Successful innovation strategies to overcome the technical challenges in the development of wave energy technologies

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Pablo Ruiz-Minguela, Jesus M. Blanco, Vincenzo Nava

Abstract— **The process of designing wave energy technologies is complex and time-consuming, involving many decisions. Despite numerous wave energy concepts being developed in the last 30 years, none have reached commercial readiness due to unresolved technical challenges and high costs in comparison to other renewable energy sources. To address the wave energy industry's high aspirations, this research proposes a systematic problem-solving approach based on sound Systems Engineering methods from the outset of technology development. Quality Function Deployment (QFD) is used for problem formulation and selection, ensuring the traceability of requirements. The Theory of Inventive Problem Solving (TRIZ) is used for concept generation, providing efficiency and predictability by exploring a vast solution space. This approach has identified the top-five Inventive Principles to overcome the most critical technical challenges for wave energy technologies in the utility-scale market. Promising concepts are also suggested for each Inventive Principle. While the current research does not focus on a specific concept, this approach provides a structured way to assess the potential of innovative archetypes holistically.**

Keywords—**Wave Energy, Systems Engineering, QFD, TRIZ, Technical Contradictions, Inventive Principles.**

I. Introduction

INCREASING the share of electricity generation from renewable sources is a key pathway to achieving a fully decarbonised energy system and thus fighting climate change [1]. Wave energy is an abundant and powerful resource but at the same time, the least developed of all renewable energy technologies [2]. It is discouraging that despite the international research community's considerable efforts over the last decades, wave energy technologies have once and again failed to achieve the desired design convergence to support their future market growth [3].

Many technical challenges remain unresolved, leading to high costs of energy in comparison with other renewable energy sources [4]. This is particularly important for utility-scale generation, the most attractive market for wave energy technologies [5]. According to the ocean energy industry and research professionals, the most pressing improvements needed to reduce costs in the coming years are power performance, reliability, availability, maintainability and survivability [6].

Traditional methods, which primarily focused on evaluating technology maturity, have been insufficient to ensure that wave energy systems achieve their technical, economic and social aims [7]. It becomes apparent that incremental innovation alone cannot fill the gap between the current techno-economic estimates and the medium-term policy targets established for wave energy [8].

Instead, a systematic problem-solving approach must be embedded from the outset of technology development to meet the high sector expectations [9]. This approach should support the engineering design processes, facilitate traceability of engineering analysis, and provide practical tools for understanding the wave energy context, formalising wave energy system requirements, guiding techno-economic design decisions and overcoming technical challenges.

Several industrial sectors have effectively employed Systems Engineering methods to develop complex commercial products [7]. Among the many tools developed in Systems Engineering, it is worthwhile mentioning two structured innovation techniques: Quality Function Deployment (QFD) for problem formulation and selection [10]; and the Theory of Inventive Problem Solving (TRIZ) for concept generation [11]. Searching for solutions is a constructive and creative step in Systems Engineering. Its purpose is to develop solution variants appropriate to the level of detail in each design phase, from the results obtained during the problem definition [12]. The inherent problem difficulty (or size of the solution space) depends on the ratio of possible variants and the number of acceptable solutions that might exist [13].

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Unfortunately, the potential for Systems Engineering tools in wave energy has not been fully utilised yet.

In this paper, we have applied QFD to obtain the prioritisation of the technical characteristics that may offer the greatest impact to the overall design for a wave energy system starting from the technology-agnostic assessment of wave energy capabilities performed in [9] for the problem formulation and concept selection. Further, we employed the TRIZ approach to problem-solving to bring efficiency and predictability into the process in order to investigate the large solutions space to explore in wave energy.

As a result of the application of System Engineering techniques, we identified the top-five Inventive Principles that can be used to overcome the most critical technical challenges faced by wave energy technologies for the utility-scale market. Furthermore, for each of these Inventive Principles, promising concepts worth exploring are also suggested.

The rest of the paper proceeds as follows. Section II presents the specific methods and tools used in this research. Section III derives the prioritisation of inventive principles when multiple technical parameters simultaneously conflict. Section IV analyses the three most impactful contradictions and corresponding inventive principles as a way to identify promising concepts worth exploring. Section V draws some conclusions. Finally, the Appendix presents several tables for the reader's convenience, including the list of requirements, and TRIZ 39 technical parameters and 40 inventive principles.

II. Methodology

To address the high aspirations of the wave energy industry, this research proposes a systematic approach from the outset of technology development that ensures traceability of requirements, creates fair performance assessments and applies sound innovation strategies to overcome the remaining technological challenges.

The specification of requirements establishes the agreement of the technical capabilities and levels of performance required for the wave energy system to achieve its mission and objectives within a prescribed solution space [14]. Requirements that bind a solution space are hierarchical and interrelated.

The common evaluation framework developed in [9], based on sound Systems Engineering principles is adopted in this work. It encompasses the external context, system requirements and evaluation criteria. QFD is used to produce traceable mappings between the environmental, stakeholder, functional and technical domains as represented in Figure 1. Information is presented systematically to encourage the search for solutions and make it easier to recognise and combine fundamental solution characteristics [15].

Wave energy drivers are an essential part of the context where the wave energy system operates. System Drivers (SDs) are exogenous forces outside the system boundaries that can constrain, enable or alter the design solution [16]. Besides, Stakeholder (SH) identification is vital to achieving an effective system. A survey of wave energy representatives was conducted to establish the importance ranking of SDs and SHs for a utility-scale generation.

The Stakeholder Requirements (SRs) are translated into several prioritised Functional Requirements (FRs) and Technical Requirements (TRs) that the wave energy system should meet. This way, the functional analysis produces a complete and unambiguous definition of the design problem space, avoiding quantum leaps from the initial specification to the physical embodiment.

TRs are then mapped to the design parameter space. Design Parameters (DPs) are used in Axiomatic Design [17] to characterise the physical attributes of a system. DPs are selected so they are independent of one another and are defined at the same level of abstraction as FRs. To avoid, as far as possible, coupled designs, the same number of DPs and FRs was considered. Table I (next page) presents the outcome of this mapping.

The list of SRs and TRs derived in [9] is shown in Tables A.I and A.II of the Appendix. The QFD matrix

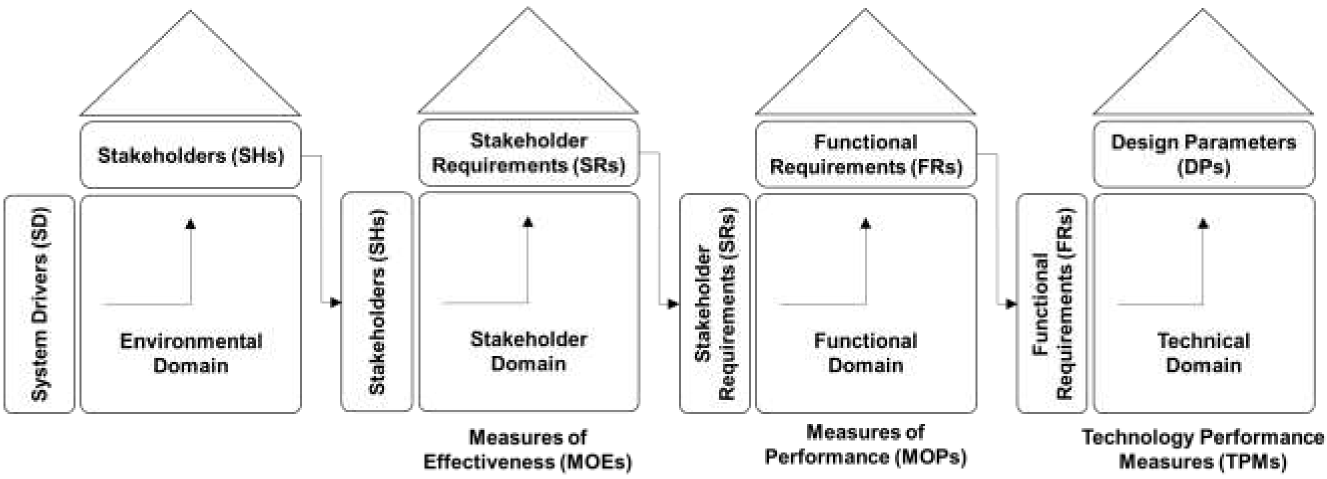


Fig. 1. Approach to building Wave Energy System Requirements.

with the relationship between FRs and DPs for the utility-scale generation market is presented in Table II.

TABLE I
MAPPING OF TECHNICAL REQUIREMENTS (TRS) TO DESIGN PARAMETERS (DPS)

Id	Design Parameters	Technical Reqmts
DP1	Area of moving object	TR1, TR23
DP2	Strength	TR2, TR10, TR20
DP3	Duration of action by moving object	TR8
DP4	Loss of energy	TR5, TR7
DP5	Loss of time	TR11, TR12, TR13
DP6	Quantity of substance	TR15, TR16, TR18
DP7	Adaptability	TR3, TR9, TR21
DP8	Device complexity	TR4, TR6
DP9	Difficulty of detecting and measuring	TR22
DP10	Productivity	TR14, TR17, TR19

Once the critical system properties are established in the form of wave energy system requirements, evaluation criteria are assigned to offer a credible means by which to assess various design options. Metrics linked to the SRs are usually referred to as Measures of Effectiveness (MOEs). Measures of Performance (MOPs) are used to gauge the FRs of a design solution, whilst Technical Performance Measures (TPMs) are used to demonstrate the successful delivery of the TRs. This hierarchy of evaluation criteria ensures a holistic assessment that captures different levels of detail and granularity in the metrics. Technology developers can use the assessment results to pinpoint showstoppers, performance barriers, and innovation needs.

In this work, we employ the structured innovation approach to problem-solving represented in Figure 2. TRIZ transforms the current problem into an existing conceptual problem. From that point, a generic solution that removes the conflicts is identified and customised to the specific situation. Hence, the conventional trial-and-error method based on expert judgement and achieving a compromise is substituted by the TRIZ inventive thinking based on identifying contradictions, applying inventive principles and translating suggested solutions into new concepts.

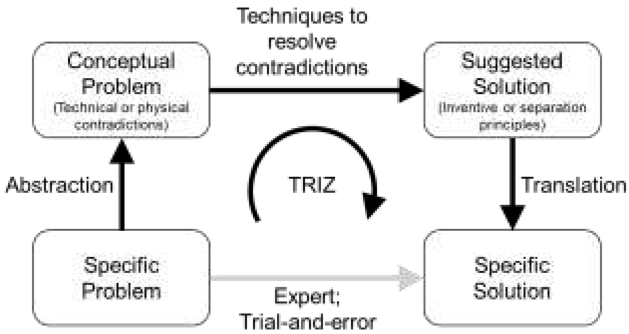


Fig. 2. The TRIZ approach to problem-solving.

The TRIZ approach to problem-solving provides a predictable technique to deal with problems based on past knowledge and proven principles, bringing efficiency into the process [13].

TRIZ is an algorithmic approach based on three main steps.

Step 1: Find technical and physical contradictions. Technical contradictions arise when there is a conflict between two different technical parameters (i.e. when one feature improves, another worsens). Physical contradictions happen when the same technical parameters conflict (i.e. they require opposite solutions). The 39 Technical Parameters [11] designate features or functions common to all engineering systems.

Step 2: Look for the corresponding Inventive Principles (IPs). The contradiction matrix is utilised to solve technical contradictions between two different technical parameters. This matrix identifies which of the 40 Inventive Principles [18] are relevant to the specific problem. For diagonal terms, that is when the same technical parameters enter into conflict, a physical contradiction exists, and separation principles are applied.

TABLE II
FUNCTIONAL REQUIREMENTS (FRS) TO DESIGN PARAMETERS (DPS)

			DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10
	Functional Requirements	Prioritisation	Area of moving object	Strength	Duration of action	Loss of energy	Loss of time	Quantity of substance	Adaptability	Device complexity	Difficulty of detecting	Productivity
FR1	Capture energy from waves	13.1%	0.26	0.26	0.00	0.09	0.00	0.09	0.26	0.00	0.03	0.00
FR2	Transform into useful energy	10.1%	0.00	0.11	0.00	0.32	0.00	0.04	0.11	0.32	0.11	0.00
FR3	Deliver energy to point of consumption	8.5%	0.00	0.05	0.00	0.41	0.00	0.14	0.00	0.41	0.00	0.00
FR4	Maximise total uptime	9.3%	0.00	0.31	0.31	0.00	0.03	0.00	0.31	0.03	0.00	0.00
FR5	Minimise total downtime	11.3%	0.00	0.00	0.05	0.14	0.41	0.05	0.05	0.05	0.14	0.14
FR6	Manufacture by industrial processes	9.0%	0.10	0.10	0.10	0.00	0.00	0.30	0.00	0.10	0.00	0.30
FR7	Install/retrieve by service vessels	6.5%	0.13	0.00	0.00	0.00	0.04	0.39	0.00	0.04	0.00	0.39
FR8	Maintain by service vessels	8.8%	0.09	0.00	0.09	0.00	0.09	0.27	0.00	0.09	0.09	0.27
FR9	Survive the harsh environment	13.9%	0.09	0.28	0.03	0.00	0.00	0.00	0.28	0.03	0.28	0.00
FR10	Avoid risks to receptors	9.7%	0.53	0.00	0.00	0.18	0.06	0.00	0.00	0.00	0.18	0.06
	Total	**100%**	**12.4%**	**12.6%**	**5.5%**	**11.1%**	**6.6%**	**10.8%**	**11.8%**	**10.0%**	**9.4%**	**9.7%**

Step 3: Select and apply one of the suggested principles. Both physical and technical contradictions can be solved with the 40 Inventive Principles.

Tables A.III and A.IV in the Appendix present the list of the standard 39 Technical Parameters and 40 Inventive Principles considered in the TRIZ method.

III. PRIORITISATION OF INVENTIVE PRINCIPLES

The contradiction matrix [11] is a useful tool to identify the IPs that solve one technical contradiction (i.e. a pair of technical parameters in conflict). However, in most engineering problems, it is common that several improving and worsening features to happen at the same time [19]. Moreover, applying TRIZ to solve a single contradiction may lead to a local optimum, which TRIZ theory calls “local ideality” [13]. When multiple technical parameters simultaneously conflict, a different approach must be implemented to improve TRIZ's innovation potential.

In 2004, Ivashkov and Souchkov [20] noticed that IPs could be ranked according to their number of appearances in the contradiction matrix. Those principles appearing most frequently will have a better chance in overcoming the design challenges. To improve a positive feature, a ranking of inventive principles was built by counting the frequency they are mentioned in the same row of the technical parameters. Later on, Bonnema [21] added an alternative ranking by counting the frequency of IPs mentioned in the same column of the technical parameter, in this case, aiming to minimise the impact of a worsening feature. This is an interesting use of TRIZ at early design stages when the specific analysis of the system capabilities is lacking.

Other authors such as [22] and [23], have established the priority of TRIZ IPs from the system analysis of Design Parameters (DPs). They identify the most critical contradictions in the engineering system and assign a weighting to each pair of conflicts using dissimilar approaches. Next, they rank the corresponding TRIZ IPs from the contradiction matrix. Moreover, [19] presents an example of the ranking of IPs involving two improving features and two worsening features which have been assigned weights.

Having applied QFD to create a traceable prioritisation from SRs to DPs, now the weightings in Table II can be used to rank the IPs having the most significant impact on the initial requirements. It is important to note that the DPs have been defined by mapping the TRs to a subset of the 39 Technical Parameters in TRIZ for convenience.

Two different rankings can be created. When the aim is to improve a positive feature (i.e. DP), the weightings for the IPs, W_{k+}, are computed as follows:

$$W_{k+} = \sum_{j=1}^{10} w_j \sum_{i=1}^{10} k_{ij} w_i \qquad k_{ij} = 1 \; if \; IP_k \neq 0 \tag{1}$$

where w_i is the DP weight in row i, w_j is the DP weight in column j, and k_{ij} is a non-zero value when the IP_k is suggested in the contradiction matrix for the combination of design parameters DP_{ij}.

Table III presents the ranking of inventive principles for solving technical contradictions in the utility market when the aim is to improve a positive feature (or DP). Only the top 10 principles are shown. The number of repetitions (Times) in the rows of the contradiction matrix and the corresponding importance (W_{k+}) are also included.

TABLE III
TOP-10 INVENTIVE PRINCIPLES FOR THE UTILITY MARKET – IMPROVING A POSITIVE FEATURE

IP	Inventive Principles	Times	W_{k+}	Rank
10	Prior useful action	17	16.1%	1
28	Replacement of the mechanical working principle	11	11.5%	2
15	Dynamism	11	10.7%	3
29	Pneumatic or hydraulic constructions	11	10.2%	4
13	Inversion	9	10.1%	5
18	Mechanical vibration	10	7.4%	6
1	Segmentation	7	7.2%	7
27	Disposability / Cheap short-living objects	6	5.7%	8
35	Transformation of physical/chemical properties	8	4.8%	9
14	Sphericity and rotation	4	4.7%	10

Likewise, when the aim is to minimise the impact of a worsening feature (i.e. DP), the weightings for the inventive principles (IP), W_{k-}, are computed as follows:

$$W_{k-} = \sum_{i=1}^{10} w_i \sum_{j=1}^{10} k_{ij} w_j \qquad k_{ij} = 1 \; if \; IP_k \neq 0 \tag{2}$$

Table IV presents the ranking of inventive principles for the same technical contradictions in the utility market but, in this case, when the aim is to minimise the impact of a worsening feature (or DP). The number of repetitions (Times) in the rows of the contradiction matrix and the corresponding importance (W_{k-}) are also included.

TABLE IV
TOP-10 INVENTIVE PRINCIPLES FOR THE UTILITY MARKET – MINIMISING TH IMPACT OF AWORSENING FEATURE

IP	Inventive Principles	Times	W_{k-}	Rank
15	Dynamism	13	13.0%	1
28	Replacement of the mechanical working principle	13	12.6%	2
35	Transformation of physical/chemical properties	15	12.6%	3
10	Prior useful action	13	11.4%	4
29	Pneumatic or hydraulic constructions	11	10.1%	5
13	Inversion	9	9.4%	6
3	Local quality	8	7.4%	7
1	Segmentation	7	7.2%	8
18	Mechanical vibration	9	6.3%	9
27	Disposability / Cheap short-living objects	6	6.0%	10

It is worth noticing that almost the same IPs (nine out of ten) are suggested for fulfilling the objectives of improving a positive feature and minimising the impact of a worsening feature. However, the ranking of IPs differs. Inventive Principle no. 10 "Prior useful action" scores the highest when the aim is to improve a positive feature, whereas Inventive Principle no. 15 "Dynamism" is ranked first when aiming to minimise the impact of a worsening feature.

Finally, combining the prioritisation of both objectives results in the single ranking presented in Table V.

TABLE V
TOP-10 INVENTIVE PRINCIPLES FOR THE UTILITY MARKET – BOTH OBJECTIVES

IP	Inventive Principles	Times	W_k	Rank
10	Prior useful action	30	27.4%	1
28	Replacement of the mechanical working principle	24	24.1%	2
15	Dynamism	24	23.7%	3
29	Pneumatic or hydraulic constructions	22	20.3%	4
13	Inversion	18	19.5%	5
35	Transformation of physical/chemical properties	23	17.4%	6
1	Segmentation	14	14.5%	7
18	Mechanical vibration	19	13.7%	8
3	Local quality	12	11.7%	9
27	Disposability / Cheap short-living objects	12	11.7%	10

To solve physical contradictions, separation principles are used. Separation in time is the most promising strategy since it applies to six of the top ten inventive principles. Separation in condition is suggested for Inventive Principle no. 28 "Replacement of the mechanical working principle". It is necessary to get till Inventive Principle no. 13 "Inversion" to apply separation in scale and/or system.

IV. PROMISING CONCEPTS WORTH EXPLORING

The weightings of the inventive principles in Table VI have been added in each DP cell of the contradiction matrix to detect the most impactful conflicts. This results in the following matrix.

TABLE VI
IMPACT OF THE DP CONFLICTS (BLUE=HIGH; RED=LOW)

Feature to improve	Feature to preserve: DP1 Area of moving object	DP2 Strength	DP3 Duration of action	DP4 Loss of energy	DP5 Loss of time	DP6 Quantity of substance	DP7 Adaptability	DP8 Device complexity	DP9 Difficulty of detecting	DP10 Productivity
DP1	0%	43%	15%	38%	8%	45%	26%	42%	28%	44%
DP2	34%	0%	29%	17%	83%	59%	38%	57%	47%	73%
DP3	24%	51%	0%	0%	67%	57%	51%	73%	44%	38%
DP4	38%	6%	0%	0%	46%	22%	0%	5%	55%	89%
DP5	11%	70%	67%	45%	0%	33%	41%	24%	68%	0%
DP6	52%	55%	57%	22%	33%	0%	56%	70%	57%	63%
DP7	43%	35%	51%	52%	41%	53%	0%	76%	14%	53%
DP8	44%	52%	77%	73%	24%	70%	76%	0%	83%	34%
DP9	48%	71%	32%	59%	41%	57%	38%	83%	0%	31%
DP10	37%	85%	67%	89%	0%	17%	64%	36%	51%	0%

The most impactful contradictions and the corresponding inventive principles and potential ideas to overcome these recurrent challenges are discussed below.

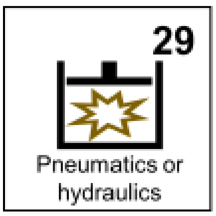
A. *Loss of energy (DP4) vs Productivity (DP10)*

This conflict is related to the need to minimise conversion losses and reduce the maintenance frequency. The IPs suggested by TRIZ to remove this contradiction are as follows:

- 28 - Replace the mechanical working principle
- 10 - Prior useful action
- 29 - Pneumatic or hydraulic constructions
- 35 - Transform physical and chemical properties

There are several ways of grouping inventive principles to work with a smaller set, which significantly speeds up the process of finding solutions. It can be appreciated that IPs 28, 29 and 35 belong to group 4 "Using scientific effects, special fields and substances" [24]. A review of the extended list of TRIZ IPs in [18] reveals that the inventive operators of pneumatic or hydraulic constructions provide more useful insights for wave energy application.

Wave energy systems must convert the slow wave motion (< 1 Hz) to high-speed generator rotation (50-60 Hz). Different mechanical configurations have been used to gear up the low velocity and high force input.



a) *Use gas or liquid as working elements.*
b) *Replace solid parts with gas or liquid.*
c) *Use negative pressure, partial vacuum, and vacuum chambers.*
d) *Use fluidisation of powders, dusts or granulates in the air flow.*
e) *Use fluids and gases for heat and energy transfer.*

Fig. 3. Pneumatics or hydraulics and corresponding inventive operators [18].

However, the increased complexity of the transformation steps coupled with the reciprocating movement can lead to important reliability issues. Using pneumatic or hydraulic constructions can remove the technical contradiction by replacing solid parts with gas or fluid.

Examples of the application of this IP are the classical OWC devices which replace the complex mechanical transmission by the airflow through an air turbine (see Figure 4-a). NoviOcean device [25] implements a similar approach but, in this case, with high-pressure water as the energy carrier. The heaving motion of the floater is used to actuate a hydraulic cylinder. Then, the pressurised water hits a conventional Pelton turbine (see Figure 4-b).

(a)

(b)

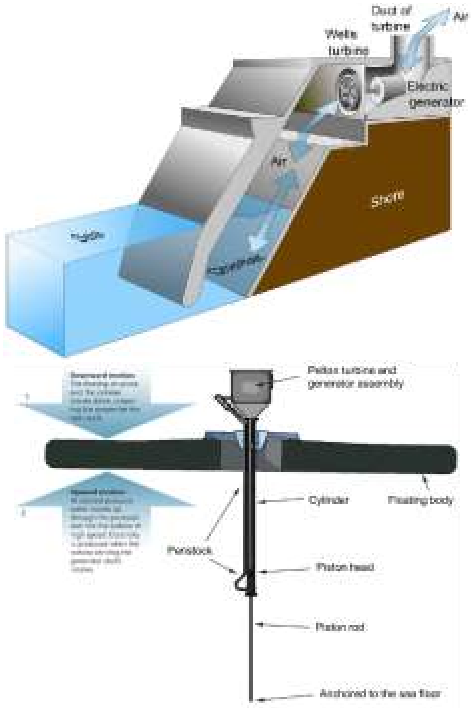


Fig. 4. Use of pneumatics or hydraulics (a) Onshore OWC device [10]; (b) NoviOcean device [9].

Wave energy is also characterised by its high variability. The electrical generator is sized to accommodate the highest possible power to avoid an accelerated lifetime reduction of the wave energy system in the previously suggested configurations. Electrical generators are very efficient when they are operated at nominal power. However, due to the significant fluctuation of wave energy levels, they are forced to operate at partial loads during long periods, significantly reducing the conversion efficiency and increasing the energy losses.

This issue is investigated in the H2020 VALID project [26]. OWC technology developer IDOM is testing an electrical generator under variable operating conditions exceeding several times its rated power. The high-voltage instantaneous peaks accelerate the generator insulation's thermal degradation, leading to total failure. They aim to find an optimum sizing as a compromise between the conversion efficiency and durability of the generator.

The inherent contradiction is approached by TRIZ using fluids and gases for energy transfer. The pulsating energy capture calls for power smoothing which means that the PTO system must have some temporary storage means at least for the short term (10-60 s). Although temporary energy storage inevitably leads to some additional energy loss, the advantages gained can be significant. The generator's rated power is reduced, and the efficiency is maintained while generating steady high-quality electric power.

B. *Device complexity (DP8) vs Difficulty of detecting (DP9)*

This conflict is related to the need to reduce the conversion steps in the energy transformation and delivery while detecting conditions above a threshold. The power transported in a wave is the product of speed and force. The slow wave motions mean huge forces that must be geared up to handle them. More complex design structures require a greater number of interfaces which can fail. Actually, large systems can fail because of very small components. Detecting conditions above a threshold becomes extremely difficult in complex systems.

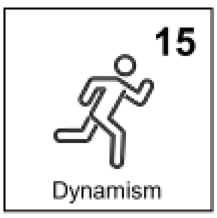
The IPs suggested by TRIZ to remove this contradiction are as follows:

- 15 – Dynamism
- 10 - Prior useful action
- 28 - Replace the mechanical working principle

It can be appreciated that the IPs belong to three different groups, whose only common feature is the trends of technical evolution. IP 15 aims to increase effectiveness and ideality; IP 10 deals with harmful actions; and IP 28 uses scientific effects, special fields and substances.

Systems tend to evolve following the same patterns to increase ideality [11]. They start simple, become more complex as new elements are added or segmented and then become simple again. Likewise, systems become more flexible and variable.

Dynamism is a significant driver for increasing ideality. Particularly, two suggested inventive operators are using adaptive and flexible elements and making the

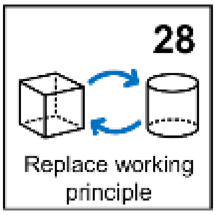


a) *Make an object, external environment or process adjustable to enable optimal performance parameter at each stage of operation.*
b) *Divide an object into elements whose position changes relative to one another. Make object movable and adaptive.*
c) *If a process is rigid or inflexible, make it adaptive.*
d) *Use adaptive and flexible elements like joints, springs, elastomers, fluids, gases, magnets/electromagnets.*
e) *Change static force fields to movable or dynamics fields, which change in time or in structure.*

Fig. 5. Dynamism and corresponding inventive operators [18].

object movable and adaptive.

Similarly, replacing the working principle with an electric, magnetic, or electromagnetic one is another powerful driver.



a) *Replace the mechanical working principle with an electric, magnetic, or electromagnetic one.*
b) *Use optical working principle.*
c) *Use an acoustic or sound system.*
d) *Use thermal, chemical, olfactory (smell) or biological system.*
e) *Use electromagnetic fields in conjunction with ferromagnetic particles, magnetic or electro-rheological*

Fig. 6. Replace the working principle and corresponding inventive operators [18].

FlexWECs [27] are an example of increased flexibility and replacing the working principle. The device structure is made of base materials that enable flexing, stretching, and distention without using discrete joints or hinging mechanisms. Therefore, their PTO is distributed, allowing the wave energy harvesting throughout the device structure continuously (see Figure 7-a). It is proposed the use of dielectric elastomer generators or any other type of solid-state conversion technologies [28]. According to NREL, FlexWECs are not restricted to harvesting energy from a particular motion, can be easily manufactured from low-cost sustainable materials and offer a high degree of redundancy. However, the PTO's distributed nature could certainly be hard to control. Likewise, flexible wave energy converters and distributed, segmented, modular, and cell-based direct generating systems are of special interest to WES [29].

Similarly, PNNL is exploring the use of a frequency-multiplied cylindrical triboelectric nanogenerator (FMC-TENG) for converting wave energy into electricity to power devices at sea [30]. The FMC-TENG converts the low-frequency wave energy into the potential energy of a mass using magnetic repulsion. Whenever the restoring force exceeds the magnetic force, the potential energy is transformed into a high-frequency swing motion for generating output power (see Figure 7-b). TENGs are low-cost, lightweight and can efficiently convert slow random waves into power.

(a) (b)

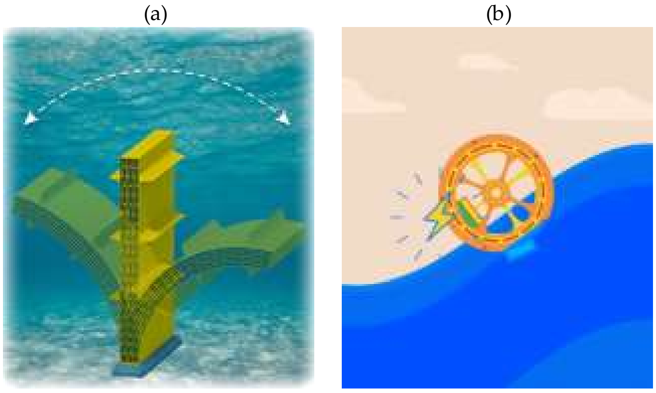


Fig. 7. Dynamism and replacing working principle (a) NREL's FlexWEC [12]; (b) PNNL's FMC-TENG device [14].

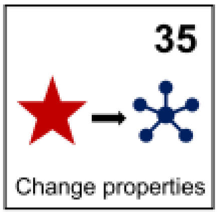
Compared with current offshore wind turbines, WECs have much smaller unit power. In most cases, this is due to hydrodynamic limitations or physical constraints. Using relatively low TRL technologies such as elastomeric generators makes it even more challenging to scale unit power beyond 1 MW. The problem with small devices is that they tend to be uneconomic because of their operational costs, since they have similar routine maintenance than larger devices but provide much less revenue.

In 2018, WES commissioned a study into the potential of very large-scale (> 10MW) WECs [31]. One of the WECs configurations analysed exploited the trends of system evolution. It could likely achieve larger power by grouping individual devices into shared configurations leading to less infrastructure (i.e. moorings, foundations, cabling), installation and maintenance needs. Unfortunately, this study found evidence of high costs associated with early deployment.

C. *Strength (DP2) vs Productivity (DP10)*

This conflict is related to the need to provide a reaction to capture wave energy, transfer loads to the seabed, and reduce maintenance frequency or downtime. The IPs suggested to remove this contradiction are the same as for section IV.A but in a slightly different order:

- 29 - Pneumatic or hydraulic constructions
- 28 - Replace the mechanical working principle
- 10 - Prior useful action
- 35 - Transform physical and chemical properties



a) *Change an object's aggregate state (e.g. solid to liquid or liquid to gas - or vice versa).*
b) *Change the object's concentration or consistency.*
c) *Change other relevant physical properties or operational conditions (pressure, density, hardness, viscosity, conductivity, magnetism, etc.) separately or together.*
d) *Change the object's temperature.*
e) *Change other chemical properties or operational conditions (formulation, pH, solubility, etc), change*

Fig. 8. Change properties and corresponding inventive operators [18].

WECs must be designed to withstand the most extreme sea states. However, they generate income in the smaller but most frequent wave conditions. The wave forces which act upon a floating body in extreme waves can be enormously large compared to the forces in normal waves (one or two orders of magnitude). Resisting the large horizontal forces and not getting any power from them should be avoided. Adding weight does not solve the problem since it means extra inertia that increases the probability of large instantaneous forces. WECs must be able to limit the wave force on it in larger waves, ultimately becoming near transparent to them in the survival condition.

IP 35 suggests changing the physical properties or operational conditions.

A greater load-shedding capability would allow the separation of the load and strength distributions without introducing large safety factors which is too expensive. Control of pitch angle has been used in wind turbines to reduce loads and increase system reliability. The principle of variable geometry has been proposed by NREL [32]. It has been applied to wave energy such as OSWC, submerged pressure differential and attenuators. Controllable airfoils change the hydrodynamic response of the device, thus shedding loads in extreme wave conditions (see Figure 9-a).

The concept of large-scale geometric variability has also been considered in the Danish WEPTOS [33]. In this case, the floating structure can adjust the opening angle between the two legs (see Figure 9-b). Additionally, the device allows 360º weather-vanning through its single anchor leg mooring system to reduce the load ratios further.

Thirdly, the CorPower Ocean C4 design has a small size and low hydrodynamic efficiency at extreme waves as opposed to normal waves [34]. Thus, the device is naturally detuned making it transparent to incoming waves. In normal operating conditions, it uses a negative spring mechanism and control to capture energy (see Figure 9-c).

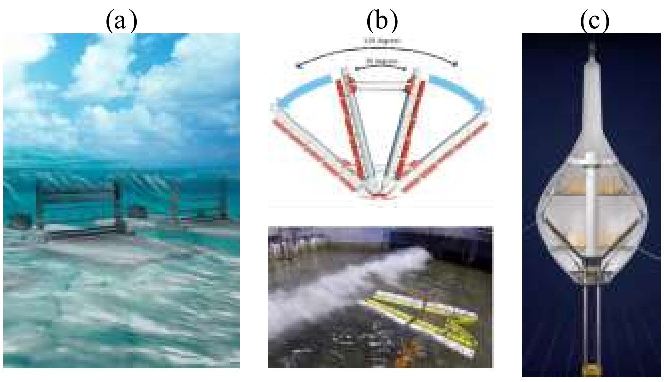
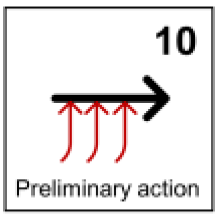


Fig. 9. Change properties (a) NREL's Variable Geometry OSWC [16]; (b) WEPTOS [17]; (c) CorPower C4 [18].

The previous strategies can increase the wave energy system reliability. However, they do not improve the productivity of the installation and maintenance operations. IP 10 suggests pre-arranging the objects so they can come into action at the most convenient position and without losing time.



a) *Perform the required action or useful function in advance, either fully or partially.*
b) *Pre-arrange the objects so they can come into action at the most convenient position and without losing time.*
c) *Perform part of the process step or operation beforehand.*

Fig. 10. Preliminary action and corresponding inventive operators [18].

This inventive operator calls for modular designs, accessibility to components for repair/replacement and quick connection/disconnection systems. WES has paid attention to quick connection systems through their competitive innovation calls. Three consortia are currently demonstrating their solutions at Stage 3 [35].

V. Conclusion

While the findings of this research do not focus on a specific concept that can deliver the necessary step change, the method provides a holistic and structured approach to assessing the potential of innovative archetypes.

The TRIZ structured innovation approach has permitted the identification of the most impactful contradictions and corresponding Inventive Principles (IPs). Design Parameters (DPs) weights resulting from the application of QFD have been used to rank the IPs having the greatest impact on the initial Stakeholder Requirements (SRs).

The most recurrent challenges were found to be:

- Need to minimise conversion losses and reduce the maintenance frequency.
- Need to reduce the conversion steps in the energy transformation and delivery while detecting conditions above a threshold.
- Need to provide a reaction to capture wave energy, transfer loads to the seabed and simultaneously reduce the maintenance frequency or downtime.

IPs suggested are the use of pneumatic or hydraulic constructions (air or water turbines) together with some temporary storage means, the use of adaptive and flexible elements and making the object movable and adaptive (FlexWECs), direct energy conversion (dielectric elastomers and triboelectric nanogenerators), grouping individual devices into shared configurations leading to less infrastructure, load-shedding and geometric variability (VG-OSWC, WEPTOS, CorPower C4), modular designs, accessibility to components for repair/replacement and quick connection/disconnection systems.

Appendix

The following tables are used in the methodology.

Table A.I
Stakehorder Requirements (SRs) [9]

Id	Stakeholder Requirements
SR1	Convert wave energy into consumable power
SR2	Operate when needed
SR3	Reduce upfront costs
SR4	Reduce annual costs
SR5	Prevent business risks

TABLE A.II
TECHNICAL REQUIREMENTS (TRS) [9]

Id	Technical Requirements	Id	Technical Requirements
TR1	Provide working surface	TR13	Avoid unplanned delay time
TR2	Provide a reaction force	TR14	Employ mature manufact. processes
TR3	Control energy capture	TR15	Manufacture in large quantities
TR4	Reduce transformation steps	TR16	Use low-cost vessels to install
TR5	Minimise transf. losses at partial loads	TR17	Reduce vessel trips
TR6	Deliver energy effectively	TR18	Use low-cost vessels to maintain
TR7	Minimise delivery losses at partial loads	TR19	Reduce maintenance frequency
TR8	Decrease uncertainty in limit strength	TR20	Transfer loads to the seabed
TR9	Reduce variation in environ. loading	TR21	Reduce the severity of threats
TR10	Increase design margins	TR22	Detect conditions above the threshold
TR11	Use near maintenance port	TR23	Reduce environmental pressure
TR12	Increase weather accessibility		

TABLE A.III
TRIZ 39 TECHNICAL PARAMETERS [11]

1	Weight of moving object	14	Strength	27	Reliability
2	Weight of stationary object	15	Duration of action by a moving object	28	Measurement accuracy
3	Length of moving object	16	Duration of action by a stationary object	29	Manufacturing precision
4	Length of stationary object	17	Temperature	30	External harm affects the object
5	Area of moving object	18	Illumination intensity	31	Object-generated harmful factors
6	Area of stationary object	19	Use of energy by moving object	32	Ease of manufacture
7	Volume of moving object	20	Use of energy by stationary object	33	Ease of operation
8	Volume of stationary object	21	Power	34	Ease of repair
9	Speed	22	Loss of energy	35	Adaptability or versatility
10	Force	23	Loss of substance	36	Device complexity
11	Stress or pressure	24	Loss of information	37	Difficulty of detecting and measuring
12	Shape	25	Loss of time	38	Extent of automation
13	Stability of the object's composition	26	Quantity of substance/the matter	39	Productivity

TABLE A.IV
TRIZ 40 INVENTIVE PRINCIPLES [18]

1	Segmentation	15	Dynamism	28	Replacement of the mechanical working principle
2	Leaving out / Trimming	16	Partial or excessive action	29	Pneumatic or hydraulic constructions
3	Local quality	17	Shift to another dimension	30	Flexible shells or thin films
4	Asymmetry	18	Mechanical vibration	31	Porous materials
5	Combining	19	Periodic action	32	Changing colour
6	Universality	20	Continuity of useful action	33	Homogeneity
7	Nesting / Integration	21	Skipping / Rushing through	34	Discarding and restoring
8	Anti-weight	22	Converting harm into benefit	35	Transformation of physical and chemical properties
9	Prior counteraction of harm	23	Feedback and automation	36	Phase transitions
10	Prior useful action	24	Mediator	37	Thermal expansion and contraction
11	Preventive measure	25	Self-service / Use of resources	38	Strong oxidants
12	Equipotentiality	26	Copying and modelling	39	Inert environment
13	Inversion	27	Disposability / Cheap short-living objects	40	Composite materials
14	Sphericity and rotation				

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