% of the development cost of T1 – Conventional. Trajectory T3 – Combined requires intermediate development funds at a level of 74% of T1 – Conventional.

The resulting overall range of the technology development costs of the three generic scenarios can be regarded as realistic and reasonably supported by actual WEC technology development data from the industry, when public domain figures are considered. For example, some characteristic values of the development cost for five leading WEC technologies (OPD Pelamis, Aquamarine Oyster, OPT PowerBuoy, Oceanlinx, Carnegie CETO) developed up to varying TRL stages (6–8) are provided in [1]. This data is in approximate agreement with the above range of total development time to full precommercial maturity at TRL 9, when considering the estimations of the remaining development cost to reach TRL9 and TPL 9 and that TRL 8 and TRL 9 have estimated cost contributions of $15 and $30 million, respectively.

Reflecting on the superiority of T2 – Alternative and considering the required cost in the different phases of development, it is evident that a technology developer could easily fund a number of technology development trajectories with a TRL of 4 or below. This approach could maximize the TPL over a number of WEC technology concepts prior to maturing the chosen technology through the cost-, time-, and risk-intensive higher TRL activities in order to achieve commercial readiness and economic competitiveness, thus satisfy the requirements for market entry.

B. Technology Development Time

The total technology development time of the three trajectories also differs significantly, ranging from 13 to 23 years. Once again, T2 – Alternative is superior and requires just 59% of the development time of T1 – Conventional and 57% of the development time of T3 – Combined. The overall range of the technology development times of the three trajectories mirrors the actual durations when reflecting on the encountered durations of the developers that have achieved a high technology maturity of TRL 7–8 while attaining an intermediate techno-economic performance of a TPL of 4–5. For example, some characteristic values of the development time for five leading WEC technologies (OPD Pelamis, Aquamarine Oyster, OPT PowerBuoy, Oceanlinx, Carnegie CETO) developed up to varying TRL stages (6–8) are provided in [1]. This data is in approximate agreement with the above range of total development time to precommercial maturity at TRL 9, when considering the estimations of the remaining development time to reach TRL9 and TPL 9 and that TRL 8 and TRL 9 have estimated time requirements of 2 and 3 years, respectively

A further practical example is provided in [5] for the WaveStar technology that required about 12 years to complete TRL 8 and reached a total development time of 16 years. Assuming the achievement of an estimated TPL 4 or 5 of the development of WaveStar, the remainder of T1 – Conventional to (TRL, TPL) = (9,9) would require significant additional time. This supports the estimate of the total time requirement for T1 – Conventional of 22 years as listed in Table V. Another example is the Wavebob technology [6]. Sea trial at ¼-scale were conducted after 7 and 9 years. The development ended after 14 years at approximately TRL 6. Again, time estimations of the remainder of trajectory T1 – Conventional lead to significant durations supporting the above analysis. Another ten examples of Danish WEC technology development and required times are provided in [7]. The development times and achieved development stages varies from 3–19 years and TRL 6–8, respectively. Again, most development times support the estimated derived in this analysis, assuming the technologies achieved low to intermediate TPLs.

Furthermore, in practice, it is reasonable to assume that the completion of the generic trajectory T1 – Conventional is difficult or even unrealistic, as it requires three TRL 8 and three TRL 9 activities to achieve (TRL, TPL) = (9,9). The associated time and cost requirements represent a significant burden and the required public and private investment is challenging to obtain. Thus, many developments that follow T1 – Conventional are likely to come to a halt approximately at stage (TRL, TPL) = (8,5). This phenomenon is also further alluded to in [1], [3].

The cost and time estimations presented here consider representative continuous developments without the omission of intermediate technology development steps. The implementation of trajectories at the upper end of the range of the development time estimates may be less likely to implement as it represents considerable corporate challenges.

In practice, it can be assumed that multiple development activities can be conducted in parallel but also that most stages will be covered multiple times, thereby allowing research and development interactions. These circumstances will lead to deviations of actual durations from the development times determined in this analysis.

It is important to note that the technology development trajectory T3 – Combined requires the highest amount of development time. This signifies that the decisions made during the early stages of development regarding the technology direction and chosen trajectory are crucial to the overall duration, even when significant rectifications of the trajectory are conducted along the way.

C. Technology Development Risk

The results of the technology development risk assessment show substantial differences. The total encountered risks of the three technology development scenarios vary beyond one order of magnitude, ranging between \$9 and \$165 million years. T2 – Alternative is by far superior of the three and the technology development is only subject to 5% of the total technology development risk encountered during the development along T1 – Conventional. During the development along T3 – Combined, a total risk of 24% of the total development risk along T1 – Conventional is encountered. These results emphasize the significance of the chosen technology development route with respect to the likelihood of technical, commercial, and corporate success of WEC technology development and are crucial in the strategic decision-making of WEC technology developers (and particularly for start-up companies).

The assessment of technology development risk considers the likelihood and severity of risk as well as the effect of reducing or retiring risk on a continuous technology development trajectory. This reduction or retirement of risk is essential and these circumstances are apparent through the observation that the risk of a single and isolated TRL 9 activity (see Table VI) is one order of magnitude higher than the total risk encountered along T2 – Improved. This outcome reflects reality and underpins the importance of a sequential and incremental development path in which previous, faster, and more affordable development stages are related and relevant to subsequent development stages to effectively reduce and retire development risk along the development path.

The likelihood of the risk of a considered development activity to be a failure when conducted in isolation is assumed to be high and set to 90% for all TRL development stages. This value may initially appear as being too high, however, it is realistic when analysing a number of WEC technology developments, while considering the applied scrutiny (or the lack thereof) with respect to the sequencing of development stages, resulting development steps, and the encountered failures of individual development stages. It is important to note that the overall conclusions of this investigation of development risk are primarily associated with the relative results, rather than the absolute values, and are not fundamentally affected by the choice of the risk of a considered development activity to be a failure when conducted in isolation.

D. Summary

The advantages of WEC technology developments along trajectory T2 – Alternative over developments along trajectories T1 – Conventional and T3 – Combined are substantial with respect to technology development cost, time, and particularly encountered risk. This superiority of technology development trajectories that initially prioritise technology performance over readiness (T2 – Alternative) over those trajectories that initially prioritise technology readiness over performance (T1 – Conventional) was first identified in [3] and [4]. That assessment was based on qualitative considerations and included strategic development criteria associated with the requirements and opportunities of fundamentally different development domains, such as early stage research versus large-scale prototype demonstration. In the work presented in this article the technology development cost, time, and encountered risk of the three generic technology development trajectories, considered here, has been evaluated in a quantitative way. This quantitative assessment supports and confirms the previous findings that were based on qualitative considerations.

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