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Universidad
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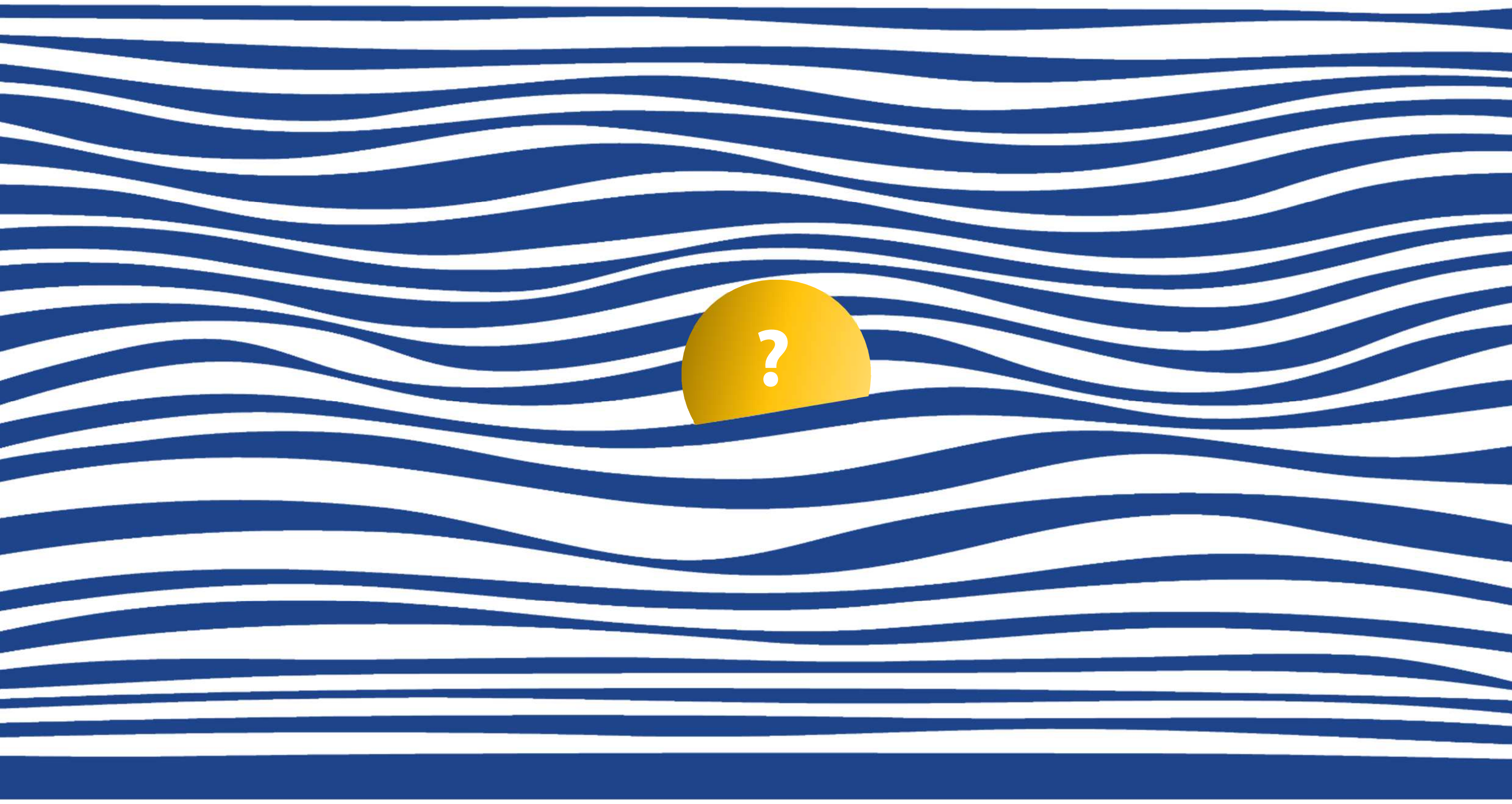
A NOVEL METHODOLOGY FOR THE ASSESSMENT OF WAVE ENERGY OPTIONS AT EARLY STAGES

Pablo Ruiz-Minguela

Supervisors: Prof Jesús Maria Blanco Ilzarbe & Dr Vincenzo Nava



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A novel methodology for the holistic assessment of wave energy technologies at early design stages

AUTHOR:

José Pablo Ruiz Minguela

SUPERVISORS:

Prof Jesús María Blanco Ilzarbe

Dr Vincenzo Nava

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In loving memory of my dear mother Lucía (1929-2020)

“Pygmies placed on the shoulders of giants see more than the giants themselves”

Friar Diego de Estella (1524 – 1578)

ABSTRACT

Increasing the share of electricity generation from renewable sources is key to ensure a fully decarbonised energy system and fight against climate change. Wave energy is an abundant and powerful resource but at the same time, the least developed of all renewable energy technologies. It is discouraging that despite the considerable efforts the international research community has made over the last decades, wave energy technologies have once and again failed to achieve the desired design convergence to support their future market growth.

Traditional approaches mainly focused on assessing technology maturity have proven insufficient to ensure that wave energy technologies achieve their technical, economic and social goals. To meet the high sector expectations, 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 common evaluation framework is based on sound Systems Engineering principles. It encompasses the external context, system requirements and evaluation criteria. This step of the methodology creates a prioritisation of the various wave energy attributes for the qualitative assessment of wave energy technologies. The analysis of the external context provides an understanding of the factors influencing the development of wave energy technologies and the corresponding impact on system requirements. The identification of the market application, key drivers and stakeholders' groups provides an excellent foundation for the objective assessment of wave energy technologies against the systems requirements.

This framework avoids any inconsistency with the formulation of system requirements and can be applied to different levels of technology maturity. It provides flexibility for adapting it to rapidly changing market conditions or stakeholder priorities and can be expanded to focus the analysis on specific wave energy sub-systems. Besides, it grasps the qualitative aspects related to the stakeholder expectations that higher-level metrics such as LCOE cannot provide.

On the other hand, the proposed novel approach guides design decisions along the development process for the adequate management of risk and uncertainty. To this purpose, the holistic assessment developed through this research comprises the evaluation at intermediate development stages and the projection of future costs when the technology has been sufficiently replicated. This step of the methodology facilitates wave energy technology selection and benchmarking at different levels of maturity in a controlled manner.

The fair assessment of wave energy technology performance creates awareness of potential technology gaps throughout the various development stages. It facilitates the selection of the most suitable option for a particular market application and enables benchmarking of technologies across different markets. Additionally, it offers a tool for exploring uncertainties, drawing attention to the cost estimate accuracy and identifying potential learnings from the beginning of technology development.

The innovation strategies proposed in this research deliver valuable information for focusing innovation efforts on areas having the highest influence on technology performance. The methods include the analysis of structural patterns in the wave energy system architecture and the identification of technical trade-offs and corresponding inventive principles. This final step of the methodology results in the identification of promising concepts worth exploring.

Incorporating effective innovation strategies into wave energy development helps to manage system complexity, enhance the understanding of causality within the system, and channel innovation toward useful improvements. It substitutes the conventional trial-and-error method based on expert judgement and engineering compromise. Moreover, it provides a predictable technique to deal with problems based on past knowledge and proven principles, bringing efficiency into the process.

The practical implementation of this methodology to various illustrative cases of hypothetical wave energy systems, public reference models and state-of-the-art technologies has produced promising results. While the findings of this research do not focus on a specific concept that can deliver the necessary step change, the thesis provides a holistic and structured approach to assessing the potential of innovative archetypes. Furthermore, future work could expand and adapt this novel methodology for the assessment of wave energy options to other possible settings.

RESUMEN

El aumento de la proporción de electricidad generada a partir de fuentes renovables es clave para garantizar un sistema energético totalmente descarbonizado y luchar contra el cambio climático. La energía de las olas es un recurso abundante y potente, pero, al mismo tiempo, es la menos desarrollada de todas las tecnologías renovables. Resulta desalentador que, a pesar de los considerables esfuerzos que los investigadores internacionales han realizado en las últimas décadas, las tecnologías de captación no hayan conseguido lograr la deseada convergencia de diseño para sustentar su futuro crecimiento comercial.

Las metodologías convencionales centradas principalmente en evaluar la madurez de la tecnología han demostrado ser insuficientes para garantizar que las tecnologías undimotrices alcancen sus objetivos técnicos, económicos y sociales. Para cumplir con las altas expectativas del sector, esta investigación propone un enfoque sistemático desde el inicio del desarrollo de la tecnología que garantiza la trazabilidad de los requisitos, crea evaluaciones de desempeño objetivas y aplica estrategias de innovación sólidas para superar los retos pendientes.

El marco de evaluación común se basa en los principios sólidos de la Ingeniería de Sistemas. Abarca el contexto externo, los requisitos del sistema y los criterios de evaluación. Este paso de la metodología crea una priorización de los diversos atributos de un sistema de energía undimotriz para la evaluación cualitativa de las tecnologías de energía de las olas. El análisis del contexto externo proporciona una comprensión de los factores que influyen en el desarrollo de dichas tecnologías y el impacto correspondiente en los requisitos del sistema. La identificación de la aplicación de mercado, los factores clave y los grupos de interés proporciona una base sólida para la evaluación objetiva de las tecnologías de energía de las olas frente a los requisitos de los sistemas.

Este marco evita cualquier inconsistencia en la formulación de los requisitos del sistema y se puede aplicar a diferentes niveles de madurez tecnológica. Proporciona flexibilidad para adaptarlo a las condiciones del mercado o prioridades de las partes interesadas rápidamente cambiantes además de poderse extender para centrar el análisis en subsistemas específicos de energía de las olas. Asimismo, capta los aspectos cualitativos relacionados con las expectativas de los grupos de interés que métricas de alto nivel como el LCOE no pueden proporcionar.

Por otro lado, el enfoque novedoso propuesto orienta las decisiones de diseño a lo largo del proceso de desarrollo para una adecuada gestión del riesgo y la incertidumbre. Para ello, la evaluación holística desarrollada a través de esta investigación comprende la evaluación en etapas intermedias de desarrollo y la proyección de costes futuros tras haber replicado suficientemente la tecnología. Este paso de la metodología facilita la selección y

evaluación comparativa de la tecnología de energía undimotriz a diferentes niveles de madurez de una manera controlada.

La evaluación objetiva del desempeño de la tecnología de energía undimotriz crea conciencia sobre las posibles brechas tecnológicas a lo largo de las diversas etapas de desarrollo. Facilita la selección de la opción más adecuada para una aplicación de mercado en particular y permite la evaluación comparativa de tecnologías en diferentes mercados. Asimismo, proporciona una herramienta que se puede utilizar para explorar incertidumbres, centrar la atención en la precisión de las estimaciones de costes y el aprendizaje potencial desde las etapas iniciales del desarrollo tecnológico.

Las estrategias de innovación propuestas a través de esta investigación proporcionan información valiosa para concentrar los esfuerzos de innovación en mejorar aquellas áreas con mayor impacto en el desempeño de la tecnología. Los métodos incluyen el análisis de patrones estructurales en la arquitectura del sistema de energía de las olas y la identificación de compromisos técnicos y sus principios inventivos correspondientes. Este paso final de la metodología da como resultado la identificación de conceptos prometedores que merece la pena explorar.

La integración de estrategias de innovación eficaces en el desarrollo de sistemas de energía undimotriz ayuda a gestionar la complejidad del sistema, mejorar la comprensión de la causalidad dentro del sistema y canalizar la innovación hacia mejoras útiles. Sustituye el método convencional de prueba y error basado en el juicio de expertos y el compromiso de ingeniería. Además, proporciona una técnica predecible para resolver problemas basada en conocimientos pasados y principios probados, aportando eficiencia al proceso.

La implementación práctica de esta metodología por medio de varios casos ilustrativos de sistemas hipotéticos de energía undimotriz, modelos públicos de referencia y tecnologías punteras ha arrojado resultados prometedores. Si bien los hallazgos de esta investigación no se centran en un concepto específico que pueda generar el cambio radical necesario, la tesis proporciona un enfoque holístico y estructurado para evaluar el potencial de los arquetipos innovadores. Más aún, futuros desarrollos podrían ampliar y adaptar esta nueva metodología para la evaluación de alternativas de energía de las olas a otros escenarios posibles.

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NOMENCLATURE

Abbreviations and Acronyms

1C	Primary Conversion
2C	Secondary Conversion
3C	Tertiary Conversion
AACE	Association for the Advancement of Cost Engineering
AEP	Annual Energy Production
AF	Availability Factor
AHP	Analytical Hierarchy Process
BOCR	Benefits, Opportunities, Costs and Risks
BoP	Balance of Plant
CA	Commercial Attractiveness
CAPEX	Capital Expenditure
CF	Capacity Factor
CI	Consistency Index
CR	Consistency Ratio
CS	Complexity Score
CW	Capture Width
CWR	Capture Width Ratio
DD	Degree of Difficulty
DEA	Data Envelopment Analysis
DfX	Design for X
DL	Detection Level
DP	Design Parameter
DSM	Design Structured Matrix
EMEC	European Marine Energy Centre
EIS	Environmental Impact Score
EPCI	Engineering, Procurement, Construction and Installation

FAST	Functional Analysis and System Technique
FCR	Fixed Charge Rate
FD	Farm Density
FMEA	Failure Modes and Effects Analysis
FOAK	First-Of-A-Kind
FR	Functional Requirement
FTA	Fault Tree Analysis
GC	Grid Connection
GM	Global Merit
HMRC	Hydraulics & Maritime Research Centre of the University College Cork
HoQ	House of Quality
HS	Hydrodynamic System
IC	Instrumentation and Control
IEA-OES	International Energy Agency's Collaboration Programme for Ocean Energy Systems
IEC	International Electrotechnical Commission
INSTEX	Installation Expenditure
IP	Inventive Principle
JRC	Joint Research Centre
LCOE	Levelised Cost of Energy
LF	Load Factor
LR	Learning Rate
LSP	Logical Scoring of Preference
MANEX	Manufacturing Expenditure
MAUT	Multi-Attribute Utility Theory
MBSE	Model-Based Systems Engineering
MOE	Measure of Effectiveness
MOP	Measure of Performance
MR	Manufacturing Requirement
MRL	Manufacturing Readiness Level
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair

NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
OPEX	Operational Expenditure
OWC	Oscillating Water Column
OWSC	Oscillating Wave Surge Converter
PA	Point Absorber
PESTLE	Political, Economic, Social, Technological, Legal and Environmental
PNNL	Pacific Northwest National Laboratory
PPA	Power Purchase Agreement
PR	Performance Ratio
PTO	Power Take-Off
QC	Quasi-Conjunction
QDF	Quality Function Deployment
QPA	Quasi Point Absorber
REPEX	Repair Expenditure
RB	Reaction Body
RI	Random Index
RM	Reference Model
SB	Seabed
SBD	Set-Based Design
SC	Storage and Power Conditioning
SD	System Driver
SE	Systems Engineering
SET Plan	Strategic Energy Technology Plan
SF	Safety Factor
SH	Stakeholder
SIDS	Small Island Development Country States
SK	Station Keeping
SPV	Special Purpose Vehicle
SR	Stakeholder Requirement
SSG	Sea-wave Slot-cone Generator
Std	Standard deviation

SURV	Survivability
SWOT	Strengths, Weaknesses, Opportunities and Threats
TA	Technical Achievability
TC	Technology Class
TENG	TriboElectric NanoGenerator
TPL	Technology Performance Level
TPM	Technical Performance Measure
TR	Technical Requirement
TRL	Technology Readiness Level
TRIZ	Teoriya Resheniya Izobretatelskikh Zadatch (Theory of Inventive Problem Solving)
TS	Transmission System
UC	Unit Cost
UN	United Nations
VoC	Voice of Customer
WACC	Weighted Average Cost of Capital
WEC	Wave Energy Converter
WES	Wave Energy Scotland

Symbols

Roman Letters

a	Cost of the first commercial deployment
a_{ij}	Numerical value of the pairwise comparisons in AHP
A	Arithmetic mean
b	Rate of cost reduction
B	Scaling factor of the value function
B_r	Relative bandwidth
c	Curve coefficient of the value function
c_{kj}	QFD correlation matrix coefficients
C_f	Fixed Cost
C_v	Variable Cost
C_{wn}	Normalised Capture Width
d	LSP coefficients (from $-\infty$ for pure conjunction to $+\infty$ for pure disjunction)
d_j	Relative importance of input requirements in QFD
F_f	Maximum permissible foundation load
F_{PTO}	Maximum permissible PTO force
F_p	Primary function
F_s	Secondary function
G	Geometric mean
H	Harmonic mean
I_s	Number of interfaces
k	Curve coefficient of the value function
L	Learning capacity
L_s	Load shedding capability
m	Number of evaluation criteria
M	Measured performance
M_s	Number of subsystems
n	Neutral point of the value function
n_a	No. of aggregation steps
n_c	No. of conversion steps

n_i	No. of installation trips per device
n_s	No. of service trips per device
O	Plant operator
p	shape factor of the value function
P	Rated power
r	Discount rate
r_{ij}	QFD relationship matrix coefficients
s_i	Suitability
S	Area of the hydrodynamic object
t	Tolerance of the value function
t_c	Cycle time
t_l	Logistic time
t_t	Travel time
t_w	Waiting time
T	Target performance
U	Uncertainty level
v(x)	Value function
w	Importance weightings
W	Ocean waves
W_{k+}	Weightings for the IPs when the aim is to improve a positive feature
W_{k-}	Weightings for the IPs when the aim is to improve a worsening feature
X	Cumulative experience
y	Project lifetime
Y	Future cost of the technology

Greek Letters

δ	Uncertainty
λ	Failure rate
λ_{max}	Maximum eigenvalue of the judgement matrix in AHP
μ	Mean
η_d	Delivery Efficiency
η_t	Transformation Efficiency
ρ	Repair rate
σ	Standard deviation
ω	Wave Frequency

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CHAPTER 1 INTRODUCTION

> "If you cannot make knowledge your servant, make it your friend"
>
> *Baltasar Gracián (1601 – 1658)*

1.1 Overview

This chapter begins with an introduction to the social, technical and commercial landscape and the underlying challenges that motivate this research (section 1.2). The research goal and objectives are described in section 1.3. Section 1.4 summarises the main contributions of the thesis. Finally, the thesis structure is presented in section 1.5.

1.2 Motivation and Problem Statement

Nations all over the world are setting ambitious decarbonisation targets as a means to fight climate change [1]. However, despite the need to increase the share of electricity generation from renewable sources, ocean energy, and particularly wave energy, remains a largely untapped resource [2]. Wave energy is abundant, predictable, widely distributed and indigenous for many populations living in coastal areas [3]. Together with tidal stream, wave energy has the potential to satisfy up to 10% of the global electricity demand by 2050 [4].

All in all, the path to developing effective wave energy technologies has been poised with many challenges [5]. Designing wave energy technologies is a long and intricate process implying many decisions. In an early stage, multiple design parameters must be assigned, which significantly influence its ultimate cost and performance expectations [6]. Failure of the wave energy sector to meet those expectations has more than once delayed the industrial development of wave energy [3].

Hence, the engineering challenge is to create robust devices that harness wave energy efficiently, reliably and cost-effectively while also surviving the roughest seas. For this purpose, the technology development process should gradually replace initial assumptions with knowledge since these uncertainties represent a significant risk.

Furthermore, any successful innovation must contain three essential features, namely social desirability, technical feasibility and commercial viability [7]. Although these criteria may not be developed simultaneously, all must be present incidentally to ensure a thriving business.

Social desirability explores whether the innovation will meet real user needs, in other words, if we are solving the right problem. On the other hand, the technical feasibility and commercial viability investigate our capability to deliver the innovation and its profitability in the market respectively, that is, if we are solving the problem right. At the intersection of the three lenses lies the optimum design space for successful innovation.

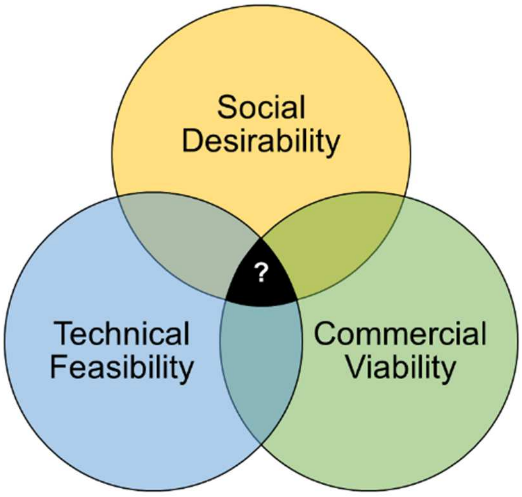

Figure 1.1: The three perspectives of successful innovation (adapted from [7]).

Right now, social desirability is quite favourable for wave energy. The transition to a sustainable and resilient carbon-neutral economy is no longer a political decision but an ample social demand. With world energy consumption estimated to rise considerably over the next decades, international instability (e.g. Ukraine war) and high energy prices, increasing security of supply and reducing fossil fuel dependence are becoming powerful drivers [8].

Wave energy can play a broad role in attaining UN Sustainable Development Goals [9] by providing affordable and clean energy (Goal 7), creating jobs in coastal regions (Goal 8), promoting energy security (Goal 9), reducing CO_2 (Goal 13) and protecting ecosystems (Goal 14). Additionally, the need for a vigorous forward-looking recovery from the harm inflicted by Covid-19 may revive interest in wave energy development [10]. Lastly, with a high penetration of renewable energies in the energy system, wave energy can provide significant value in balancing the grid due to its complementarity to other renewable energy sources such as wind and solar [4].

Many wave energy concepts have been developed over the last 30 years. Various technologies are in different development stages, but none have achieved commercial readiness [11]. The great diversity of archetypes can explain why the maturity of wave energy technologies is still relatively low. However, the limited number of technologies deployed in the water has shown harnessing wave energy is technically feasible [12]. Due to the wide variety of wave energy technologies and the strong dependence of their performance on the sea conditions in which they are tested, it is extremely difficult to objectively assess the relative merits of the markedly different designs.

The ocean is a ruthless environment wherein technologies must demonstrate long-term reliable performance to compete with more mature alternatives. At present, commercial viability is the main missing innovation factor for wave energy technology success. The business case of wave energy is made upon the cost of producing energy. To demonstrate an attractive business case proposition, wave energy technology developers are expected to gather significant evidence. This is especially challenging since the development process for wave energy technology is particularly costly and lengthy [13].

To achieve system cost and performance requirements, early technological development is essential. According to several experts, the conceptual design phase determines around 70–80% of the product lifecycle costs [14] [15] [16]. The logical conclusion is that decisions made during the early stages of product development are far more important than those made later on. Too little time spent on conceptual design can result in a lack of understanding of the problem's requirements and an insufficient ability to generate novel concepts. This might result in a design being developed that cannot perform well enough to be a viable commercial solution, wasting time and resources [17].

It is disappointing that many wave energy companies have moved through the technology readiness levels, reaching the pre-commercial scale, just to realise they fail to meet their targets. Therefore, it is highly advisable to have clear guidance on the potential of wave energy technologies from the early stages of design.

Common methodologies mainly focused on assessing technology maturity have proved inadequate to ensure wave energy technologies reach their technical, economic and social goals. Hence, a rigorous development process of wave energy technologies is needed to help regain investor confidence, improve the social perception of the sector’s potential and provide compelling evidence to drive technical decisions.

Many industrial sectors (e.g. automotive, aerospace, and oil & gas) have successfully applied Systems Engineering methods to develop innovative products meeting very diverse and demanding customer needs. For instance, Muller and Falk [18] illustrate the contribution of Systems Engineering to oil & gas with concrete case studies from subsea production. Discouragingly, their application in wave energy is still limited and fragmented.

1.3 Research Objectives

The ultimate research goal of this thesis is to develop a novel methodology for the holistic assessment of wave energy systems from the early stages of technology development based on the application of sound Systems Engineering principles. This systematic design approach aims to:

1. Build a common framework that ensures traceability and consistency of wave energy system requirements and metrics.
2. Create fair performance assessments of wave energy technologies to objectively guide design decisions throughout the development process.
3. Apply sound innovation strategies to suggest promising concepts that can improve the cost-effectiveness of wave energy technologies.

The research goal will be achieved through the following specific objectives:

- Review the existing methods applicable to the specification and assessment of wave energy technologies.
- Analyse the external forces influencing decisions related to the conception, development and operation of wave energy systems.
- Propose a standard set of stakeholder, functional and technical requirements for wave energy systems.
- Guarantee the traceability of system requirements throughout the entire wave energy design process.
- Establish a hierarchy of metrics and corresponding aggregation methods.
- Develop value functions to facilitate the qualitative assessment of wave energy.
- Allocate design targets and uncertainty ranges to benchmark wave energy technology performance along the intermediate development stages.
- Improve the accuracy, consistency, and usefulness of projected cost predictions for emerging wave energy technologies.
- Visualise potential problems in the functional allocation of wave energy system capabilities to the physical embodiment.
- Identify the most impactful trade-offs for wave energy systems and corresponding inventive principles.
- Implement the novel approach in a performance assessment and innovation tool developed in Excel.
- Apply this assessment methodology to illustrative cases of hypothetical wave energy systems, public reference models and state-of-the-art technologies.

1.4 Contributions

The main contributions of this thesis are outlined below.

1.4.1 Analysis of external forces influencing the development of wave energy technologies

Understanding wave energy requirements is critical to the creation of any successful technology. However, wave energy development cannot be separated from the larger context in which the technology is intended to operate, because multiple external forces influence its conception, development, and operation.

The two fundamental elements that constitute this broad environment are external drivers and stakeholder groups. External drivers are closely related to the intended market use, whereas stakeholder groups express technological performance expectations. Each intended market application may call for a different combination of external drivers. In turn, ranking those external drivers to each stakeholder group will ultimately dictate the importance of the wave energy requirements.

External drivers are identified and ranked for two market applications based on the Analytic Hierarchy Process (AHP) method. Similarly, wave energy stakeholders are elicited and prioritised regarding the external drivers using a Quality Function Deployment (QFD) approach for the same application markets. This ranking can be easily customised to local contexts and expanded to new wave energy application markets.

1.4.2 Hierarchical formulation of wave energy requirements and metrics

The formulation of requirements aims to create a systematic overview of the purposes underpinning the search for solutions. Requirements that bind a solution space are hierarchical and interrelated.

Initially, the wave energy specification includes all necessary and prioritised Stakeholder Requirements (SRs) that are compatible with the technical, financial and risk constraints. Upon completion, the next step is to define the Functional Requirements (FRs). FRs define what the system must do to achieve the SRs without addressing how the system should accomplish them. Last but not least, Technical Requirements (TRs) specify the issues related to the technology needed for the successful implementation of the system in physical components.

Systems engineering is driven by the need to satisfy requirements. Thus, for Systems Engineering to be successful, evaluating and validating those requirements is equally crucial. Verification and validation are processes based on evidence used to evaluate if a system fulfils the specification of requirements. They rely on metrics and data. A QFD approach has been used to collect and rank stakeholder, functional, and technical requirements common to wave energy market applications. This framework guarantees the seamless traceability of design information for each stage of the design process together with a three-level hierarchy of metrics.

1.4.3 Assessment of wave energy technology performance

The result of the performance evaluation for a wave energy concept offers an estimate of how close or distant the technology is from reaching its techno-economic objectives. It is essential to understand that most estimates of wave energy are based on projected data. The assessment method introduces risks due to the reliance upon projected figures, which can be significant depending on the stage of technological progress, the amount of innovation, the quality of the assumptions, and the evaluation detail. The projected accuracy of the estimations will increase as development proceeds, resulting in a decrease in the uncertainty range.

A qualitative assessment of the Global Merit of a wave energy technology is enabled by an aggregation method of metrics based on the Logical Scoring of Preference (LSP) theory. Besides, two new concepts are introduced for performance benchmarking of wave energy technologies. Commercial Attractiveness (CA) enables not only the selection of the best wave energy alternative for a certain market application but also the comparison of technologies across various market applications. The concept of Technical Achievability (TA) provides a method to assess the ability of technologies under development to achieve the system requirements, based on the unmet performance and the Degree of Difficulty (DD). The DD is defined by technology maturity and fundamental limits.

1.4.4 Method to project future costs of emerging wave energy technologies

Direct LCOE computation is highly inappropriate for prototype technologies. Assessing the affordability of emerging technologies needs a future projection of costs with a reference to the mature technology and a first-of-a-kind commercial deployment.

Starting from the current breakdown of wave energy costs, the suggested approach allocates uncertainty bands depending on the estimation accuracy used to determine the first-of-a-kind cost of the commercial technology. After installing a certain capacity through several commercial projects, component-based learning rates are then used to estimate the LCOE of the mature technology. This method counters the human propensity to over-optimism in preliminary estimates, which produces highly unrealistic LCOE values for commercial technology. It offers a tool that may be used to investigate uncertainties, concentrate efforts on the accuracy of cost projections, and identify any lessons that might have been learned during the early stages of technological development.

Statistical propagation of uncertainties is achieved by combining uncertainties from multiple sources into the final LCOE metric. Besides, a disaggregated technique is utilised to consider individual learning effects at the component level, resulting in more accurate cost reduction estimates for technologies under development that lack historical data.

1.4.5 Innovation strategies to overcome technical challenges

The development of cost-effective wave energy systems is a difficult endeavour due to the size of the solution space, which calls for innovative technologies or designs. Many technical challenges remain unresolved and incremental innovation alone cannot fill the gap between the current techno-economic estimates and the medium-term policy targets established for wave energy.

A standard representation of wave energy subsystems and their interfaces is presented based on the Design Structured Matrix (DSM) method. DSM is a tool to support the wave energy system improvement, helping visualise potential problems that can lead to major changes in later phases, longer integration time, and greater uncertainties and risks.

Structured innovation methods are applied to point out potential innovation strategies. The TRIZ problem-solving approach has permitted the identification of the most impactful trade-offs and corresponding inventive principles having the greatest impact on the initial Stakeholder Requirements (SRs). Inventive principles suggested can be used to overcome the main technology showstoppers and recurrent challenges.

1.5 Thesis Structure

The remainder of the thesis is structured into seven chapters to address the research goal and objectives, as shown in Figure 1.2.

The following descriptions briefly outline the content of each chapter.

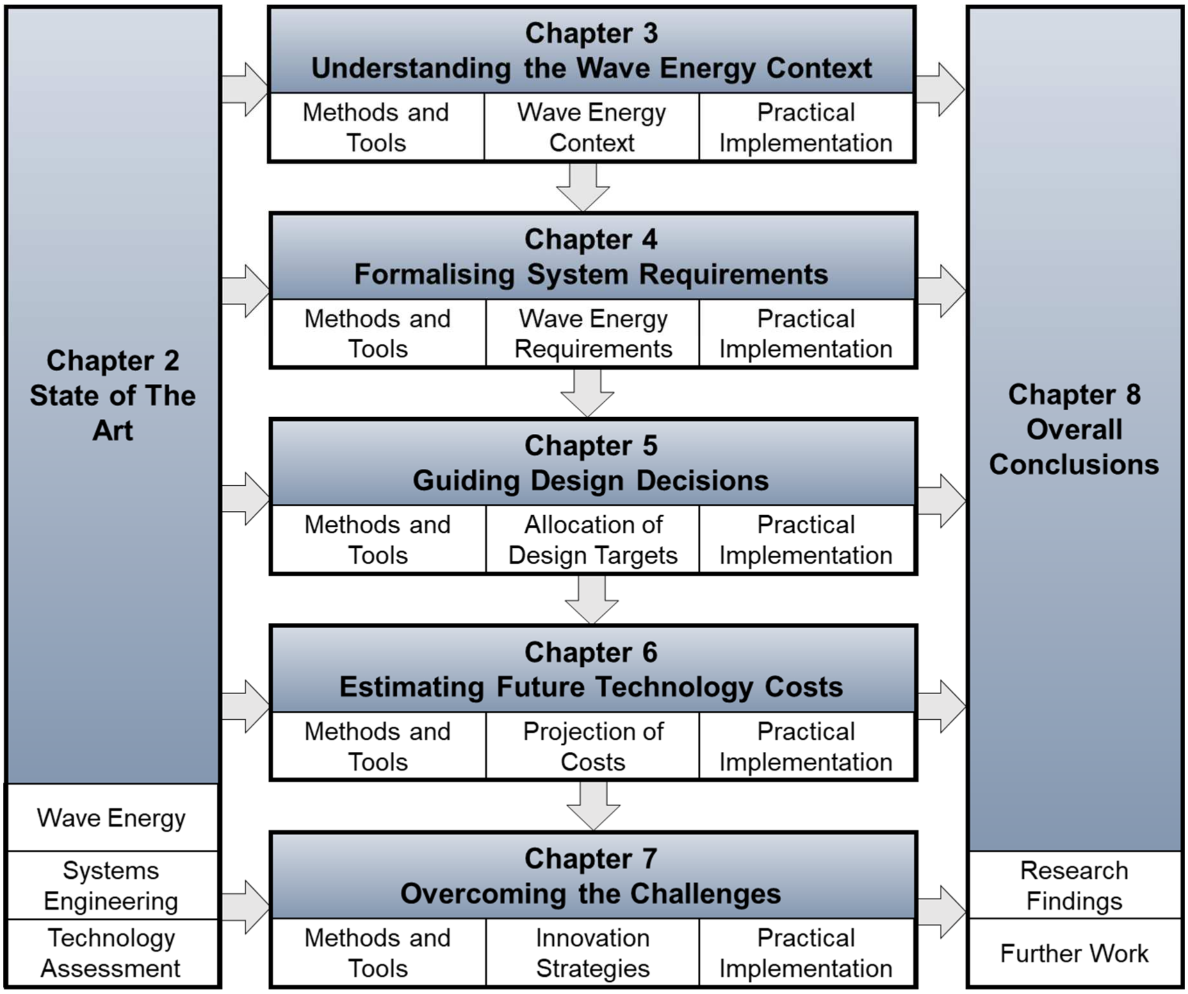

Figure 1.2: Summary of thesis structure.

CHAPTER 2: STATE OF THE ART

This chapter covers the literature review conducted to establish the main pillars of the novel methodology for the assessment of wave energy technology options at the early phases of the design process. The chapter is divided into three main areas: 1) Wave energy, 2) Systems Engineering, and 3) Technology performance assessment. It ends with a summary and conclusions.

CHAPTER 3: UNDERSTANDING THE WAVE ENERGY CONTEXT

This chapter provides an early understanding of the overarching context and its potential influence on system requirements and dependencies to ensure wave energy technologies meet stakeholders' expectations. The chapter is structured in three main areas: 1) Methods and tools used in this step of the methodology, 2) External forces acting in the wave energy context, and 3) Practical implementation and discussion of results. It ends with a summary of findings and conclusions regarding the prioritisation of System Drivers and Stakeholder Groups for two markets.

CHAPTER 4: FORMALISING SYSTEM REQUIREMENTS

This chapter builds a structured inventory of the goals that should guide the search for solutions. The chapter is structured in three main areas: 1) Methods and tools used in this step of the methodology, 2) Analysis of wave energy requirements, and 3) Practical implementation and discussion of results. It ends with a summary of findings and conclusions regarding the prioritisation of Stakeholder, Functional and Technical Requirements.

CHAPTER 5: GUIDING THE DESIGN DECISIONS

This chapter provides a holistic assessment of wave energy technology performance to guide design decisions throughout the various development stages, select the most suitable option for a particular market application, and identify the challenges to achieving system requirements. The chapter is structured in three main areas: 1) Methods and tools used in this step of the methodology, 2) Assessment of wave energy capabilities, and 3) Practical implementation and discussion of results. It finishes with a summary of findings and conclusions on the Commercial Attractiveness and Technical Achievability of wave energy technologies.

CHAPTER 6: ESTIMATING FUTURE TECHNOLOGY COSTS

This chapter seeks to improve the accuracy, consistency, and usefulness of projected cost predictions for emerging wave energy technologies. The chapter is structured in three main areas: 1) Specific methods and tools, 2) Future costs of wave energy, and 3) Practical implementation and discussion of results. It ends with a summary of findings and conclusions regarding the several paths that emerging technology make take depending on the uncertainty range and learning capacity.

CHAPTER 7: OVERCOMING THE CHALLENGES

This chapter explores the solutions space and provides structured innovation approaches to overcome the performance barriers identified in the development of wave energy systems. The chapter is structured in three main areas: 1) Specific methods and tools, 2) Innovation strategies, and 3) Practical implementation and discussion of results. It ends with a summary of findings and conclusions regarding the desirable characteristics of a wave energy system architecture and some potential innovation areas worth exploring.

CHAPTER 8: OVERALL CONCLUSIONS

This chapter summarises the main research findings and contributions to the state-of-the-art of this research in the wave energy field. The benefits and limitations of the novel method are examined, and the broader implications of the study are discussed. Finally, an overview of potential areas for further work is presented.

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CHAPTER 2 STATE OF THE ART

“I never did anything alone. What was accomplished, was
accomplished collectively”

Golda Meir (1898 – 1978)

2.1 Overview

This chapter reviews three topic areas relevant to this research: 1) Wave energy, 2) Systems Engineering, and 3) Technology performance assessment. Together they provide the background for the development of the novel methodology.

Section 2.2 introduces wave energy's resource potential and briefly describes the history and recent developments. Besides, a technology classification and system breakdown are suggested to understand and bring structure to the large variety of wave energy concepts.

Section 2.3 presents the design methods successfully used in analysing and solving complex engineering problems. Systems Engineering provides tools to organise and propagate design information, define the problem space and search for solutions. The extent to which Systems Engineering methods have been applied to wave energy is thoroughly reviewed.

Section 2.4 describes the evaluation framework for wave energy technologies. It includes the review of the assessment criteria hierarchy, and the aggregation structure together with the effort, relevance and impact of the assessment, and projection of future costs.

Finally, section 2.5 summarises the chapter and discusses some partial findings that drive the research work in the following chapters.

2.2 Wave Energy

2.2.1 The Resource Potential

Wave energy can be considered a derived and concentrated form of solar energy. The differential solar heating of the earth's surface creates winds and, in turn, the action of the wind blowing across the surface of the oceans produces waves. The power in a wave is proportional to the wave period and the square of the wave height [19]. Moderate ocean swells, in deep water, can carry an energy flux exceeding 40-50 kW per meter of wave crest [20]. Wave power decreases exponentially with the water depth. In fact, in deep water, 95% of the energy transport occurs between the surface and a quarter of the wavelength [21].

This largely untapped renewable energy source is attractive for several reasons:

- The global wave resource is abundant, predictable and widely distributed,
- It has a higher power density than other renewable energy sources,
- It can be a local resource for a large proportion of the world's population living near the coasts with low environmental and visual impact.

The theoretical worldwide wave energy potential has been estimated as 29,500 TWh/year [22], roughly equating to the global electricity production in 2021 [23]. However, these estimates do not account for geographical, technical or economic constraints and the total energy that could be practically harnessed will eventually be an order of magnitude less. The practical worldwide wave energy potential has been considered to be in the range of 2,000-4,000 TWh/year [24], similar to today's wind energy or annual hydropower production. This is still a significant resource with the potential to supply about 10% of the global electricity demand.

Wave energy can generally be predicted several days in advance, as waves result from the action across the surface of the ocean and then can travel very large distances almost without energy loss. Like most forms of renewables, wave energy is unevenly distributed over the globe and can display large variability across different time scales.

Figure 2.1 shows the regional distribution of the global annual wave energy potential, whereas Figure 2.2 presents its seasonal variability. As it can be appreciated, this resource is most abundant in the mid (~30°) to high (~60°) latitudes of both hemispheres, caused by the predominant western winds blowing in these areas. Southern and Western seaboards of Australia, New Zealand, South Africa and Chile have high average wave power with low seasonal variability. The North Atlantic coastline also has high average wave power but seasonal variability. Finally, the Western coast of the USA and Canada display medium average wave power with medium seasonal variability.

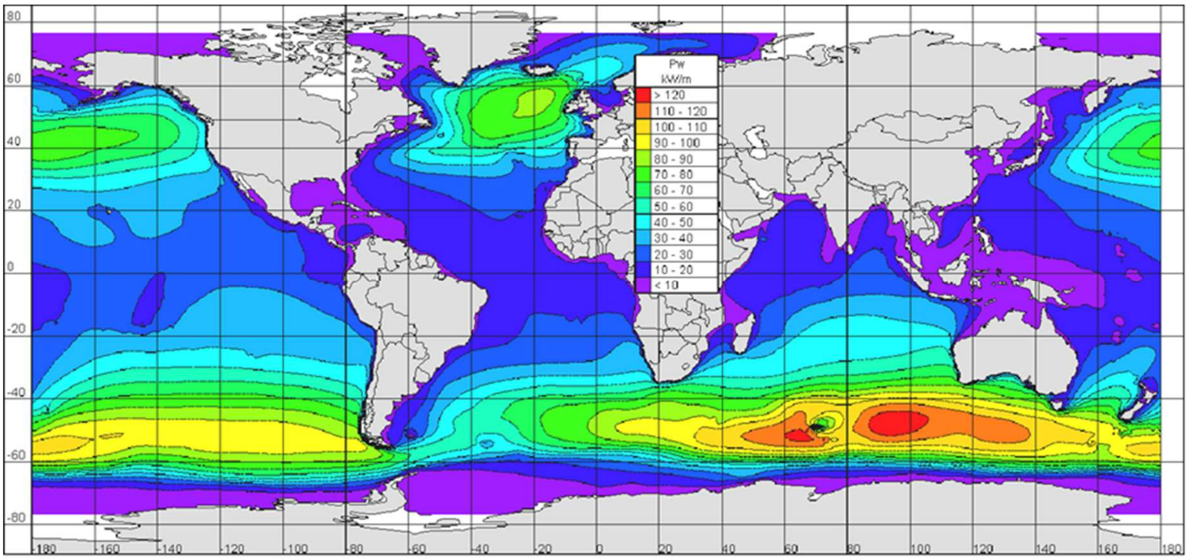


Figure 2.1: Global distribution of annual mean wave power in kW/m [25].

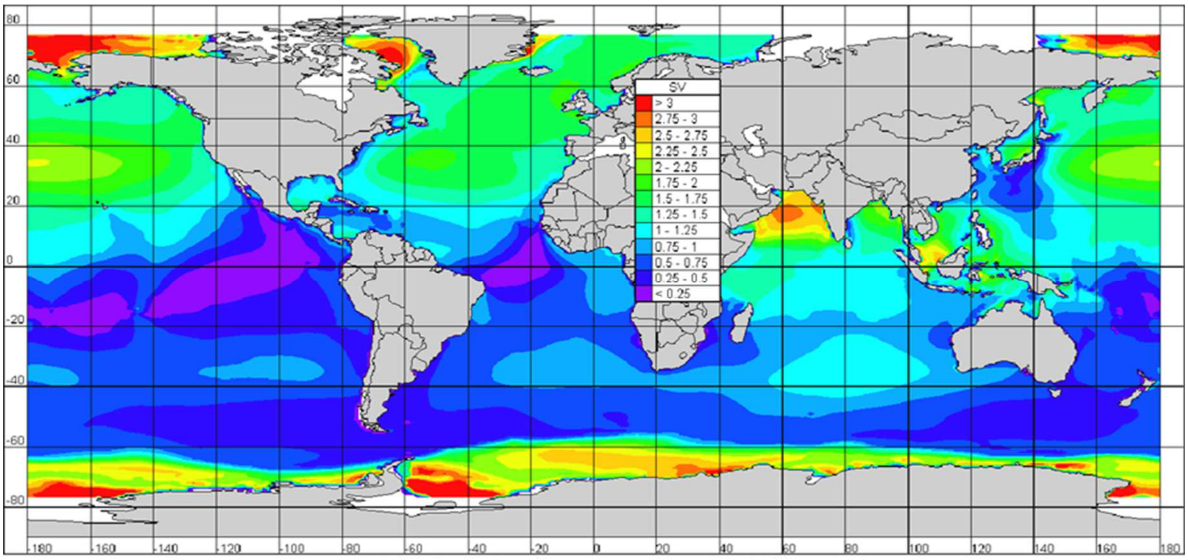


Figure 2.2: Global distribution of wave power seasonal variability [25].

Wave energy is a highly concentrated energy resource. The average energy transport is typically five times denser than wind and at least ten times denser than solar energy [26]. Furthermore, wave energy can provide a good correlation between resource and demand, since around 40% of the world's population lives within 100 km of the coasts [27].

2.2.2 Brief Historic Review

The prospect of capturing wave energy and transforming it into usable energy has long inspired the ingenuity of numerous inventors. The development of wave energy conversion can be traced back over two centuries. The first patent to provide power from ocean waves was filed in France in 1799 by Messrs Girard, father and son [28]. Since then, more than 3,000 applications have been filed worldwide, and this number has not yet stopped growing.

The European Marine Energy Centre (EMEC) lists 256 concepts on its website [29]. Besides, the ELBE project identified 87 companies in 2021, 60% still in the early phase of development [30]. One reason for the large diversity of concepts is the wave energy resource’s high temporal and geographical variability.

The history of wave energy has undergone a cyclic process of optimism, setback and reassessment [5]. In the early years of wave energy development, many concepts were proposed. Progress was slow and inconsistent as inventors lacked a complete understanding of the complex hydrodynamic interactions. Figure 2.3 illustrates the main milestones from this early period, which ended with the first commercial application of wave energy, a navigation buoy from Japanese commander Yoshio Masuda, considered the father of modern wave energy technology [31].

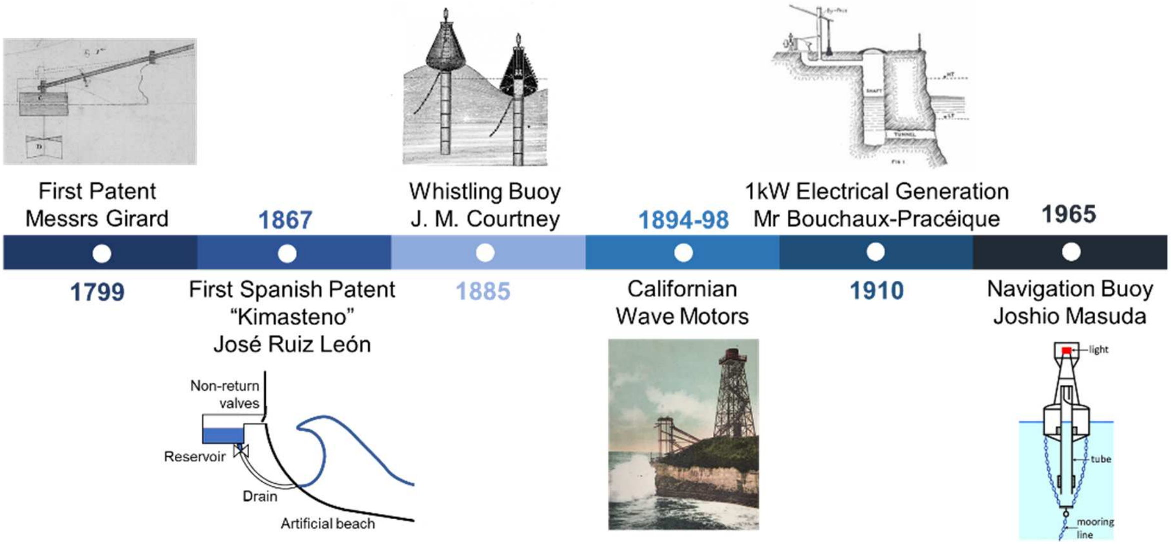


Figure 2.3: Milestones of wave energy development: Early history (1799-1970).

The oil crisis of 1973 triggered a significant change in the renewable energy scenario, drawing attention to wave energy. A scientific paper published in 1974 by Stephen Salter [32] became a landmark for the research community. This was the time for the first pioneers of the hydrodynamic theory and maximum power absorption, the first National funded concepts and the first scientific conferences. In this period, many concepts of wave energy technologies were proposed whose design sought to maximise the annual power generation. Figure 2.4 illustrates the main milestones from this period.

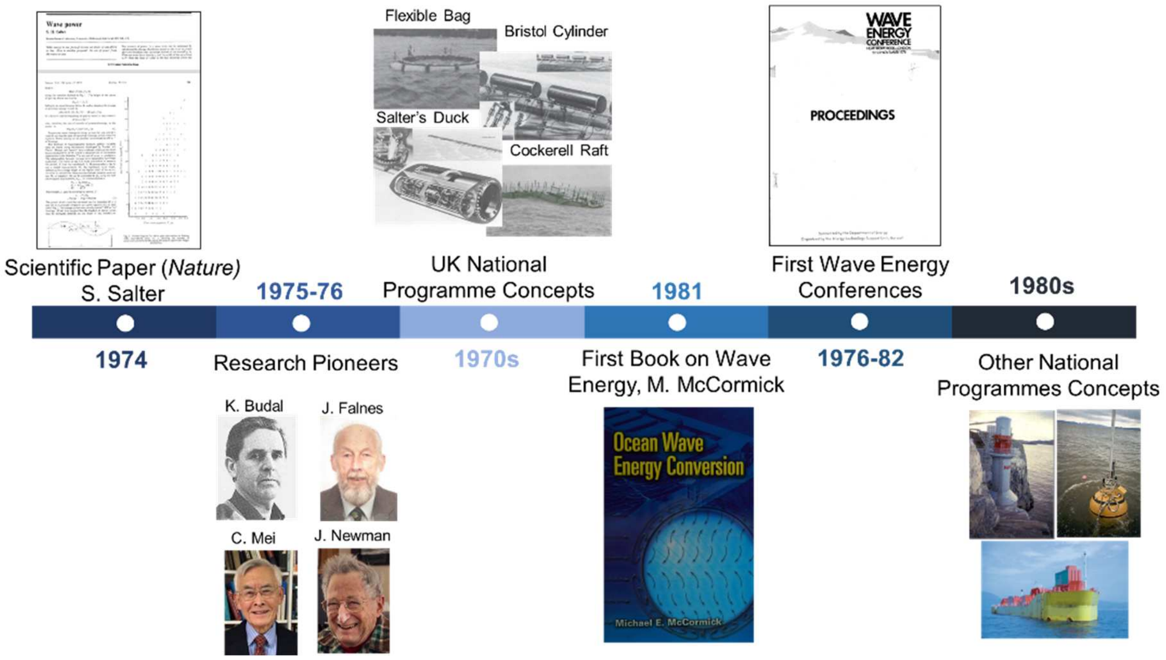


Figure 2.4: Milestones of wave energy development: Age of Enlightenment (1970-1990).

More recently, concerns about climate change, the security of energy supply and an increase in energy prices renewed the interest in other renewable sources, and more precisely in wave energy. The available R&D funding in this period increased steadily from the first preliminary actions started in 1991 to the most recent programmes. Fruit of this European and National support, a wealth of prototypes was developed, and a small portion was demonstrated at sea. Survivability concerns mainly drove the design of wave energy technologies. International conferences, cooperation and standardisation facilitated sharing of good practices and promoted consensus in the sector. Figure 2.5 illustrates the main milestones from the contemporary age. Despite the considerable efforts, the only grid-connected project is the Mutriku Wave Power Plant, which has been continuously operating since 2011 and delivered more than 2.7 GWh.

Figure 2.5: Milestones of wave energy development: Contemporary age (1990-2020).

Despite the increased efforts over the last decades, harnessing wave energy continues to fox the best engineering minds. Failure of the wave energy industry to deliver on the initial expectations of investors has once and again delayed its commercial-scale development [3]. Although technologies have not reached full maturity, there is still significant activity in wave energy development around the world, including in the United Kingdom, Europe, the United States, Australia, Japan, China, and India. Further R&D is needed to explore and identify the best solutions and to achieve convergence in design.

2.2.3 Technology Classification

The design of effective wave energy devices is a complex endeavour that brings into play a large set of decisions. Many design parameters, such as the size and deployment position or the extraction principle, must be selected at an early stage. Even though wave harnessing concepts are so diverse, technologies can be classified according to three main criteria: device location, orientation and working principle.

To begin with, the classification based on the device location and distance to the coast distinguishes among three generations of devices (see Figure 2.6). This classification was adopted by the European thematic network WaveNet [33].

- **Onshore** (first generation). Devices which are fixed to or embedded in shorelines, from where the electricity is easily transmitted. These are less energetic locations due to energy loss as the waves reach the shore. Examples include Mutriku [34] and SSG [35].
- **Nearshore** (second generation). Floating or bottom-mounted devices installed in shallow waters (10-40 m). Devices must be placed beyond the breaker zone to avoid any survivability issues. Performance might be sensitive to tidal range. Examples include WaveRoller [36] and CorPower C4 [37].
- **Offshore** (third generation). Floating or submerged devices deployed in deep waters. They benefit from the much larger energy resource but also imply higher costs of seakeeping and energy transmission to shore. Examples include Mocean [38] and SBM S3 [39].

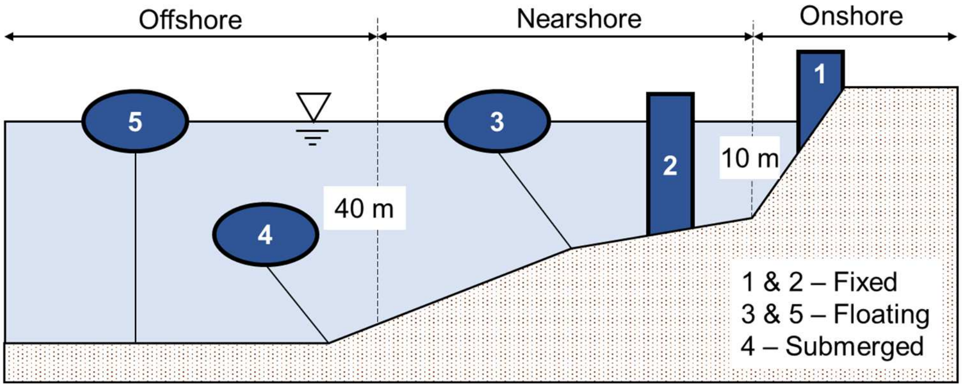


Figure 2.6: Classification according to the device location.

The second classification considers the device size and orientation concerning the dominant direction of the incident wavefront (see Figure 2.7). This classification originated in the work by Budal and Falnes in 1975 and was later extended by Falnes and Hals [40].

- **Terminator** (T). A device with has a larger dimension in the direction across the predominant wave crests. The main dimension is larger than one wavelength. Examples include Wave Dragon [41] and CycWEC [42].
- **Attenuator** (A). A device with a larger dimension aligned with the direction of the predominant wave propagation. Examples include Pelamis [43] and Anaconda [44].
- **Point Absorber** (PA). A device with small dimensions relative to the incident wavelength and able to absorb energy from all directions. Examples include OPT-PB3 [45] and AWS [46].
- **Quasi Point Absorber** (QPA). An axisymmetric device with relatively large dimensions compared with the wavelength. The primary dimension is between a PA and a Line Absorber (i.e. the aggrupation of T & A). Examples include OE Buoy [47] and Wello [48].

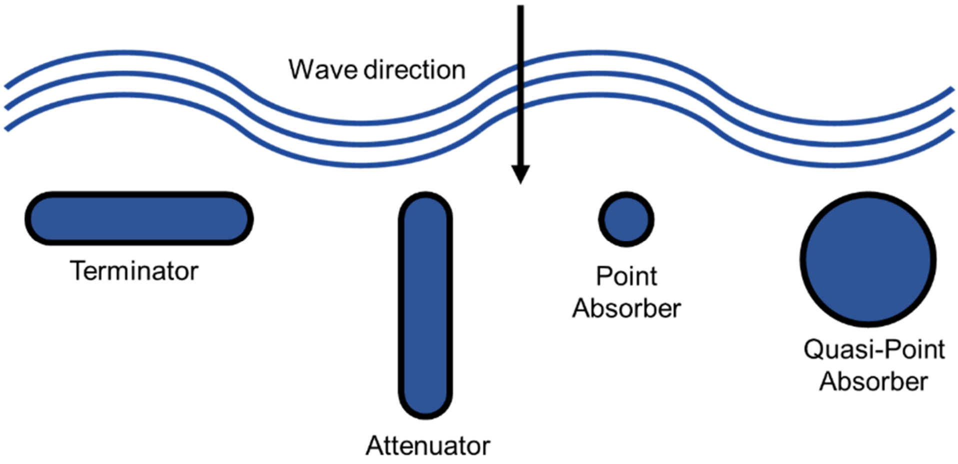


Figure 2.7: Classification according to device orientation (adapted from [49]).

The great diversity of concepts has motivated a third classification of devices. This time, devices are classified according to their working principle. The nine groupings are based on recent classification efforts of [2], [3], [50] and [51].

- **Oscillating Water Column** (see Figure 2.8-a): Partially submerged structures open below the sea level and with air trapped above the water surface. Incoming waves make oscillate the water surface within the device, moving the air like a piston. Examples include Mutriku [34] and OE Buoy [47].
- **Hinged Contour** (see Figure 2.8-b): Devices with two or more separate bodies that move relative to each other as a wave passes them. Energy is extracted from

the reaction between the individual components. Examples include Pelamis [43] and Mocean [38].

- **Buoyancy** (see Figure 2.8-c): Energy is extracted from the motion induced as waves pass the relatively small buoyant bodies. Examples include OPT-PB3 [45] and CorPower C4 [37].
- **Oscillating Wave Surge** (see Figure 2.8-d): Devices which extract energy from wave surges and the movement of water particles within them. Examples include WaveRoller [36] and WavePiston [52].
- **Overtopping** (see Figure 2.8-e): Devices which are essentially reservoirs that waves fill with water. The water is then returned to the sea via a turbine. Examples include SSG [35] and Wave Dragon [41].
- **Submerged Pressure Differential** (see Figure 2.8-f): Submerged devices in which a pressure differential is created as the wave passes above due to the sea level fluctuation. The alternating pressure is used to generate energy. Examples include AWS [46] and mWave [53].
- **Bulge Wave** (see Figure 2.8-g): Submerged tubular devices filled with pressurised seawater and moored to the seabed. The passing wave causes pressure variations creating a bulge that travels along the length of the tube and is used to generate energy. Examples include SBM S3 [39] and Anaconda [44].
- **Inertia** (see Figure 2.8-h): Devices that use the motion of the waves to rotate, swing or precess an inertial mass. Examples include Wello [48] and ISWEC [54].
- **Lift Force** (see Figure 2.8-i): The passing waves produce lift on a hydrofoil creating a torque at the main shaft of rotation. Examples include CycWEC [42] and LiftWEC [55].

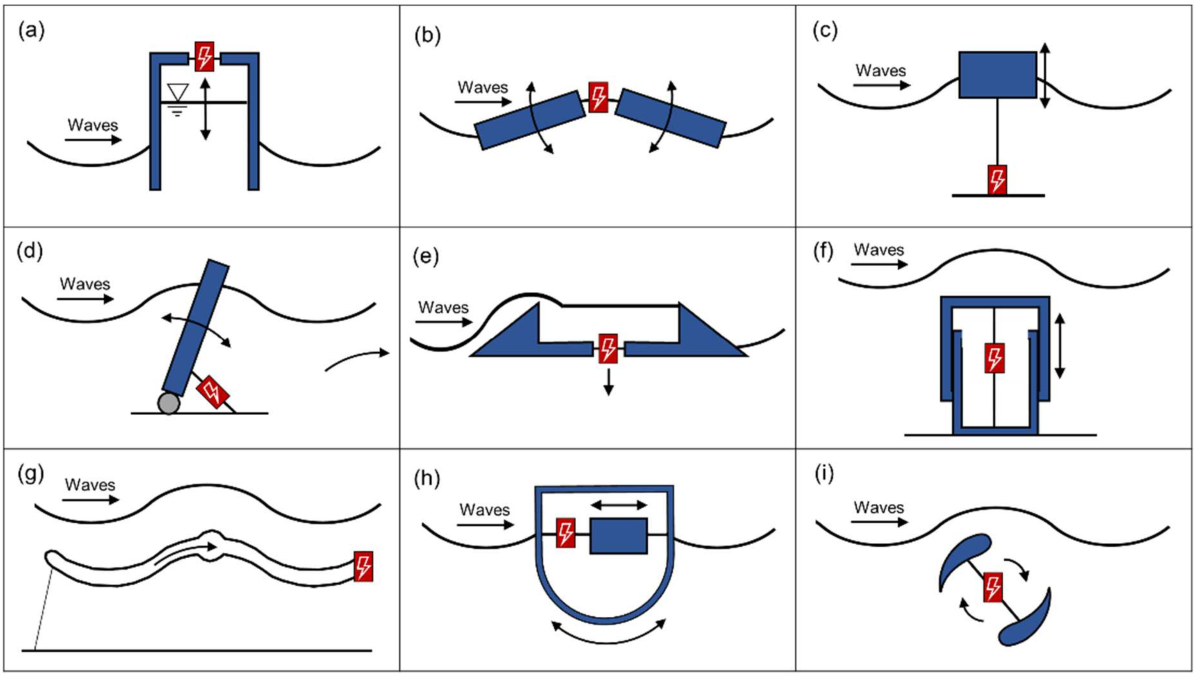


Figure 2.8: Classification according to device working principle.

2.2.4 Main Subsystems

An overview of the key subsystems that require consideration for wave energy systems is provided in [56], [57] and [58]. According to these sources, the WECs can be grouped into five main subsystems, Reaction System, Power Take-Off, Hydrodynamic System, Power Transmission and Control, leading to many combinations. The large variety of wave energy concepts makes it challenging to analyse all possible decompositions and to produce a generic and manageable system breakdown.

Thus, the standard approach adopted in the sector is to define the high-level breakdown concerning the various functions the device must fulfil. The taxonomy of subsystems described below is mainly derived from [56] and [59].

Table 2.1: System breakdown for wave energy technologies.

Function	**Subsystems**
Capture energy	Hydrodynamic System (HS)
Provide reaction point	Reaction Body (RB)
Convert energy	Power Take-Off (PTO)
Store and condition energy	Storage and Power Conditioning (SC)
Deliver energy	Transmission System (TS)
Maintain position	Station Keeping (SK)
Control operation	Instrumentation and Control (IC)

Hydrodynamic System (HS). This term describes the device structure and mechanisms directly interacting with the waves, which can be either floating or submerged. It is therefore the primary wave absorption system. The HS is connected to the RB and the PTO for the active transfer of forces and motions.

Reaction Body (RB). It is the structure that provides a reaction point for the PTO and/or support for the HS. Three main reaction types can be identified (see Figure 2.9):

- **Fixed reference**: A static coupling to the Seabed or a dynamic one through the SK. In the latter, the RB has a large mass to emulate a fixed reference avoiding the need to adjust to the tidal range.
- **Self-reference**: In this case, the HS reacts against another HS without needing a physical RB.
- **Inertial reference**: The RB is somehow encapsulated within the HS and reacts against it. Examples are a pendulum, sliding or rotating mass, trapped water and gyroscope. The RB mass is smaller than that of the HS.

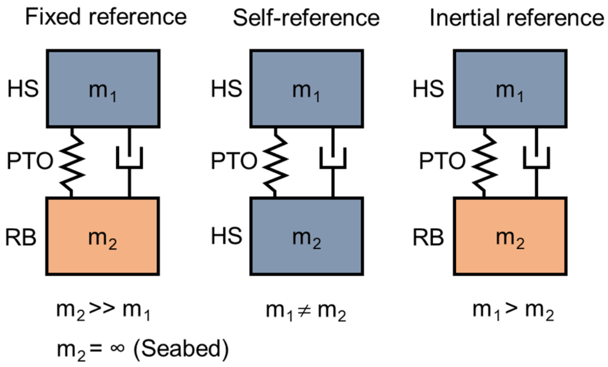


Figure 2.9: Types of reaction points.

Power Take-Off (PTO). This system converts the mechanical energy extracted from the waves into a useful form, generally electricity. Several alternative configurations have been proposed involving a combination of fluid, mechanical and electrical power flows (see Figure 2.10).

For each primary energy conversion stage, different commercial solutions exist (see [60], [61]):

- **Air Turbine**: Wells turbine, Dennis-Auld turbine, Impulse turbine, Bi-radial turbine.
- **Hydro Turbine**: Pelton turbine, Kascheme turbine, Francis turbine.
- **Hydraulic System**: Hydraulic ram, Hydraulic pump.
- **Mechanical Transmission**: Gearbox drive, Rack and pinion drive, Ball screw drive.
- **Direct Drive**: Linear generator, Ball screw generator, Electroactive polymers, Triboelectric nanogenerators (TENGs).

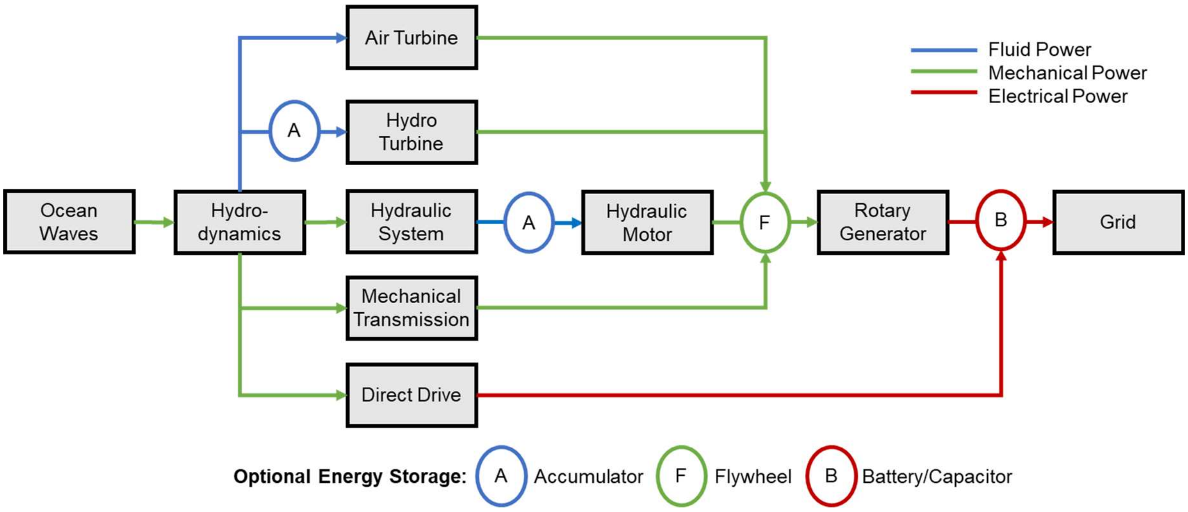


Figure 2.10: Alternative PTO Configurations.

Storage and Power Conditioning (SC). The instantaneous wave power absorbed by the PTO fluctuates broadly between individual waves and wave groups. When present, this optional subsystem aims to avoid excessive peaks, allow a smooth output and improve the power quality. Depending on the WEC configuration, it can be placed at different points of the transformation chain (see Figure 2.10) and can make use of either fluid power (Accumulator), mechanical power (Flywheel), electrical power (Battery, Capacitor, Inverter) or a combination of them.

Transmission System (TS). This is the method by which energy is transferred to shore. It generally involves aggregation, export and grid connection. Although topologies vary, electricity transmission from individual devices to an onshore substation requires inter-array cables connected to a collection point, which is likely to involve step-up transformation and isolation switchgear and an export cable.

Station Keeping (SK). This system maintains the device in position relative to the seabed. It can be either rigid (foundation) or compliant (mooring). The former is more likely to be used nearshore (i.e. shallow water), whereas the latter is more appropriate for offshore locations (i.e. deep water). Mooring systems are comprised of one or more lines and an anchoring system. In turn, mooring lines can be slack, taut or combined.

Instrumentation and Control (IC). Hardware and software systems to safeguard the device and optimise its performance under a range of operating conditions. They comprise sensors, data acquisition, communication, and data transfer equipment to implement control actions.

2.3 Systems Engineering

2.3.1 A Systematic Problem-solving Approach

Systems Engineering (SE) has a relatively short history. The first documented use of this term dates to Bell Telephone Laboratories in the early 1940s [62]. Developed at Bell Labs in the following decade, SE was further refined during the successful NASA Apollo programme in the 1960s. Since then, it has evolved into a formal discipline that can be adapted to various types of product developments.

SE uses a system thinking approach to analyse engineering problems. The individual outcome of such efforts is the engineered system. A system can be defined as an interacting combination of elements to accomplish a defined objective [63].

Fundamental to SE is the notion of the system life cycle [64]. The life cycle of a product begins with the identification of a need. It extends through conceptual and preliminary design, detailed design and development, manufacture and installation, operation and maintenance, decommissioning and finally disposal or recycling.

The need for SE arises with the increase in the complexity of engineered systems. SE is a holistic, top-down approach to understanding stakeholder needs, exploring opportunities, documenting requirements, and synthesising, verifying, validating and evolving solutions while considering the complete problem [63]. The ambiguity in defining the requirements and the lack of proper planning are the major factors that drive the need for a SE approach [65].

SE hinges upon several fundamental principles. Among them, five of the most important ones are [66]:

- **Abstraction**. SE is based on the idea that the purpose of design is not to produce a concrete solution but to create an abstract entity called a system. Such a system can then be materialised through several different solutions.
- **Decomposability**. A system can be broken down into separate elements (modularisation) that may cover several layers (hierarchy). These elements have an integrative architecture.
- **Pluralism**. The system can be addressed from complementary points of view, which must be organised in ways that permit the sharing of complex knowledge.
- **Alignment**. SE concerns both the product and the way the design is organised. Developing a solution requires aligning design processes and product structure.
- **Incremental improvement**. Design organisation is based on “routines” that can be codified, generalised, learned and re-cycled from one project or team to another.

SE is about both design and decision-making [66]. The success of any complex engineering project depends upon four main activities:

- Identifying and evaluating alternatives,
- Managing uncertainty and risk,
- Designing quality into a system, and
- Dealing with project management issues.

The first activity is critical as it defines the probability of success, whilst the rest help the engineer to avoid any errors. A Systems Engineer needs to understand that decisions must be made with the best information available at the time, and therefore there are always subject to some degree of uncertainty.

SE approaches and methods have been successfully applied in many industrial sectors (e.g. automotive, aerospace, oil & gas) to develop innovative products meeting very diverse and demanding stakeholder requirements. Several standards have been developed for SE such as [67], [68], and [69].

Through the years, the initial practice-based SE has been enriched with a plethora of theoretical approaches, tools and models in different SE schools worldwide [70]. Among the many methodologies used, the SE approaches can be grouped into three categories according to their primary focus:

- Generic design methodologies such as Systematic Design [16], [71], and Axiomatic Design [72];
- Process-oriented methodologies such as Concurrent Engineering [73] and Design Structure Matrix [74]; and finally
- Design methodologies to achieve concrete goals such as DfX [75], QFD [76], FMEA [77] and TRIZ [78].

Abstract models are replacing the traditional document-based SE as the primary means of retaining and communicating information. Model-based Systems Engineering (MBSE) enhances the ability to capture, analyse, share, and manage the data associated with the specification of a product [63]. MBSE helps to identify issues early in the system definition, thus improving system quality and lowering both the risk and cost of system development.

As introduced in CHAPTER 1, initial ideas or expectations about the engineering system are built on a relatively insecure information basis at an early stage [79]. Frequently, neither the problem nor the solution field is particularly well-known. Therefore, a systematic and well-structured process should underpin the search for solutions and selection.

2.3.2 The Concept of Design Domains

The design of a new product is an endeavour that involves a mix of creativity, technical skills and decision-making. No matter where an innovative concept may come from, its realisation should always be the outcome of a thorough design process. To that purpose, organising the design information is critical.

Design involves an interplay between what the engineer wants to achieve and how this need is satisfied. However, there is no single commonly acknowledged sequence of steps in engineering systems design. The concept of design domains helps systematise this process by creating boundary lines between different design activities [72].

Design domains provide engineers with an improved way of arranging design information to facilitate better SE [80]. They help to organise information on requirements and to discriminate it from the information associated with design solutions. The systematic presentation of information stimulates the search for solutions and facilitates identifying and combining essential solution characteristics [71]. Ultimately, this framework avoids quantum leaps from the initial requirements to the physical realisation that are ad hoc, inefficient, ineffective, and often lead to cost and schedule overruns [81].

Design domains structure information in particular ways to accommodate their own needs. Much attention should be paid to the consistency of information within and across domains. Each design domain has an associated model, which acts as a framework for capturing domain-specific information. Depending on the actual level of abstraction and degree of detail, different models can be used to represent a system in each domain [82].

Even though most SE approaches agree on the benefits of arranging design information in different domains, there is a lack of consensus on defining the domains common to all engineering projects. Table 2.2 presents a representative sample of design domains identified by different authors. Hyphens (-) in cells denote the authors do not cover the corresponding design domain.

Table 2.2: Design domains according to different authors.

SE Approach	**Design Domains**					
	Environ.	**Stakeholder**	**Functional**	**Technical**	**Physical**	**Process**
Suh [72]	-	Needs or attributes	Functional requirements	-	Design parameters	Process variables
Wasson [81]	-	System requirements	Operations & Behaviours	-	Physical implementation	-
Mizuno & Akao [76]	-	Customer needs	Design requirements	-	Components	Manufacturing requirements
Pahl & Beitz [71]	-		Functional decomposition	Working principles	Physical design	-
Hansen & Andreasen [82]	-	-	Transformations, Functions	Organs	Parts	-
Erens [83]	-	(Specifications)	Functions	Solution principles	Assemblies & parts	(Process chains)
Bartolomei [80]	System drivers	Stakeholders	Objectives & Functions	Objects	-	Activities

Up to six different design domains are described in SE literature. However, individual frameworks typically limit their use to a maximum of 3-4 domains. It is worth mentioning that a single source [80] considers the **environmental domain** in his conceptual framework. The environmental domain accounts for the exogenous components that affect or are affected by the engineering system. This domain can be characterised by system drivers and system drivers' interactions.

The **stakeholder domain** defines the design problem in the customer's language, which is still general, ambiguous and highly unmeasurable. Stakeholders and their relationships represent the human components interacting with the system. Key stakeholders are those who can significantly influence the project or who are important to its success. Stakeholder needs, attributes or requirements are a set of desirable characteristics that the final solution should satisfy. Some frameworks, such as Erens [83], do not consider this domain. In that case, it is argued that the initial specifications cannot be attributed to one domain as they provide an often-informal description of the required function and the technological and physical constraints.

The **functional domain** is formalised in every framework. The functional domain aims to produce a complete, unambiguous, technology-agnostic definition of the design problem space. Functions describe the purposes of the engineering system. The functional analysis in SE aims to define the system's functional (or logical) architecture and characterise its functional behaviour. It is important to note that every system operates in different phases during its lifecycle (i.e. pre-mission, mission and post-mission) which need to be accounted for when identifying the appropriate functions [81].

The solution space is characterised by the technical, physical and process domains. Some authors, such as Pahl & Beitz [71], Hansens & Andreasen [82], and Erens [83] distinguish the technological realisation of the design problem consisting of a set of modules, organs or solution principles from the physical implementation of the technologies that are allocated or distributed into components and parts. Together, the **technical and physical domains** describe the physical embodiment to achieve the system functions.

Finally, the **process domain** determines the process variables, manufacturing requirements and activities that enable the production of specific components and assemblies to achieve the final system. Some authors exclude this domain from their frameworks as they mainly focus on conceptual and embodiment design.

2.3.3 Matrix-based Modelling Methods

System design requires integration and iteration activities, invoking a process that coordinates synthesis, analysis, and evaluation over the system life cycle. Design results from a series of mappings across design domains as shown in Figure 2.11. The design of an engineering system is hindered if these domains are not linked consistently.

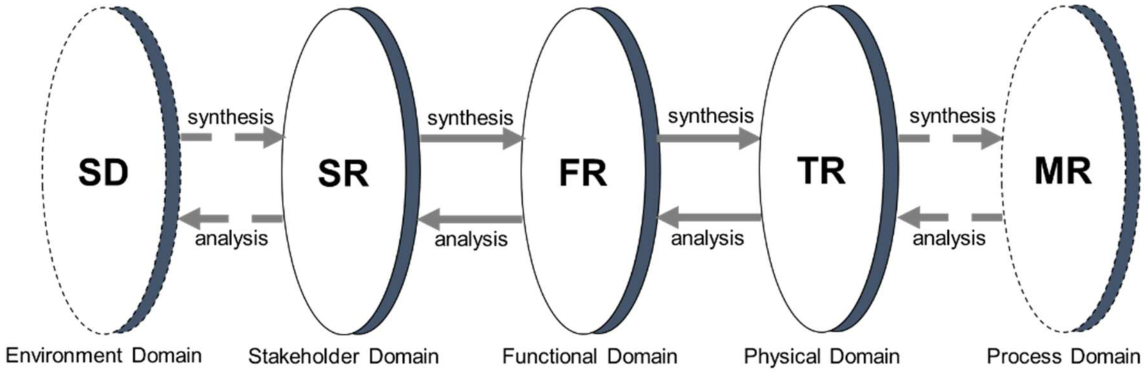


Figure 2.11: Domains of the design world (adapted from[84]).

The design takes place both within and between domains. The successful transition from different domains requires efficient design synthesis and analysis processes. Moving from left to right illustrates the engineer’s synthesis activity from what is needed to how to achieve the design that satisfies the requirements. Conversely, moving from right to left shows the engineer’s analysis activity, which supports validation and verification.

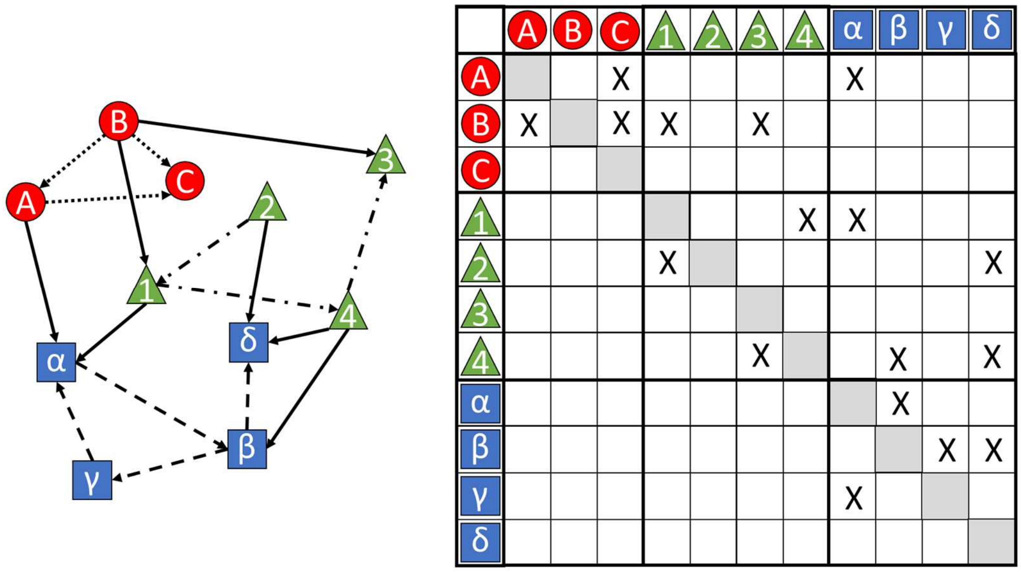
Synthesis is to be understood as a creative step, whereas analysis represents a critical step. The analysis drives the evaluation process and therefore the design decisions.

It is worth noting that the three central domains are also consistent with the design processes of the V-model [85], a popular SE approach. The V-model establishes a relationship between the system design definition and its associated system integration and evaluation.

Matrix-based design methods enable designers to arrange information, understand complex interactions, quantify interrelationships, and propagate information across design domains. These methods sequentially transform design information across domains starting from System Drivers (SDs) to Stakeholder Requirements (SRs), Functional Requirements (FRs), Technical Requirements (TRs) and Manufacturing Requirements (MRs). Translation of design information across domains should be performed to ensure full traceability of design. The purpose of traceability is threefold [86]:

- Manage engineering changes across the system development,
- Understand the decomposition of the system at each hierarchical level, and
- Manage the overall quality of the developed system.

There are several well-established matrix-based modelling frameworks [87]. These include intra-domain models such as the Design Structure Matrix (DSM) introduced by [88] and extended by [74]; inter-domain models such as the Cause and Effect Matrix [89], the Interface Structure Matrix [90] and the Domain Mapping Matrix [91]; and multiple-domain models such as QFD [76], Axiomatic Design [84], and the Engineering Systems Multiple-Domain Matrix [80], the Unified Program Planning [92], and the Function Transformation Matrix [93].



	A	B	C	1	2	3	4	α	β	γ	δ
A	▨		X					X			
B	X	▨	X	X		X					
C			▨								
1				▨			X	X			
2				X	▨						X
3						▨					
4						X	▨		X		X
α								▨	X		
β									▨	X	X
γ								X		▨	
δ											▨

Figure 2.12: Representation of dependencies in a multiple-domain model (adapted from [87]).

Figure 2.12 illustrates a conceptual representation of intra-domain dependencies (i.e. diagonal matrices A-B-C, 1-2-3-4 and α-β-γ-δ), inter-domain dependencies (e.g. A-B-C <-> 1-2-3-4 matrices) and multiple-domain dependencies (i.e. full matrix).

2.3.4 Requirements and Metrics

The formulation of requirements aims to build a systematic summary of the purposes underlying the search for solutions. A specification of requirements establishes the agreement of the technical capabilities and levels of performance required for an engineering system to achieve its mission and objectives within a prescribed solution space [81].

Requirements that bind a solution space are hierarchical and interrelated. They can be broken down at different levels of detail and should be fully traceable within and through the various design domains. At the high level, requirements focus on what should be achieved and not on how to achieve it. According to Kar and Bailey [94], the specification of requirements should be comprehensive, whereas individual requirements should be characterised by the following set of features: necessary, concise, achievable, complete, consistent, unambiguous and verifiable.

The satisfaction of requirements is the driving force behind SE. Therefore, verifying and validating those requirements is equally important to a successful SE. Decision-making is supported when the requirements at all levels can be balanced and evaluated against each other [95]. Verification and validation are evidence-based processes that rely on metrics and data to assess whether a system meets the specification of requirements. Metrics must be correctly defined and articulated for adequate verification and validation.

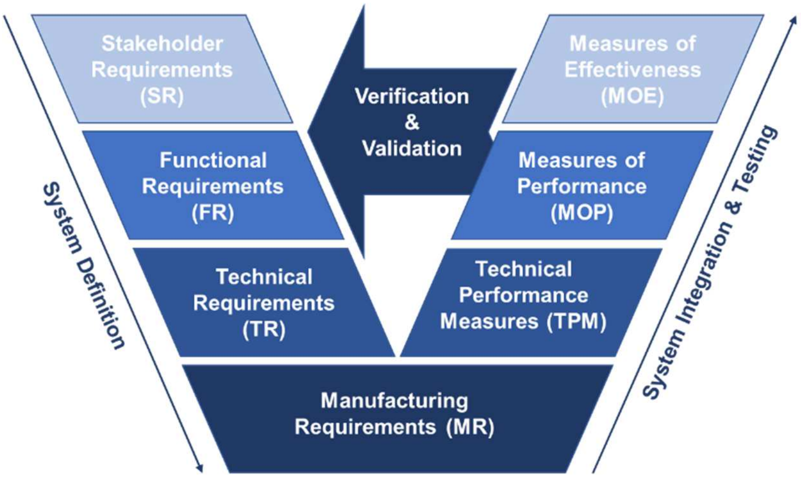


Figure 2.13: Requirements and Metrics in the Systems Engineering V-model.

Using the classical V-model, Figure 2.13 visualises the various hierarchy levels, showing the interrelations between requirements-based system definition processes and corresponding metrics-based verification and validation processes.

At the top level, the specification captures all essential and prioritised **Stakeholder Requirements** that fit within the technical, financial and risk constraints. SRs comprise operational requirements, which define the major purpose of a system, together with the key system constraints, such as physical attributes, overall performance and quality features [96]. Stakeholders may begin with desires and expectations that contain vague, ambiguous statements that are difficult to use for SE activities. Care must be taken to ensure that those desires and expectations are transformed into a set of clear and concise requirement statements that are useful as a starting point for system definition [63].

The SRs identify specific system properties that are needed to satisfy the end-user or stakeholder. Once the critical system properties are established, metrics must be assigned to offer the system engineer a means to assess various solutions. Metrics linked to the system's operational objective, performance, suitability and affordability are usually referred to as **Measures of Effectiveness** (MOEs). MOEs should not be strongly correlated to each other to provide insight into different operational aspects of the technical solution or solution alternatives. Since the other two evaluation metrics are successively derived from MOEs, their number should be reduced, often one for each major output from the system. Results from a questionnaire in [97] showed a range of 2 to 12 MOEs with an average of six.

At the next level, the specification moves onto the **Functional Requirements**. FRs specify what the system must do to achieve the SRs, but they do not address how the system should accomplish it. In other words, FRs should not go into the details of implementing the function. FRs establish the product's intended purpose, its associated constraints and environment, the operational and performance features for each relevant life-cycle situation, and the permissible flexibility [98]. They produce a complete, unambiguous, technology-agnostic definition of the design problem space and are the baseline for investigating and comparing candidate concepts. FRs are the bridge between the stakeholders and technical teams.

A system's capability is characterised by a function and its level of performance [81]. **Measures of Performance** (MOPs) are used to gauge the capabilities of a design solution specifically. Hence, establishing the MOPs will involve tracing FRs through the system's functional breakdown to specify a measure. Traceability should be maintained throughout the decomposition process and the higher-level MOEs. There are generally several MOPs (range of 1 to 10) for each MOE with a recommended average of five [97].

Technical Requirements define the issues related to the technology that must be considered to implement the system in physical parts and assemblies successfully. TRs depend on the design solution and are sometimes called Design Requirements. Design variables characterise the actual free space for creating solutions [79]. Whilst FRs describe what the system must do, TRs focus on how the system does it. TRs must be compatible with the intended purpose of the system, its associated constraints and environment, and the operational and performance features for each relevant situation of its lifecycle [98].

They are thus the practical baseline of the agreement for the technical team to design and develop the selected solution.

The key indicators used to demonstrate a compliant and successful delivery of specific and detailed technical requirements are called **Technical Performance Measures (TPMs)**. Selection should be limited to critical technical thresholds and goals that, if not met, put the project at risk in terms of cost, schedule or performance. They are usually derived from MOPs. Generally, there is at least one TPM per MOP, but often there are several TPMs (range of 1 to 7) per MOP with a suggested average of four [97].

Last but not least, **Manufacturing Requirements** are used to ensure producibility in early development phases and as a source for continuous improvement of the manufacturing system [95]. MRs are typically considered constraints since they limit the engineering system design. MRs are derived from the TRs product and the Manufacturing System. The Manufacturing System comprise materials, equipment and process parameters needed to produce the engineering system. As with any other system, **MOEs** can be used to measure the Manufacturing System's operational objective, performance, suitability and affordability.

2.3.5 Search for Solutions

The search for solutions is a constructive and creative step in SE. 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 [79]. The level of detail of the variants should be suitable to allow comparison and selection of the most appropriate one.

Several systematic search strategies can be used depending on whether the solution space is navigated linearly or cyclically. Mathematical algorithms can be used sometimes to find the optimal solution. However, to apply these techniques, it is necessary to develop quantitative models, and this renders their implementation difficult in complex engineering systems or, at least, only applicable to partial design areas. Search processes can be improved and supported by intuitive work that uses heuristics [99], based on a deliberate transfer of analogies, similarities or even oppositions as the TRIZ algorithm [78].

Solution alternatives are examined following a critical analysis process of their adherence to the initial requirements. Only suitable options are evaluated. Evaluation criteria are required for signifying which qualities or effects are considered essential. The various categories of metrics defined in section 2.3.3 serve both for solution validation and comparison of alternative solutions.

Trueworthy et al. [17] propose a Set-Based Design (SBD) approach for concept selection. Designers can avoid choosing a concept based on inaccurate data by developing many concepts and eliminating the inferior ones instead of selecting one for further development and iteration. When evaluating concepts, trade-offs and preferences can be included by combining utility analysis with SBD methods. To apply utility-based decisions in SBD, designers create a utility function that weights each concept's attribute. Within each attribute, the concept is given an interval score. The interval score allows the designers to account for the span of possible values given the imprecision of conceptual design.

Multi-criteria analysis methods inform the decision-making process for selecting solutions to complex engineering problems, mainly when alternative solutions can be heterogeneous. Many methods have been developed to solve different types of decision problems. However, the decision maker is faced with the arduous task of selecting an appropriate decision support tool [100]. One way to address this task is to look at the modelling effort (i.e. required input data) and the granularity of outcomes (i.e. feasible solution, partial or complete ranking). Multi-Attribute Utility Theory (MAUT) [101] is used at the highest modelling effort when a representation of the perceived utility for every selection criterion can be built. Analytical Hierarchy Process (AHP) methods [102] use pairwise comparisons between criteria and options at a medium scale of the modelling effort. Finally, at the lowest end of the modelling effort, Data Envelopment Analysis (DEA) [103] is mostly used for performance evaluation or benchmarking, where no subjective inputs are required.

Solving a real problem using a linear approach is seldom achievable. The SE approach can be applied iteratively to move towards an acceptable solution to a problem within a larger cycle of stakeholder value [63]. The evaluation is repeated at increasing levels of technological maturity as the concept progresses from an initial idea to a thoroughly tested and proven system. This iterative risk-based analysis method for product development is formalised in SE through the spiral model [85] and the Stage-Gate model [104]. Over the years, SE has developed many tools and techniques for risk management, such as FMEA [77], FTA [105], Fuzzy Logic [106], Bayesian Analysis [107] and Monte Carlo simulation [108]. If a SE approach is established early in the project, the system metrics achieved at any stage are compared to the design goals and improvements implemented, if necessary, to achieve these goals.

2.3.6 Application of SE Methods to Wave Energy

Wave energy technology is a clear example of a complex engineering product, whose development is inevitably multidisciplinary. So far, wave energy development experience shows that excellence in each discipline is a necessary but not sufficient condition to achieve a viable product. SE provides a framework for a holistic approach that might allow progress towards a successful wave energy technology [109].

The need for a more comprehensive systems perspective on the development of wave energy technologies was also highlighted in a recent workshop on identifying future emerging technologies in the ocean energy sector [60]. The report points out that some practical aspects neglected at an early stage can become a problem if taken up at a later stage. Therefore, technology developers should move from a sequential to a system design process. To overcome failures previously experienced in the sector, an integrated systems approach is required to develop wave energy systems; subsystems cannot be developed in isolation.

Similarly, sector experts have recognised SE principles as a way to accelerate marine energy research [110]. Survey results recommended focusing on common components to enable affordable ways to harvest marine energy and not on specific technologies. Experts also suggested proving that a system works reliably, checking its functionality in the early project stages and consequently focusing on end-user requirements.

As presented in section 2.2, wave energy technologies span a broad design space. The variety of concepts makes it extremely difficult to identify common design approaches. Moreover, there is little published work on the specific design methods used in developing these devices since most technology developers are private companies.

Even though some companies seem aware of existing SE methods, it is a strikingly recent phenomenon (only documented in the last 10-year timeframe). Also, the application of SE might have been limited and fragmented, since these technology developers have not been free from suffering expensive, high-risk, slow, rigid and discontinued technology developments.

A small fraction of references to activities carried out during the **environmental analysis** can be found in the literature:

- Bull et al. [111] presented the context diagram used to define the external systems that directly influence the success of a grid-connected wave energy farm. This list identifies the factors that are out of the control of the external systems and the farm (i.e. political, social, and economic climate). It is pointed out that the overarching context can influence the external systems and the farm's success. However, the SDs are not explicitly analysed.
- Sandberg et al. [112] analysed the critical factors to the commercial viability of WECs in off-grid luxury resorts and small utilities using PESTLE tools and Porter's five competitive forces. Factors like the available wave resource, distance from shore, existing infrastructure, power demand, supply chain logistics, alternative energy sources and current cost of energy were found to have significant impacts.
- de Andres et al. [113] carried out a similar analysis to reveal the risks and uncertainties facing large-scale grid-connected wave and tidal energy projects. This work showed that although the political, economic and social aspects have great importance, the technological barriers are key to attracting investors.
- PNNL and NREL are conducting a three-year project to review the grid value for marine energy development at scale on an intermediate- to long-term horizon. Grid values are arranged into three categories: marine energy's spatial or locational aspects, temporal or timing factors, and specific applications to capture the most situational benefits [114].

- H2020 DTOceanPlus project presented a summary of non-technical barriers and enablers to wave and tidal stream commercialisation in its public deliverable D8.1 [115]. The factors listed from literature sources comprise private and public financing, insurance, continued cost reduction, supportive consenting and regulation, infrastructure, standards and certification, innovation, cross-sectoral interlinkages, and ethical and environmental concerns.

Attributes that characterise the System Drivers (SDs) are fairly covered for wave energy, but unfortunately, there is no reference to how these SDs interact with each other and are prioritised.

Regarding the **stakeholder analysis**, the review of the literature reveals very diverse classifications of stakeholders for marine energy projects, such as:

- Isakhanyan and Wilt [116] identify six main stakeholder groups, namely Designers & developers, Governments & public authorities, Partner companies, Financial institutions, Knowledge institutes, and Environmental organisations
- The FP7 EQUIMAR project [117] considers stakeholders during the entire project lifecycle. At the initial stages of project development, owners, developers, suppliers, employees, the government, unions, and individuals or whole communities located near or in the vicinity have a crucial influence. When operational, creditors and end energy users can be included as well. Stakeholders are then grouped into four categories: Statutory consultees, Strategic stakeholders, Community stakeholders, and Symbiotic stakeholders.
- More recently, in [118], twenty-six wave energy stakeholders are identified, who are grouped into four categories: Highest-level stakeholders, Core stakeholders, First-tier suppliers, and Low-tier suppliers.

Despite the underpinning research that assists in identifying wave energy stakeholders, stakeholder prioritisation has not been carried out systematically. Stakeholder mapping techniques, usually based on two or three dimensions (e.g. power, interest and urgency), have been used in other sectors to determine the priority of identified stakeholders [119] [120].

The elicitation of Stakeholder Requirements (SRs) largely depends on the type of market being addressed. As explained in subsection 2.3.2, the environmental domain accounts for the factors linked to the added value to the intended market. Both Wavebob [121] and utility company PG&E [122] mention using SE to reflect end-user needs and develop top-level requirements.

At the time of writing, the Wave-SPARC project [123] has produced the most comprehensive analysis of the wave energy stakeholder domain. Wave-SPARC has delivered a complete and agnostic formulation of a utility-scale wave energy project through SE and stakeholder analysis. The analysis of stakeholders' needs in [118] led to seven high-level SRs and a total of 33 low-level SRs. Costs and risks are identified as two of the high-level requirements. The other five categories in the high-level SRs contain a mixture of benefits (reliable for grid operations), opportunities (benefit society, deployable globally) and risks (acceptability and safety). SRs are not ranked/weighted according to their relative importance.

To rank SRs, Jahanshahi et al. [124] applied the Delphi method to assess the economic requirements and their relative importance for developing wave and tidal energy technologies based on the expert's judgment. Operational costs and revenue were ranked as the most important criteria from the experts' points of view. Pre-operation costs and investment, incentives, profitability and externalities were ordered in the next priorities, respectively. It is worthwhile noting that both the incentives and externalities are System Drivers and thus should belong to the environmental domain.

Further research efforts should be devoted to the development of a more integrated and objective approach to stakeholder analysis for various potential markets of wave energy technologies.

The **functional analysis** in SE has the objective of defining the functional architecture of the system and characterising its functional behaviour. Functional Requirements (FRs) are the bridge between the stakeholders and technical teams and shall be specified at each stage of the system lifecycle.

- Wavebob [121] defined operational scenarios right through from transportation, assembly, installation and commissioning to operation, maintenance, support and decommissioning. More recently, Babarit et al. [118] identified six lifecycle stages for a wave energy farm: Engineering, Procurement, Construction, Installation, Operations, and Disposal.
- French [125], [126] proposed a systematic approach for the conceptual design of WECs during its operational phase, identifying the functions, selecting those having an important bearing on cost, and trying to find ways of performing those functions economically. The design of WECs is exemplified through the analysis of possible combinations of three main functions: provide a working surface, provide a reaction force, and extract power.
- The University of Uppsala has applied a systems approach to develop ways to harness wave energy which considers manufacturing, maintenance and compatibility with the natural environment early in the design process [127]. These criteria are not generally used for down-selecting a concept from a set of solutions that achieve the desired functionality.
- Technology developer Martifer [128] implemented a SE approach to systematically select candidate architectures and to define FRs for system design and development. Similarly, the utility company PG&E [122] developed a set of functional block diagrams to identify functional relationships between system infrastructure segments and external systems in the WaveConnect project. [129]

described the functions performed by the OWC power plant to convert wave power into electricity.

- Partial coverage of FRs can be found in [130], where FRs are formulated in the context of wave energy conversion, but only for the mooring system, and [131], who has produced a comprehensive landscaping report for Wave Energy Scotland (WES) on FRs for WEC controls. Innosea [132] presents a functional analysis of the submergence system for a Spar OWC in the form of an octopus diagram, exposing the elements interacting with the system, and the main functions (service and constraint). The functional analysis results in a set of functional specifications, showing the expected system functions, the judgement criteria, the levels of these criteria, and the flexibility.
- Bull et al. [133] present a full taxonomy of FRs for a wave energy farm. The five top-level functions identify what the wave energy farm must do to meet its mission. The subfunctions below the top levels further decompose the top-level functions (e.g. WEC or electrical substation). These subfunctions identify the unique aspects that must be achievable to satisfy the higher-level function. Further breakdown is given to subfunctions in the form of sub-subfunctions, further focusing on the needed details (e.g. PTO within a WEC). At each level, functions are mapped to capabilities through MOPs.

The analysis of FRs for wave energy systems is reasonably well covered in the literature. There is also a growing awareness of the need to define functional performance measures to judge the success of wave energy technologies. Although this is very positive, there is still the need for methods that establish the relative importance of FRs and their interactions.

The **technical analysis** deals with the lower-level functions allocated to the system's physical architecture [65], which depend on the design solution. Hence, there is little information on the Technical Requirements (TRs) used to take design decisions and sizing components.

- Scharmann [134] presents a comprehensive functional analysis, technical breakdown and mapping of system requirements to the main cost centres of a particular WEC, i.e. rotor, PTO, substructure, installation and maintenance operations.
- Wavebob [121] and Waves4Power [135] are two examples of technology developers where system decomposition and functional allocation have also been documented. In the case of Wavebob, this process was mainly driven by reliability concerns.
- Several standards and guidelines have been produced to assist in the development of the TRs and assessment of technical performance: EMEC guidelines for Grid Connection [136], as well as IEC design requirements [137], power performance requirements [138] and power quality requirements [139].

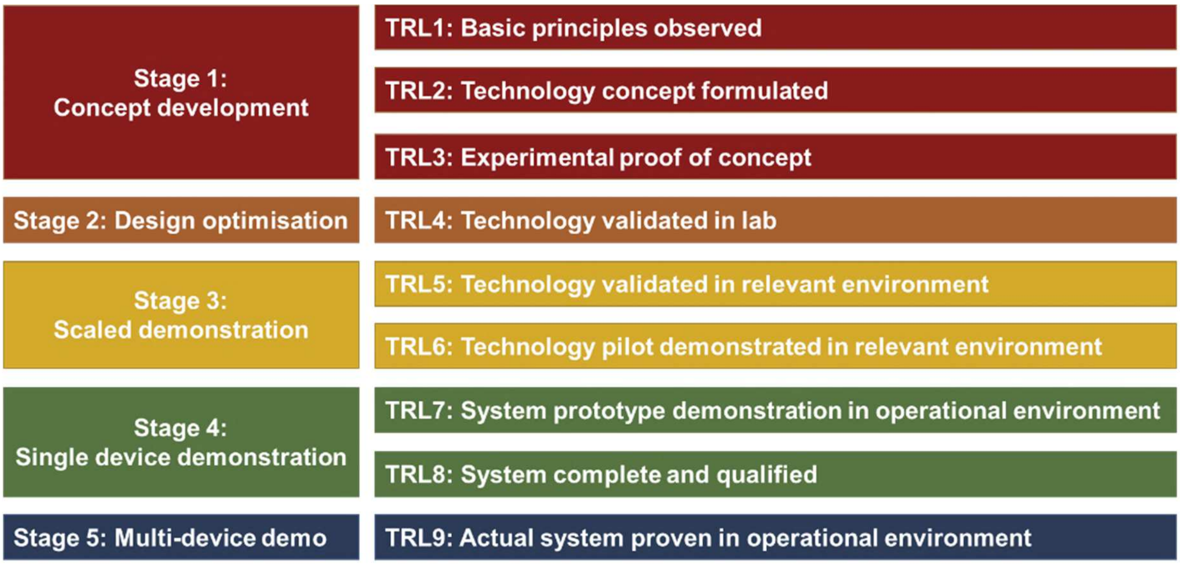
Finally, the identification of **manufacturing** risks begins at the earliest stages of technology development and continues vigorously throughout each stage of system design. Unfortunately, there are no references in the literature to the development of Manufacturing Requirements (MRs) specific to WEC devices. Manufacturing Readiness Levels (MRLs) are commonly used to measure progress on the effectiveness of producing specific components and assemblies [140]. EMEC has produced some guidelines for the Manufacturing, Assembly and Testing of Marine Energy Conversion Systems [141]. This document does not contain a list of MRs, but it could be used to inspire the development of MRs.

2.4 Technology Performance Assessment

2.4.1 An Evolving Framework

Evaluation of technology performance is a continuous activity that should occur at all development stages [63]. A commonly agreed evaluation framework can bring significant benefits for all wave energy stakeholders, including increased clarity, consistency and direction in the development [142]. Early design decisions based on objective criteria are key to lowering development uncertainties, cost and time.

Traditionally, the evaluation of wave energy technologies has heavily hinged on the Technology Readiness Levels (TRLs). The TRL scale was initially formulated at NASA in 1974 (seven levels) and formally defined as it stands today (nine levels) in 1989 [143]. The TRL concept was conceived to assist in the development of space technologies and enable more effective communication on the maturity level of emerging technologies. However, TRLs only assess the maturity and risks within the wave energy development process rather than its quality, technical or economic performance.



Stage 1: Concept development	TRL1: Basic principles observed
	TRL2: Technology concept formulated
	TRL3: Experimental proof of concept
Stage 2: Design optimisation	TRL4: Technology validated in lab
Stage 3: Scaled demonstration	TRL5: Technology validated in relevant environment
	TRL6: Technology pilot demonstrated in relevant environment
Stage 4: Single device demonstration	TRL7: System prototype demonstration in operational environment
	TRL8: System complete and qualified
Stage 5: Multi-device demo	TRL9: Actual system proven in operational environment

Figure 2.14: Technology Readiness Levels and IEC Stages.

Several TRL definitions specific to wave energy have been proposed [144], [145]. It is usual in wave energy to group the systematic TRL development in stages. A device or subsystem must fulfil stage-gate criteria at the end of each stage before passing to the next development stage. The most common framework consists of five stages. It was initially proposed at HMRC to mitigate financial and technical risks during the development of buoyant devices [146], later adopted as best practice by IEA-OES [147] and FP7 EQUIMAR [59], and finally recommended by IEC [148]. Figure 2.14 presents the TRL scale and its correlation with IEC stages.

The first attempt to derive a proper performance assessment of wave energy technologies was proposed by Nielsen [19]. Suggestions included ratios such as the Capture Width, Energy to Volume or Mass, Power Take-Off Efficiency, Capacity Factor and Capital Cost to Energy. Later, the European project EQUIMAR [59] added other assessment figures to these metrics such as the Operating Cost, Availability Factor and Levelised Cost of Energy (LCOE). In 2009, EMEC introduced some guidelines for functional performance measures of marine energy conversion systems, such as reliability, maintainability and survivability [149].

Evaluation methodologies based on the LCOE have been at the centre of wave energy technology development. LCOE combines two relevant stakeholder requirements in a single metric: lifetime costs and energy production. This is why Carcas et al. [150] examine the key performance metrics that underpin LCOE (i.e. CAPEX, OPEX, Yield, Reliability, Cost of finance, Survivability, Durability and Project size). Furthermore, the LCOE assessment method is akin to well-known cost-benefit analyses [71].

The reversed LCOE engineering [145] is a methodology to explore the limits of the WEC's technical parameters. In this approach, an LCOE target is set and the upper-cost limits for the main subsystems of the WEC are obtained. Learning rates due to factors such as production volume and automation can also be considered to assess whether the cost limits for a subsystem can be reached from current costs. This methodology relies on prior knowledge of allocating cost centres to the physical realisation. It helps existing prototypes to improve their commercial attractiveness but does not guarantee stakeholder value is maximised.

Since 2014, the United States has been developing and applying a holistic and quantitative techno-economic assessment metric system to identify technology weaknesses and strengths, ultimately advancing technology towards their market applications [133]. This de-risking approach applies to all WEC systems that are currently under development and to the novel systems invented in the project. System performance is measured through the Technology Performance Levels (TPLs) metric. The development of the TPL assessment criteria, methods and tools was first introduced by Weber [151], further developed in [152], and practically applied and enhanced in the Wave-SPARC project [123]. The latest version of the TPL Assessment Tool can be accessed online at NREL's website [153].

The list of requirements developed in Wave-SPARC serves as the components of the TPL metric [133]. The seven capabilities groups meet the seven high-level SRs and constitute the ultimate metrics a utility-scale wave energy project must satisfy. The lowest level system capabilities in the TPL method are scored and progressively aggregated following a mathematical calculation. There are three ways of combining the lowest level scores: arithmetic mean, geometric mean and multiplication with normalisation. The overall score is calculated from scores for the seven high-level capabilities arranged in three categories (weighted average of individual geometric means). However, this approach requires expert assistance to perform the assessment due to the scoring complexity. In the public version of the tool, the weighting of the different criteria is fixed. The TPL assessment cannot be adapted to changing market conditions or stakeholders' expectations, which will incidentally hinder the traceability of system requirements across domains.

Since 2016, WES has promoted the development of performance metrics and tools for ocean energy technologies via workshops with a broad international cross-sector input [154]. Similarly, the Water Power Technologies Office [155] has contributed to gaining an international consensus by compiling a list of existing Ocean Energy performance metrics for the farm level, the wave energy device, and its main subsystems (e.g. structure, PTO, control, mooring).

As mentioned before, the concept of staged development is inherent to performance assessment. IEA-OES is promoting the adoption of an international evaluation and guidance framework for ocean energy technologies based on this concept [142]. Stages are loosely related to the TRL scale; at each stage gate, an evaluation of the relevant metrics is done.

Figure 2.15: Evaluation Areas included in the Evaluation and Guidance Framework [142].

The first-of-kind implementation of this framework has been produced in the EU H2020-funded DTOceanPlus suite of design tools for ocean energy systems [156]. Assessments are grouped into four main categories, namely SPEY (System Performance and Energy Yield), RAMS (Reliability, Availability, Maintainability and Survivability), SLC (System Lifetime Costs), and ESA (Environmental and Social Acceptance). These assessments feed into a Stage-Gate tool for the overall assessment of ocean energy technologies.

As can be appreciated above, performance requirements are moving from merely evaluating energy production and cost to a more comprehensive assessment. The selection at the intermediate stages of system design contributes to reducing risks. The iteration at low TRLs until the desired performance is achieved will contribute to the analysis of the solution space and the production of more cost-effective designs.

Equally, the evaluation is evolving from analysing the basic wave energy subsystems involved in the power conversion to complete wave energy farms including multiple devices, and the balance of plant or installation and maintenance activities. Discouragingly, most novel wave energy concepts are still focusing their efforts on optimising power capture, leaving out of the initial design considerations other essential performance requirements and subsystems that later become expensive "add-ons" [60]. Experience in very diverse engineering sectors has shown that the early stages of technology development are crucial to meet cost and performance expectations [157] since engineering problems are built at the concept stage.

2.4.2 Assessment Criteria Hierarchy

Wave energy technologies require assessment criteria that can be applied at different system levels of aggregation. Hence, a subsystem must be set in the context of a device and, in turn, placed in the context of a wave farm to assess that subsystem's impact on global performance [142]. Figure 2.16 illustrates several frames of reference of wave energy technologies, including the external environment to consider the installation of the wave farm in a specific deployment site and the commercial aspects of the wave energy project.

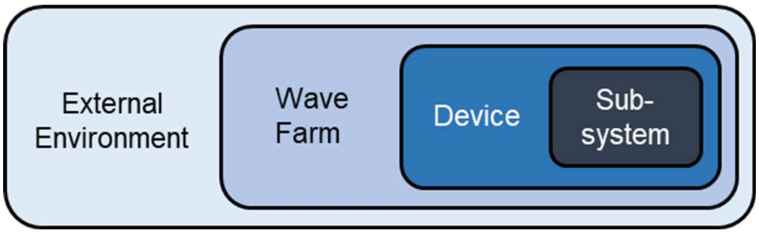


Figure 2.16: Various system boundaries for a wave energy assessment.

Full traceability of assessment criteria is needed to ensure consistency in the same way requirements are traced throughout both the system hierarchy and design domains. To do so, the key design parameters of the technical solution should be selected to calculate the TPMs; the TPMs in turn considered to compute the MOPs; the MOPs taken to determine the MOEs; lastly, the MOEs can be aggregated into a final figure of merit that distils the wave energy technology suitability. This fundamental hierarchy of assessment criteria ensures a holistic evaluation that captures the metrics' different levels of detail and granularity. Functional relationships can be established by analysing the different design domains. FAST diagrams [158] can be used to develop the hierarchy of requirements and corresponding metrics.

Technology performance should be evaluated using different metrics depending on the system boundaries (see Figure 2.16). It is worth noting that the three first levels of the assessment hierarchy can be further expanded by repeating this mapping process for each subsystem, assembly or component. The only thing to consider is that system's TRs will become the subsystem's FRs, thus creating the need for an additional layer [81]. This way the traceability of both metrics and requirements is satisfactorily maintained.

Figure 2.17 presents the evaluation areas considered in IEA-OES Task 12 [142]. It shows how high-level metrics can be combined with lower-level technology-agnostic ones until reaching a single affordability metric.

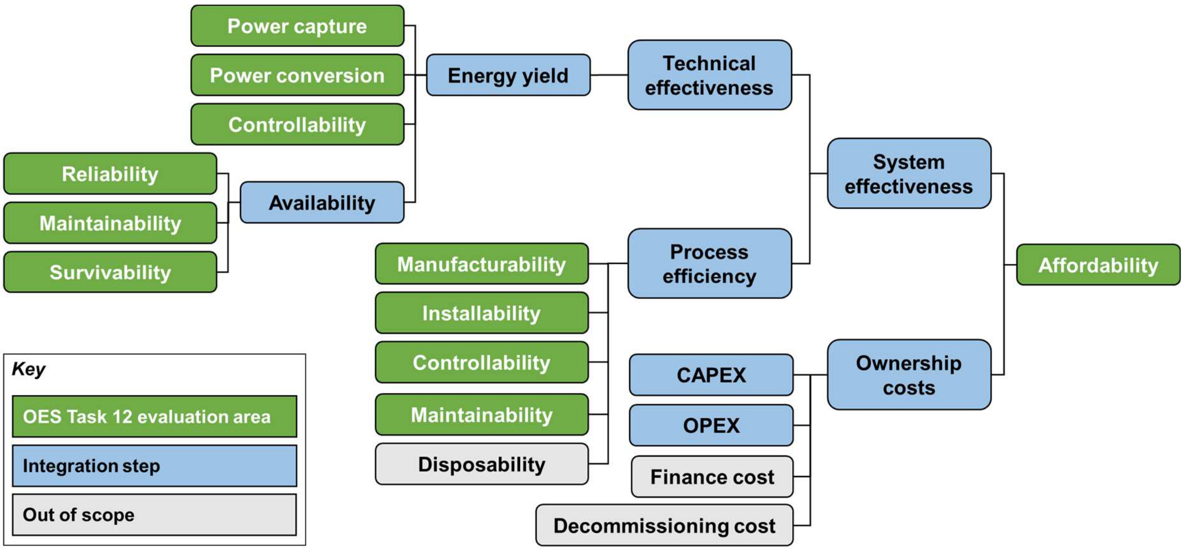


Figure 2.17: Example of a hierarchy of wave energy metrics (adapted from [142]).

For consistency, all assessment criteria should be selected so they are at the same level of detail and cover the full extent of technology requirements. Metrics should not be strongly correlated to each other to provide insight into different characteristics of the technical solution or alternatives being assessed and to avoid overlap or double accounting of criteria. Trade-offs can be captured and evaluated when metric scores for an embodiment are related to critical design parameters. Value functions shall be used to characterise the fundamental relationships between assessment criteria.

2.4.3 Aggregation Structure

Another important aspect to consider in analysing the functional relationships is the aggregation logic of the assessment criteria.

The aggregation concept is a common feature of every multi-criteria analysis method. All evaluation criteria are not equally important; some are so important that their satisfaction, above a threshold, is mandatory, but others can be optional or non-essential. The most used aggregation method is the well-known arithmetic mean. It allows full compensation and can be used to combine scores that measure similar attributes. Conversely, the geometric and harmonic means prevent compensation and can be used to integrate disparate attributes.

The concept of requirement flexibility is introduced in [118] to carry out their aggregation into higher-level requirements. A technical solution may not fully meet one low-level requirement, but a trade-off with another requirement may make the higher-level requirement viable. Depending on the satisfaction level, four degrees of flexibility are identified, ranging from high flexibility (optional) to none (mandatory).

The Logical Scoring of Preference (LSP) method proposed by Dujmovic [159] captures the underlying functional relationships. It adds more granularity to the aggregation step by allowing the definition of the degree of simultaneity of the attributes being combined from total disjunction to full conjunction. Following this approach, the evaluation criteria can be aggregated sequentially into higher hierarchy levels accounting for the degree of simultaneity of the different attributes until a final overarching merit is obtained. The overall suitability can be interpreted as the global degree of satisfaction of all specified requirements.

Given the need to combine several disparate attributes to obtain global performance, it is crucial to have a systematic method to amalgamate criteria expressed by a variety of units, orders of magnitude and qualities.

Many authors recommend normalising the assessment criteria so that its value falls in the same 0-to-1 interval. This way, zero is assigned to the worst performance level obtained by a technical solution and one is assigned to the best performance [160]. A benefit of such normalisation is that it allows a common interpretation for every weight as the effective importance of a criterion relative to the others. However, a challenge of normalisation arises when defining the range of theoretically possible performance levels for the assessment criteria. Chances are good that the maximum and/or minimum performance levels will be unbounded for at least one metric. For instance, the maximum value for the device CAPEX is unbounded. In such cases, performance limits can be based on practical considerations (e.g. lower than €10,000/MW).

Qualitative assessment criteria are expressed in units of value as opposed to physical units. The performance measure is discrete, and the scoring scale can be either linear or non-linear. For example, the severity of a wave energy system failure could be ranked on a 1-5 scale, ranging from a negligible effect (1) to the complete loss of the device (5). The corresponding suitability for this criterion may be highly non-linear to show the risk aversion behaviour to a serious consequence.

2.4.4 Effort, Relevance and Impact of the Assessment

The early stages of technology development are crucial to meet wave energy system cost and performance expectations. Huge benefits can be obtained from applying knowledge in earlier stages of wave technology development. Many authors estimate that about two-thirds of the total lifetime costs of a system are committed by the time the preliminary design is completed [64]. As seen in Figure 2.18, committed costs can reach up to 80% upon completion of the detailed design and development phase. Moreover, the ability to change typically decreases to 20% when this phase is completed. It can be easily inferred that the technology development goal is to narrow down the gap between available system-specific knowledge and committed costs.

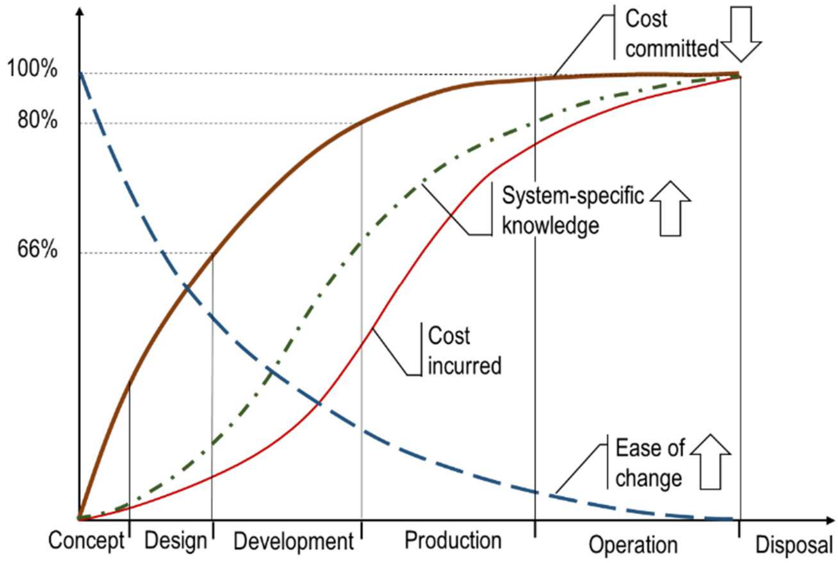


Figure 2.18: Design freedom, knowledge and related costs (adapted from [64]).

The effort needed to prepare a given estimate indicates the cost, time and resources required. This effort depends on the magnitude of the technology development challenge and the quality of estimating data and tools.

Table 2.3 shows the indicative budget to produce a complete wave farm system per development stage [144]. The assessment effort is typically expressed as a percentage of the total development costs for a given project size. The preparation effort index for each of the five stages has been derived from the ASTM guideline [161]. The estimated cost for the assessment is then calculated by considering the baseline effort to be 0.02% of the total system development budget (note this percentage will vary inversely with project size in a nonlinear fashion). Time investment can be derived by assuming an expert hourly rate (e.g. €100/h).

Table 2.3: Estimation of the assessment effort.

Development Stage *	TRL	Indicative budget (M€) **	Effort index ***	Estim. cost (k€)	Relative intensity (%)
1 - Concept	1-3	0.5	1	16	3.2
2 - Design	4	1	4	64	6.4
3 - Scaled demo	5-6	8	10	159	1.99
4 - Single device	7-8	20	20	318	1.59
5 - Wave farm	9	50	40	636	1.27
Total		79.5	75	1,193	1.5

* IEC recommended best practice [148]
** Values closely related to those specified in [144]
*** Multipliers were taken from [161]. Index 1 = 0.02% of the total budget

As the project definition increases (i.e. higher maturity or TRL), the effort to prepare an estimate of performance also grows, as does its cost share concerning the total development cost of the technology. However, it can be appreciated in Table 2.3 that the relative time and expense invested are higher during the initial developing stages, peaking at Stage 2. This result supports the previous statement regarding the early-stage guidance saving precious development time and cost.

2.4.5 Future costs of emerging technologies

According to Rubin [162], a technology can be defined as emerging if it is not yet deployed or ready for purchase on a commercial scale. The design details of emerging technology are still preliminary or incomplete, performance has not been sufficiently validated, and it may require new components and subsystems that are not available off the shelf. Its current stage of development may range from concept to single-device demonstration. On a TRL scale [163], emerging technologies encompass a TRL of 2 to 7, usually the main focus of research and development programmes. This is the case for wave energy technologies, which are still in the validation phase or TRL 5 [164].

As earlier stated in this section, a common evaluation criterion to assess the feasibility and competitiveness of renewable energies is the generating costs of the technology. The affordability metric typically used is the Levelised Cost of Energy (LCOE) [165]. However, this is not a simple task for emerging technologies due to a lack of experience and various uncertainties and unknowns (e.g. capture efficiency, reliability, capital costs and annual maintenance costs). The direct quantification of the LCOE for prototypes yields unsuitable results since it can only represent a snapshot of the technology cost at the current development stage [166]. Moreover, the generating costs of the first single devices will be much higher due to perceived risk and lack of economies of scale [167].

To overcome these limitations, a future projection is needed. The LCOE estimate thus represents the future cost of the commercial-scale version that the emerging technology could achieve with sufficient replication, provided its technical performance goals are met. The aim of such estimation is twofold: to allow comparison with other technologies currently exploited in the market and to benchmark different cost reduction targets or alternative technology concepts.

The estimation of future costs of wave energy has attracted great interest to demonstrate the potential of this renewable energy technology. Various studies have been published providing projections for the entire sector. The OES Technology Collaboration Programme by the IEA developed a study of the international levelised cost of energy for ocean energies in 2015 [168], which directly questioned developers on current costs and future targets of their wave energy technologies. The estimations were updated in 2020 following the same methodology. Although the full report is not accessible, public results show that wave technologies can reach the cost targets defined in the European Strategic Energy Technology Plan (SET Plan) [169]. These targets are €150/MWh by 2030 and €100/MWh by 2035 for wave energy.

The Joint Research Centre (JRC) periodically publishes ocean energy status reports with cost estimations [164]. Costs are mainly based on the Energy Technology Reference Indicator (ETRI) projections for 2010-2050 [170] and the scenario-based cost trajectories to 2050 [171]. These are derived from open literature (both primary and secondary sources), expert judgements, information from other similar technologies, and the application of learning curves with the cumulative capacity foreseen. The higher and lower cost estimates vary significantly due to the lack of a dominating technology and the associated uncertainties related to unproven technologies. Nonetheless, the limited data available from technologies currently under development suggest an LCOE in line with or below the SET Plan targets by 2030 in good resource sites after 1 GW installed capacity [164].

In the UK in 2018, ORE Catapult analysed the cost reduction pathway for wave energy [172]. Single devices reported a cost of over £300/MWh and key cost reductions to £100/MWh after 1 GW deployment through learning by doing, process optimisation, engineering validation and improved commercial terms. However, the lack of data, particularly energy generation, made it hard to estimate the future energy cost accurately.

Although these studies provide a helpful tool to track the progress of the wave energy sector, they cannot be used to benchmark alternative technology options or assist in decision-making during the different stages of technology development. In this respect, various approaches have been recently proposed to assess wave energy technologies at the early stages of development.

The detailed bottom-up techno-economic approach is the most common costing method used for energy technologies. Some future LCOE projections found for wave energy technologies are Oscilla Power's Triton [173], M3 Wave [174], UGEN [175] or Sandia's

Reference Model Project [176]. This approach specifies the design of the wave energy device, the balance of plant and array layout, and the corresponding technical and operational performance parameters. Based on this information, the capital expenditure (CAPEX) and operational expenditure (OPEX) costs are estimated for a particular deployment site. This cost is then aggregated with other costs such as project development, insurance and decommissioning costs and, as a result, an LCOE is obtained. However, this direct method of estimating the future cost of a commercial-scale technology is only suitable for technologies close to commercialisation and well-defined designs. Experience demonstrates that cost estimates for emerging technologies tend to be somewhat optimistic and significantly lower than the actual cost of the first commercial plant deployed [177]. As the design is further detailed and unforeseen technological issues are uncovered in the development process, the estimated costs of these technologies tend to escalate. Subsequently, the relatively high cost of early deployments declines as the technology is widely deployed and learning is capitalised through more efficient designs and processes.

Alternatively, Têtu [178] proposed a top-down approach based on the target LCOE for the specific market and a technology-agnostic breakdown of costs to derive thresholds for the different cost centres. Various uncertainty ranges are suggested per development stage, as described in [179]. Developers can use this approach internally to inform their technical decisions. However, the method lacks transparency regarding the cost estimation and the allocation of different levels of uncertainty to the detailed breakdown are concerned. A similar approach based on a reverse cost calculation was developed by Pennock [180] for emerging technologies. In this case, the current cost thresholds for early-stage devices are calculated to reach the 2030 SET Plan levelised cost targets [169]. Component-based learning curves are applied, and the resultant breakdown of costs is compared with cost estimates for current devices to identify areas where further cost reduction is still needed. This method provides more clarity but still requires the external assumption of a standard breakdown of costs for the particular class of device (e.g. point absorber), which might differ for the wave energy concept considered. Furthermore, uncertainties in the initial estimations are not embedded but only a sensitivity to the learning rates applied.

2.5 Conclusions

This chapter reviewed three topic areas relevant to the research that provide the background for developing the novel methodology.

To begin with, the literature review paid attention to wave energy, a renewable resource that has the potential to supply about 10% of global electricity demand. However, developing effective wave energy technologies is a long and intricate process fraught with many challenges. The review looked at two centuries of wave energy history and found that there have been several cycles of optimism, setback, and reassessment. Despite the increased efforts, wave energy has not exhibited any signs of convergence yet. The engineering challenge of the future is to develop robust devices that harvest wave energy effectively, consistently, and economically while also withstanding the roughest seas. This requires specific methods and tools to support engineering analysis and decision-making during the design process. Systems Engineering (SE) is a promising approach to assist in this multifaceted task.

SE offers designers a structured approach to problem-solving, preventing radical changes from original requirements to physical realisation. The focus of SE is on satisfying system requirements. The process involves capturing stakeholder requirements, followed by functional, technical, and manufacturing requirements. Searching for solutions is a creative phase in SE. Different multi-criteria analysis techniques have been developed to assist in the decision-making process and select solutions. Among them, it is worth mentioning the Analytic Hierarchy Process (AHP), Quality Function Deployment (QFD), Design Structured Matrix (DSM) and TRIZ. Unfortunately, SE is not widely applied in wave energy systems development, despite the complex decision-making involved. The US Department of Energy-sponsored Wave-SPARC project has conducted the most thorough SE experiment for a grid-connected wave energy farm to date.

The development, assessment, and selection of wave energy systems are getting more thorough, going beyond only evaluating technical maturity and cost to take into account integral performance criteria. The selection of technologies at intermediate stages reduces risks, and iteration at low Technology Readiness Levels (TRLs) leads to more cost-effective designs. However, there is a need to investigate the aggregation hierarchy for various assessment criteria and ensure full traceability of assessment criteria. The initial phases of technology development are critical as costs can reach up to 80% upon completion of detailed design, and changes become more difficult. Therefore, more time and cost should be invested in technology assessment during the initial concept and design stages. Besides, a transparent and traceable method to evaluate the future costs of emerging technologies is needed.

In summary, SE design methods have a wide potential of applicability in the wave energy sector. However, a systematic design approach must be developed to guarantee that system requirements are completely traceable throughout the design of wave energy systems, to visualise complex system data, to adapt the evaluation to rapidly changing commercial conditions, and focus the innovation efforts to overcome any performance gaps. The uncertainties involved with evaluating technologies at an early stage of development, where there is little information and evidence to quantify metrics, are a significant challenge in this method, as outlined in this chapter.

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CHAPTER 3 UNDERSTANDING THE WAVE ENERGY CONTEXT

> "For me context is the key; from that comes the understanding of everything"
>
> *Kenneth Noland (1924 – 2010)*

3.1 Overview

This chapter provides an awareness of the broader context and its potential impact on system requirements and dependencies to ensure that wave energy technologies can fulfil stakeholders' expectations.

Section 3.2 introduces the specific methods and tools used in this step of the methodology. Initially, AHP is used in the environmental domain to prioritise System Drivers (SD). The QFD tool with Chen normalisation is then used to link SD to Stakeholders (SH) and provide importance ratings to wave energy requirements in the different domains.

Section 3.3 develops the wave energy context, which comprises multiple external forces that have no direct interaction with the wave energy system, but may influence decisions related to its conception, development and operation. The identification of the market application, key drivers and stakeholders' concerns offers a solid foundation for objectively evaluating wave energy options versus system requirements.

Section 3.4 describes the practical implementation of this step. An anonymous survey was designed to prioritise the external forces. Results obtained from the consultation to wave energy representatives are presented for the application markets, key drivers and stakeholder groups listed in section 3.3.

Finally, section 3.5 summarises the chapter and discusses some partial findings from this novel methodology that might be of interest to the wave energy sector.

3.2 Methods and Tools

3.2.1 Analytic Hierarchy Process (AHP)

Complex engineering problems often require a set of interdependent and competing criteria. The Analytic Hierarchy Process (AHP) is a valuable tool that provides a systematic approach to support multi-criteria decision-making. Developed by Saaty in 1980 [102], AHP captures subjective and objective aspects of an engineering problem by breaking down decisions into a series of pairwise comparisons and combining them into a single scale. Furthermore, AHP includes an effective technique to check the evaluation's consistency, hence reducing the bias in the final decision. Since its emergence, it has become one of the more widely used multi-criteria analysis methods.

AHP is formalised in four main steps. The two last steps are optional but highly recommended to confirm the robustness of the results.

Step 1: Decompose the decision problem into a hierarchy of sub-problems. It starts by decomposing the decision problem into a hierarchy of sub-problems. The overall goal, criteria and attributes are arranged into different hierarchical levels as illustrated in Figure 3.1. The decision problem goal sits at the top of the hierarchy. The second level consists of several primary criteria of equal importance. If appropriate, a third level can be added.

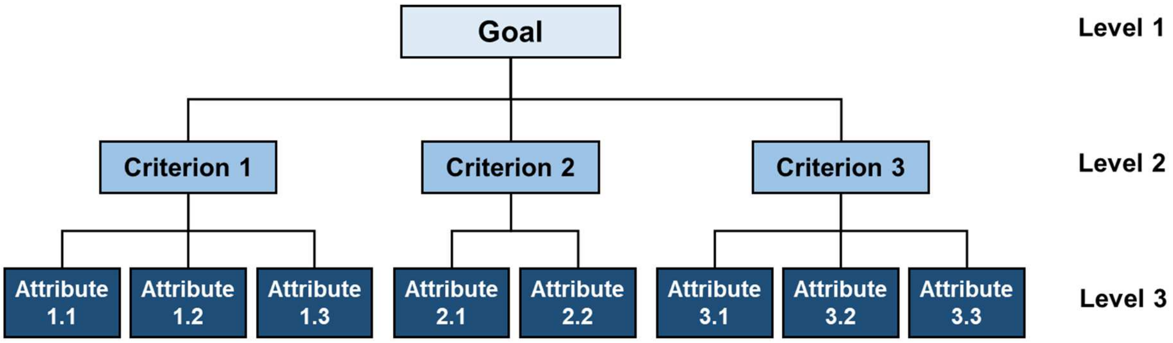

Figure 3.1: An example of a three-level decision hierarchy.

Step 2: Perform pairwise comparisons and establish priorities. Decision criteria are placed in an *mxm* squared matrix, and two criteria are compared each time to determine which one is more important. Whenever the criteria in rows are more important than the ones in columns, the 9-point gradation scale [102] shown in Table 3.1 is used to quantify the comparison, a_{ij}. Otherwise, the reciprocal value is assigned, $a_{ji} = 1/a_{ij}$.

Table 3.1: Gradation scale for pairwise comparisons [102].

Importance	**Definition**	**Explanation**
1	Equal	Factors contribute equally to the objective
3	Moderate	One factor is slightly favoured over another
5	Strong	One factor is strongly favoured over another
7	Very strong	Evidence exists for a factor dominance
9	Extremely strong	Highest possible validity of a factor
2, 4, 6, 8	Intermediate values	For a compromise between the above values

Step 3: Synthesise judgements to obtain a set of weights. Based on each criteria's priority, the overall ranking is developed by normalising the judgement matrix. The relative importance, w_i, is calculated as follows:

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, \qquad i = 1,2,\ldots,m; j = 1,2,\ldots,m \tag{1}$$

$$w_i = \frac{\sum_{j=1}^{m} a'_{ij}}{m}, \qquad i = 1,2,\ldots,m \tag{2}$$

Step 4: Evaluate and check the consistency of judgements. Finally, the degree of consistency among the pairwise comparisons is measured by computing the Consistency Index and Consistency Ratio [102]. The Consistency Index (CI) is calculated as

$$CI = \frac{\lambda_{max} - m}{m - 1} \tag{3}$$

where λ_{max} is the maximum eigenvalue of the judgement matrix. CI is then compared with that of a Random Index (RI). The ratio derived, CI/RI, is termed the Consistency Ratio (CR). A CR below 0.1 is deemed satisfactory.

Table 3.2: Random Index, RI [102].

Factors	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Until now, AHP has only been applied in wave energy to rank technology options concerning techno-economic criteria (e.g., energy capture, cost, reliability, environmental friendliness, adaptability) in a single step [61]. To limit the subjectivity of and dependence on expert judgements, AHP will be used in the environmental domain to prioritise System Drivers (SDs) at the outset of this novel methodology.

3.2.2 Quality Function Deployment (QFD)

QFD [76] is another well-known design tool developed in Japan by the end of the 1960s, being first documented at the Kobe shipyards of Mitsubishi Heavy Industries in 1972. It is used to translate the Voice of the Customer (VoC) into system requirements employing a series of matrices called the House of Quality (HoQ). System requirements initially consisted of just customer needs and technical requirements, but they can equally be functions, design parameters or critical process variables. Furthermore, QFD matrices can be linked in a waterfall manner to ensure the complete traceability of the requirements.

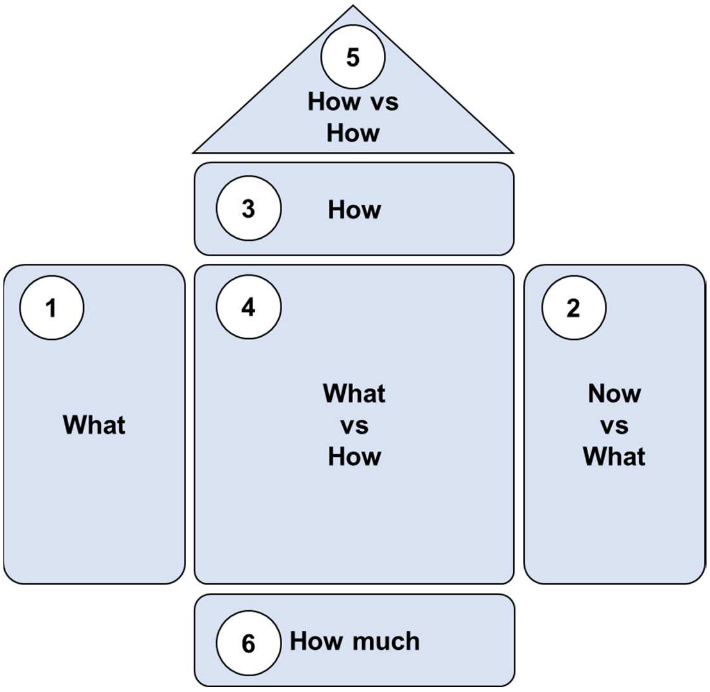

Figure 3.2: The House of Quality.

QFD is formalised in 6 main steps:

Step 1: Determine input requirements and relative importance ratings (*What*). In the proposed methodology, AHP is adopted to prioritise initial factors, that is, System Drivers (SDs).

Step 2: Benchmark input requirements (*Now vs What*). This step aims to determine how the requirements are currently satisfied. Even though the wave energy system is a new design, there will always be a competitive product that is intended to meet the same need. This step creates an awareness of what already exists and facilitates assigning target values to these requirements. Please refer to CHAPTER 5 for further details on target allocation.

Step 3: Generate output requirements (*How*). The output requirements restate the design problem in the corresponding domain. The Functional Analysis and System Technique (FAST) can be used to identify the output requirements [158].

Step 4: Fill in the relationship matrix (*What vs How*). The relationship matrix is the centre part of the HoQ and is used to relate the input and output requirements. This way the priorities of the input requirements can be translated into the relative importance ratings of output requirements (Step 6). To do so, the relationships traditionally expressed in qualitative symbols (e.g., ⊙ strong, ○ medium, and △ weak) are converted into numerical coefficients (e.g., 9-3-1).

Step 5: Complete the correlation matrix (*How vs How*). The correlation matrix placed over the "roof" of the HoQ is added to highlight interrelationships between output requirements. Positive relationships represent supporting requirements, whilst negative linkages help identify conflicts and trade-offs. Qualitative symbols (e.g., +, −) or numerical ratings (e.g., 1, −1) are used to describe these relationships.

Step 6: Determine relative importance ratings (*How Much*). The absolute level of importance of the output requirement, w_j, is obtained by summing the relative importance of the input requirements, d_i, multiplied by the quantified numerical coefficients, r_{ij}. The relative importance rating, w_j', is then computed as:

$$w_j = \sum_{i=1}^{n} d_i \cdot r_{ij}, \qquad i = 1,2,\dots,n; j = 1,2,\dots,m \tag{4}$$

$$w_j' = \frac{w_j}{\sum_{j=1}^{m} w_j} \tag{5}$$

where n and m are the number of input and output requirements, respectively.

Some authors have proposed normalisation models to determine the relative importance ratings, including the correlation matrix. Chen's approach [181] aims to overcome other models' limitations that produce unreasonable results. In this method, the numerical coefficients, r_{ij}, are normalised according to the following equation:

$$r_{ij}' = \frac{\left(\sum_{k=1}^{m} c_{kj}\right) r_{ij}}{\sum_{j=1}^{m}\left(\sum_{k=1}^{m} c_{kj}\right) r_{ij}}, \qquad c \in [1, -1] \tag{6}$$

where c_{kj} are the number ratings of the correlation matrix.

In wave energy, QFD has been applied to assess the potential of wave energy innovations defined by its functions, without any normalisation and in a single step [182]. The QFD tool with Chen normalisation will link SDs to Stakeholders (SHs) and assign importance ratings to wave energy requirements in the different domains.

3.3 The Wave Energy Context

3.3.1 Background

The engineering complexity and the wide variety of wave energy concepts require a comprehensive development approach [60]. Hence, defining the full set of requirements for the design problem from the start is paramount to developing a successful wave energy technology [62]. Furthermore, an early understanding of the overarching context and its potential impact on system requirements and dependencies will provide a solid basis for developing wave energy technologies that meet stakeholders' expectations [183].

Attention to context is not new to Systems Engineering (SE), but its consideration has increased hand in hand with the sophistication of engineering problems. The system context comprises multiple external forces that have no direct interaction with the wave energy system but may influence decisions related to its conception, development and operation [62]. A structural view of the system should consider the multiple value dimensions of the technology (or system drivers) together with the various stakeholders interested in the technology [184]. Drivers that are associated with a stakeholder group are often called concerns.

As introduced in section 2.3.6, the most comprehensive analysis of the wave energy requirements has been produced within the Wave-SPARC project [111]. This work led to a complete and agnostic formulation for a utility-scale wave energy farm through SE and stakeholder analysis. However, the definition of system context is only partially addressed. The authors present a context diagram used to define the external systems that can directly influence the success of a grid-connected wave energy farm. It is pointed out that this overarching context can influence the design of the technology, but these factors are not explicitly analysed.

On the other hand, Sandberg et al. [112] investigated the various external forces acting in the system context of wave energy for off-grid applications. They acknowledged that the external factors may not affect the viability of grid-connected systems in the same way but did not analyse this impact.

Despite the existence of research to assist in the identification of wave energy stakeholders, such as [116], [117], [118] and [185], as far as we are aware, there is no public reference to assist in the prioritisation of stakeholders in the wave energy sector.

The knowledge gained from analysing the overarching context comprising the market application, key drivers and stakeholders' concerns provides a solid basis for objectively evaluating wave energy technologies against the systems requirements.

3.3.2 Wave Energy Markets

The intended market application drives the development of innovations since new technologies are created to address existing or unexploited market opportunities and problems [186]. Knowledge about future markets is vital at all stages of the innovation process [187]. Therefore, defining the target market(s) is the first logical step to characterising the overarching context.

Wave energy devices are used to transform the motion of the ocean and waves into any usable form of energy. However, the primary product for wave energy is likely to be electricity generation due to the important contribution of this energy carrier to the decarbonisation of the global energy system [115]. Although some technology developers are interested in other products such as freshwater (through desalination) or hydrogen (through electrolysis), they mostly conceive wave energy technologies for electricity production.

Owing to its size, large-scale grid-connected electricity generation is the most attractive market for wave energy technologies [188]. Wave energy presents a great opportunity to meet international decarbonisation targets. However, integrating wave energy technologies into the utility-scale market is challenging since these emerging technologies must struggle to compete in cost with more mature renewable energies such as wind or solar.

Alternatively, non-utility markets may present an appealing option for wave energy technologies to be exploited at a smaller scale in a less competitive setting. In particular, islands and other off-grid markets could provide a stepping stone supporting the deployment of wave energy technologies while providing environmentally friendly energy to coastal communities. These territories experience a much distinct reality than their continental fellows and may require bespoke solutions [189]. Consumers mainly depend on exchanges with mainland or fossil fuel-based generation; they pay high electricity prices compared to mainstream markets and are more vulnerable to fluctuations in the tariff.

Other niche applications for wave energy systems have been proposed, given their co-location nature, potential synergies and cost savings [188]. Among them, it is worth mentioning the energy supply to offshore oil & gas platforms, marine aquaculture and ocean observation and navigation [190]. However, this chapter will not investigate these markets because of their lesser size, great variety of requirements and lack of consistent information to characterise them.

Table 3.3 summarises the main features of the two power markets analysed in this chapter: utility-scale generation and powering remote communities.

Table 3.3: Application market characterisation.

Id	Market	Characteristics
M1	Utility-scale generation	• Attractive but also very competitive • WEC design is mainly driven by this market • Increasing demand for renewable electricity • Legal obligations to meet decarbonisation targets
M2	Powering remote communities	• A narrower span of competition (sometimes just one option - diesel) • Low energy security and quality • Consumers vulnerable to price fluctuation and high energy costs • Simplified market and regulatory conditions

3.3.3 System Drivers (SDs)

Wave energy drivers are an essential part of the context where the wave energy system operates. Drivers are exogenous forces outside the system boundaries that can constrain, enable or alter the design solution [80]. The context includes the political, economic, social, technological, legal and environmental factors. The existence of favourable conditions in the intended market will undoubtedly stimulate the development of wave energy technologies.

PESTLE analysis is a standard tool used by companies to track the context they are operating or are planning to launch a new project, product or service [191]. This tool can be combined with SWOT[1] analysis to provide an excellent framework to investigate wave energy drivers from many different angles and dimensions [192]. PESTLE is an acronym which encompasses six dimensions (see Figure 3.3) and in its expanded form stands for:

- P for Political. Political drivers determine the extent to which a government may influence a specific industry.
- E for Economic. Economic drivers comprise factors that directly impact economic viability.
- S for Social. Social drivers scrutinise social trends and attitudes.
- T for Technological. Technological drivers pertain to key knowledge and technologies that affect the industry.
- L for Legal. Legal drivers include regulations that affect the business environment.
- E for Environmental. Environmental drivers allude to factors determined by the surrounding natural environment in which the wave energy system is placed.

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[1] Strengths, Weaknesses, Opportunities and Threats

Figure 3.3: The six dimensions of PESTLE analysis.

Attributes that characterise wave energy drivers are fairly covered in literature such as [51], [112], [113], and [193]. Table 3.4 provides a summary of wave energy drivers per the main category.

Table 3.4: Wave energy drivers.

Id	Driver	Attributes
SD1	Political	• Favourable policies (e.g. energy security, sustainability, job creation) • Market support mechanisms • Political stability and low bureaucracy
SD2	Economic	• Access to finance, credit & insurance • Energy price and/or volatility
SD3	Social	• Growing energy demand • Social acceptance
SD4	Technological	• Technology maturity and certification • Infrastructure readiness • Supply chain availability
SD5	Legal	• Simplified procedures (e.g. consenting, environmental assessment) • Standards and regulation
SD6	Environmental	• Stricter protection (e.g. pollution, natural disasters, climate change) • Suitable site and resource conditions

A survey of wave energy representatives was conducted to prioritise wave energy drivers and to establish the importance ranking of wave energy drivers for each application market. Respondents were asked to grade the political, economic, technological, legal and environmental factors using a Likert scale, with one being the highest importance and six the lowest. More details about the practical implementation can be found in section 3.4.

3.3.4 Wave Energy Stakeholders (SHs)

A stakeholder is an individual, group or organisation with interests or concerns relative to a system's development and operation [67]. Key stakeholders can significantly influence the system design or are crucial to its success [81]. Together with wave energy drivers, the stakeholders define the overarching context where the wave energy system operates.

Stakeholder analysis encompasses the identification and prioritisation of stakeholder groups [194]. Stakeholder identification is often overlooked but essential to achieve an effective system. As pointed out in CHAPTER 2, the literature review reveals very diverse classifications of wave energy stakeholders. Due to this lack of consensus, clarity might be gained by describing how stakeholders are expected to interact.

Commonly, renewable energy projects set up a Special Purpose Vehicle (SPV) company to develop, build, maintain, and operate the system for its lifetime [195], [196]. The SPV becomes the project owner and central administrative entity tasked with acquiring funds, hiring a developer, organising Power Purchase Agreements (PPA), and maintaining overall responsibility for the project's profitability and meeting obligations stipulated by regulators in the site lease. The shareholders of this company invest capital and secure funds to pay for the construction mainly with loans. Additionally, the national, regional or local government can provide incentives to develop the project. Common support mechanisms in renewable energy projects are feed-in tariffs, feed-in premiums, auction schemes, quota obligations based on tradable green certificates, investment support, tax incentives or exemptions, and loan interest loans [197].

The owner hires a project developer to plan and develop the wave energy farm, often from the initial site assessment through the final commissioning stage. The project developer acquires project rights for siting and permitting, whilst independent bodies will assess the project's conformity towards national and international standards. During the consultation, pressure groups such as marine users may set additional conditions for approval. Besides, project developers may freely engage with organisations (e.g. environmentalists, political parties, community bodies, trade associations, unions, and media) that can support or oppose wave energy. The owner transfers risks through contract agreements with specialised firms for the farm's construction, operation and maintenance. In turn, the main contractors rely on low-tier suppliers to provide various goods, equipment and services for the project, including certification. A crucial supply is the technology for harnessing wave energy. An insurance company is chosen to provide coverage during the construction and operation phases.

In the operational phase, the SPV will charge end-users for the energy produced, collect payments, and use that revenue to cover its costs. The broader consumer body includes individuals and organisations that consume energy and/or pay taxes. Sometimes, a PPA is signed by an off-taker, often a utility company, who ultimately sells it to consumers [198]. Financing is easier to obtain if lenders can see the company has a purchaser of its production.

Considering the interactions of the concerned parties, wave energy stakeholders play four prominent roles:

- **Financiers**. They provide economic resources or incentives to develop the project: equity (owner), debt (lenders) and incentives (government).
- **Developers**. They provide key resources, advice, services or assets. They have a direct interest in how things are managed on the project during its lifetime: project development (owner), construction and end of life (EPCI[2] contractor), as well as operation (O&M provider).
- **Condition setters**. They impose conditions and influence the direction of the project: national, regional and local policy makers (government), independent bodies with an administrative or regulatory role (regulators) together with environmentalists, trade associations, community bodies, political parties, unions and media (pressure groups).
- **Energy users**. They participate in the energy flow: seller (owner), grid operator and final users (consumers).

As seen before, wave energy stakeholders can have different roles and responsibilities. For this research, stakeholders have been grouped into eight broad categories depicted in Figure 3.4 and briefly described in Table 3.5.

Figure 3.4: Wave energy stakeholder groups.

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[2] EPCI stands for Engineering, Procurement, Construction and Installation

Table 3.5: Wave energy stakeholders.

Id	**Stakeholder**	**Main responsibilities**
SH1	Owner	• Initiate the project and design the farm • Provide equity • Set return on investment targets • Manage project risks • Sell electricity to consumers
SH2	Lenders	• Provide debt • Set interest rate • Assess financial risk
SH3	EPCI contractor	• Manage farm construction and installation • Provide insurance during construction • Select suppliers • Manage end-of-life recycling
SH4	O&M provider	• Provide spare parts and services • Perform (un)scheduled maintenance • Provide insurance during the operation • Select service suppliers
SH5	Government	• Develop and implement sectoral policies • Review compliance • Provide investment and generation incentives
SH6	Regulators	• Establish permitting requirements • Review project use of ocean space • Provide concession
SH7	Pressure groups	• Lobby for or against the project • Improve the well-being of the community
SH8	Consumers	• Set power quality requirements • Purchase generated electricity

Stakeholder prioritisation is as important an activity as stakeholder identification. Stakeholder prioritisation aims to focus on the needs and expectations of stakeholders with more power and interest in influencing wave energy technology [199]. To this purpose, the survey of wave energy representatives comprised specific questions to establish the importance ranking of stakeholders for each wave energy driver. Respondents were asked to grade the stakeholder groups in Table 3.5 using a Likert scale, with one being the highest importance and eight the lowest. More details about the practical implementation can be found in section 3.4.

3.4 Practical Implementation

3.4.1 Survey Research

A survey is a market assessment tool used to gain information about a target audience quickly. The survey benefits lie in its versatility, cost-effectiveness and ability to generalise results provided samples are correctly selected. However, as with other data collection methods, survey research presents a few disadvantages, such as its potential rigidity and validity of results [200]. The present survey aimed to assess the relative importance of external forces influencing the development of wave energy technologies. Moreover, assuming the primary product for wave energy is likely to be electricity generation, two market applications are investigated: utility-scale generation and powering remote communities. Data for identifying external drivers and stakeholder groups were collected from the literature review.

An anonymous survey was designed to prioritise the external forces. It was conducted by sending it out to various experts in the wave energy sector via email, ensuring that every question was asked in the same way to every respondent. Also, respondents are more likely to provide open and honest feedback in a more private survey method. In total, 120 participants were selected based on their extensive experience in the wave energy sector. Care was taken to include a varied mix of age, gender, origin (i.e. 14 countries from Europe and the Americas), and background (i.e. Academia, Research, Technology development, Industry, Sector associations, Test sites, Certification bodies, Consultancies, Utilities and Public investors). Answers were mainly provided individually and may not represent their organisation's position.

A total of 64 questionnaires were completed during the realisation of this survey (53% response rate). This number represents about 6% of the 1,100 full-time jobs in the nascent ocean energy estimated by IRENA [201]. An online calculator [202] was used to find that the number of responses would ensure a confidence level of 90% with a 10% margin of error. These values are acceptable when working with small populations and original research topics without previous studies.

Survey design takes a great deal of thoughtful planning and often many rounds of revision. The short structured questionnaire included in Appendix A: Survey of External Forces was designed following the principles outlined by Cowles and Nelson [203]. According to these principles, good survey questions are characterised by specificity, clarity and brevity. These principles constitute a solid guideline to increase the validity and reliability of responses. The two questions included in the survey are as follows:

1.- What are the key drivers of wave energy projects for each market application?

2.- Which of the above drivers concerns each wave energy stakeholder group more?

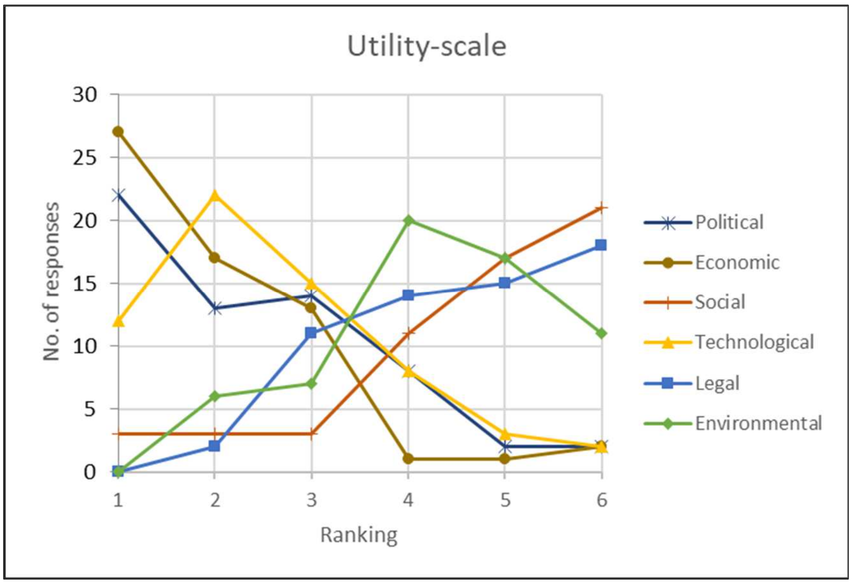
Respondents were asked to rank the two sets of factors using a Likert scale. After each question, a free text input box was also provided, where the respondents were prompted to add any missing factor, the reasoning behind their ranking choices or any other comments. Responses were collected in a spreadsheet and later processed for graphical representation. Participation in the survey was voluntary. The questionnaire was first distributed on 22nd November 2021, following a reminder on 27th November 2021 and closed on 13th December 2021.

The following sections present a series of graphics summarising the prioritisation results obtained from the consultation to wave energy representatives for the application markets, key drivers and stakeholder groups. The first set consists of line graphs showing the distribution of responses, whereas the second set of bubble charts displays the most frequently ranked factors (also known as the mode in statistics) together with the standard deviation from the mean value. The size of the bubbles is proportional to the number of responses.

3.4.2 Key Drivers of Wave Energy Projects

3.4.2.1 Utility-scale generation

The distribution of priorities per driver in a utility-scale generation market and the most frequently ranked factors are presented in Figure 3.5.



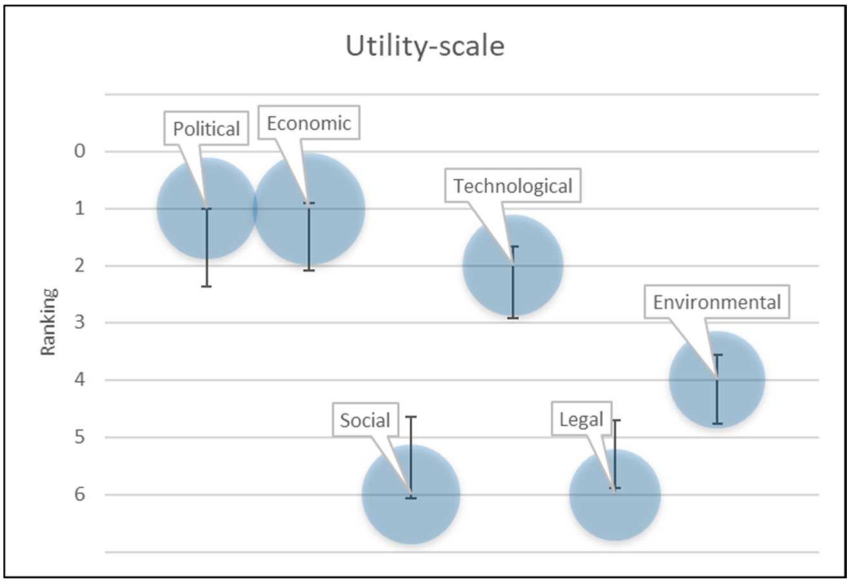


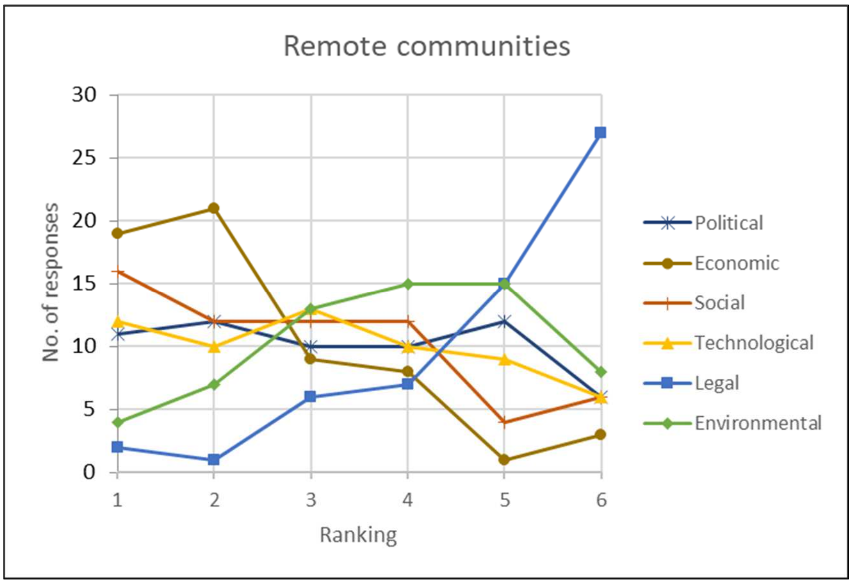
Figure 3.5: Key Drivers for Utility-scale Generation

Even though the survey did not allow assigning the same priority to the factors, it can be noted that both Economic and Political drivers did receive the highest score. Similarly, the Social and Legal drivers scored the lowest for the utility-scale generation market. In both cases, the bubble size can disambiguate between drivers if needed.

A closer analysis of the scores per driver yields a sharp rank distribution. Responses show a significant level of agreement (34-44%). The prioritisation according to the mode is not sensitive to the margin of error in the sample.

3.4.2.2 Powering remote communities

Likewise, the distribution of priorities per external driver and the most frequently ranked factors are presented in Figure 3.6. This time, the focus is on applying wave energy technologies in a remote community generation market.



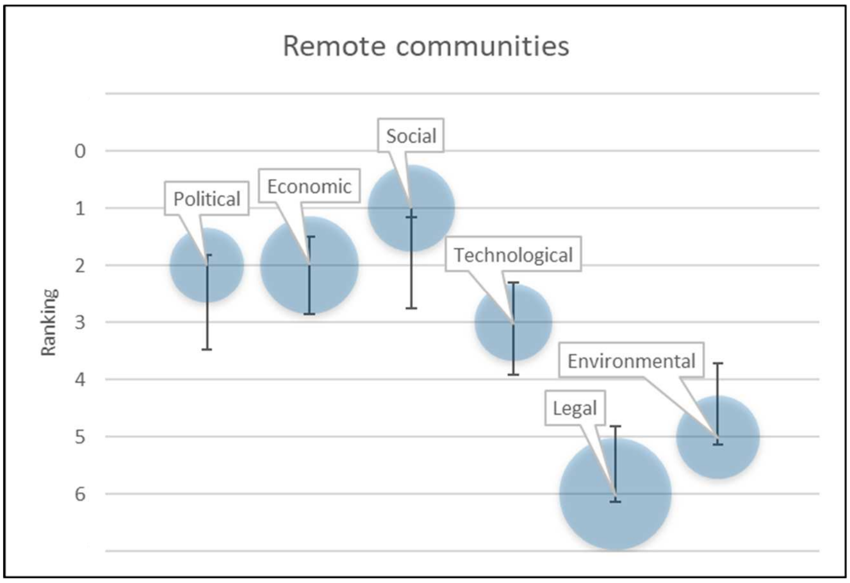


Figure 3.6: Key Drivers for Remote Community Generation

It can be observed that the Social drivers now have the top priority with 26% of responses, whereas the Legal drivers score last. The Economic and Political drivers are ranked second. The level of agreement in the responses is not so marked for all drivers as for the utility-scale generation. This means that the prioritisation of Political (20% of responses), Technological (21%) and Environmental (25%) drivers may be sensitive to the sample size. The distribution of responses is much flatter for these three drivers.

Prioritisation of Political drivers has a higher degree of uncertainty as it can get a higher rank (1) or a much lower rank (5) with minor changes in the responses.

3.4.3 Drivers Interrelationship with Stakeholder Groups

3.4.3.1 Political factors

The importance distribution of Political concerns per wave energy stakeholder group and the most frequently ranked stakeholders are presented in Figure 3.7.

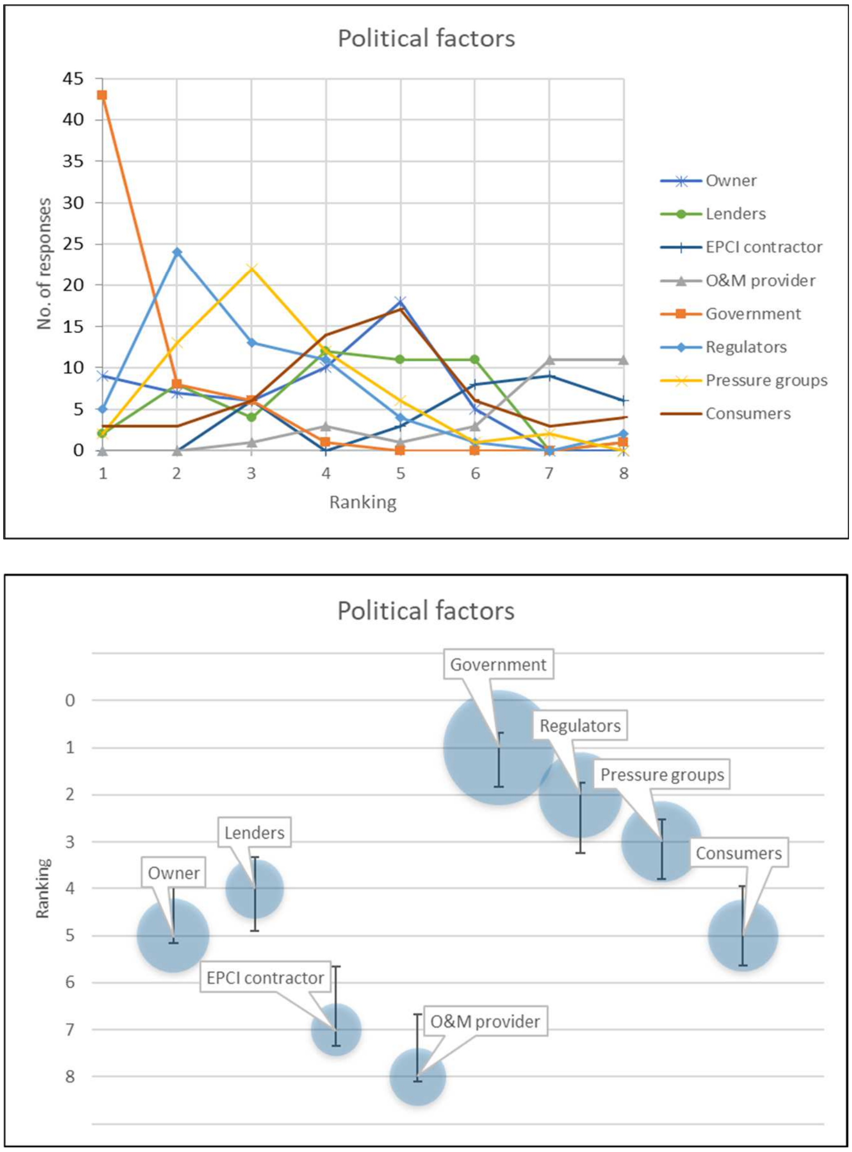


Figure 3.7: Political concerns for the wave energy stakeholders

While the Government clearly shows up in the first position with 70% of responses, the EPCI contractor and O&M provider are the least important stakeholders in terms of political concerns. These last two drivers have also received fewer responses (15% and 18%, respectively). They could step up one position accounting for the sample's margin of error, which is insufficient to alter the overall prioritisation. Lenders display the most significant degree of uncertainty. They can either be ranked 4, 5 or 6 with minor changes in the responses.

3.4.3.2 Economic factors

The importance distribution of Economic concerns per wave energy stakeholder group and the most frequently ranked stakeholders are presented in Figure 3.8.

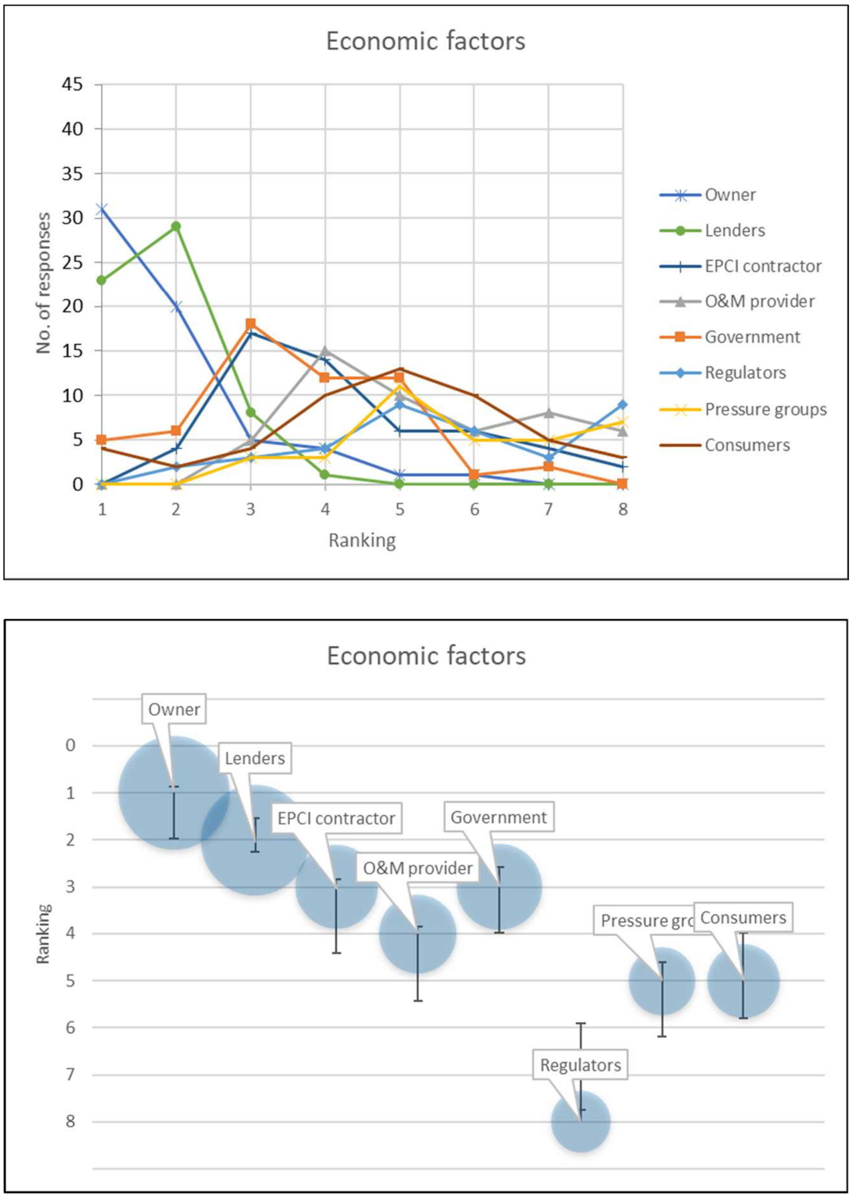


Figure 3.8: Economic Concerns for the Wave Energy Stakeholders.

The Owner stands out in the first position with 51% of responses. There is a high level of agreement in prioritising stakeholders according to Economic factors. Given the margin of error in the sample, the only uncertainty is for the Regulators who could step up to the same position as the Consumers and the Pressure groups. However, as Regulators score in the last position with fewer responses (15%), this does not change the overall ranking.

3.4.3.3 Social factors

The importance distribution of Social concerns per wave energy stakeholder group and the most frequently ranked stakeholders are presented in Figure 3.9.

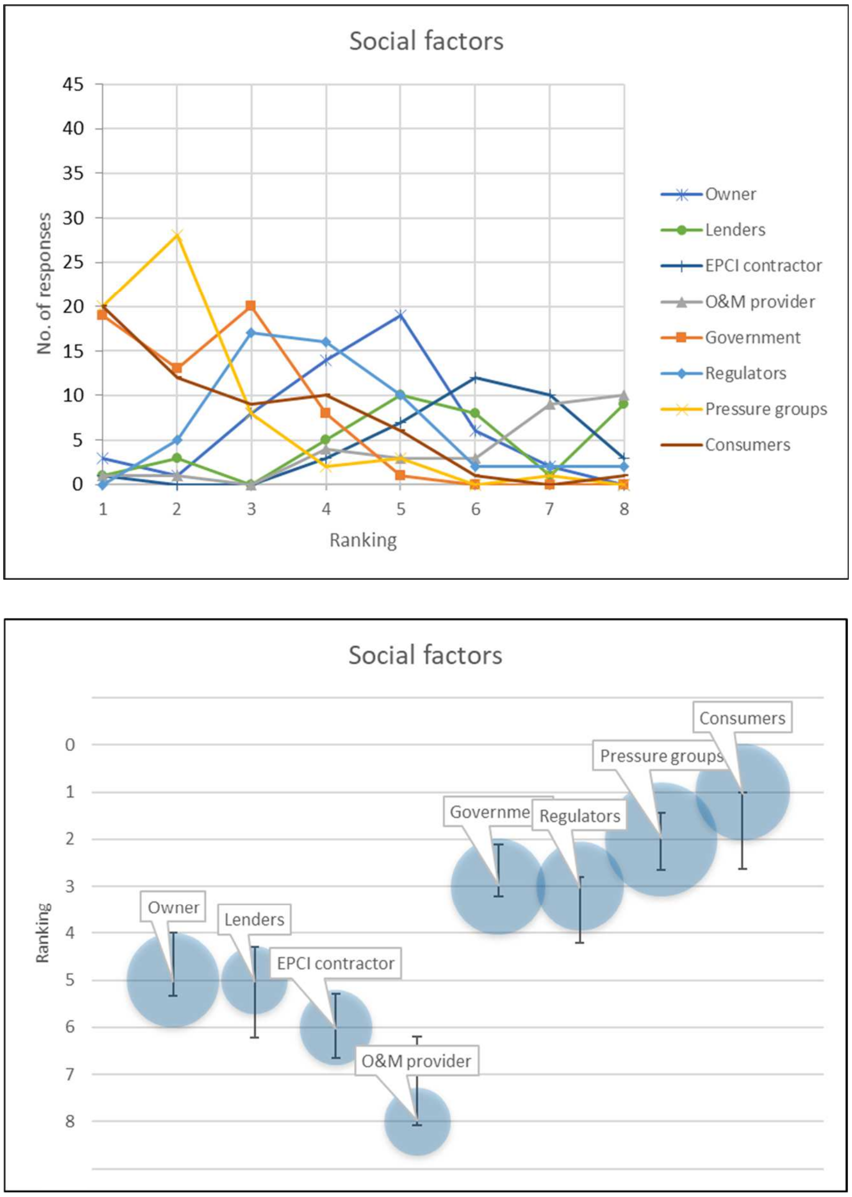
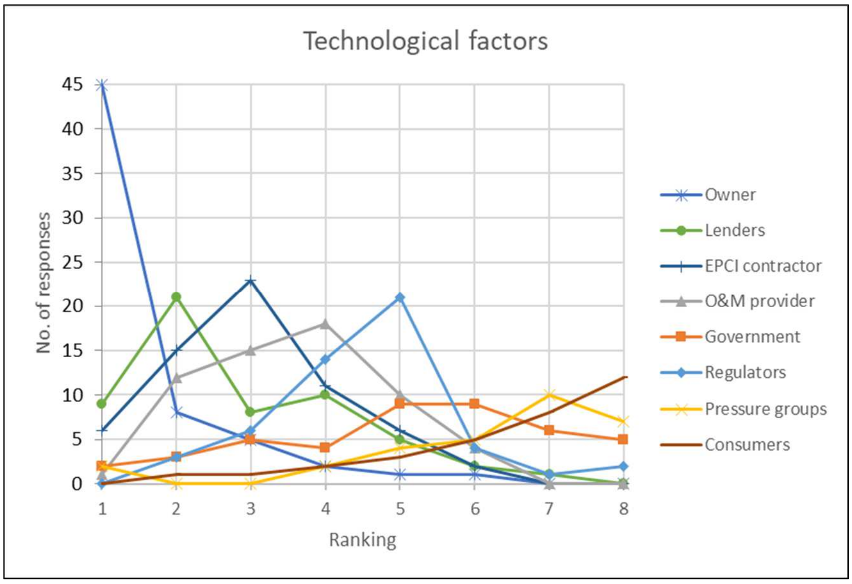


Figure 3.9: Social Concerns for the Wave Energy Stakeholders.

In this case, Consumers are ranked first according to Social factors with 33% of responses. There is a firm agreement concerning the importance of Pressure groups (46%), the Owner (33%) and Regulators (28%). However, the Government can swap from the third to the first position considering the margin of error in the sample. Finally, the EPCI contractor, Lenders and the O&M provider get fewer responses (16-20%). Their ranking, however, is unaffected by this level of uncertainty.

3.4.3.4 Technological factors

The importance distribution of Technological concerns per wave energy stakeholder group and the most frequently ranked stakeholders are presented in Figure 3.10.



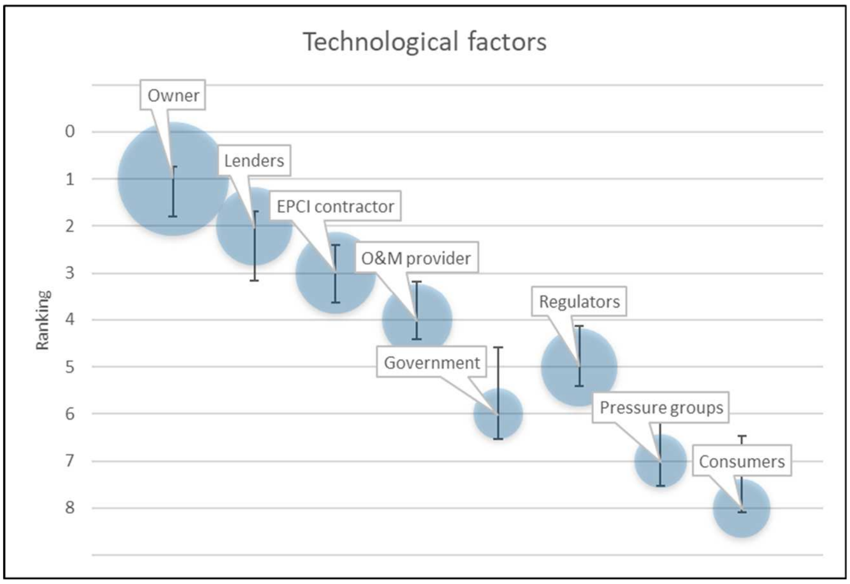


Figure 3.10: Technological Concerns for the Wave Energy Stakeholders.

As per the Economic drivers, the Owner jumps again into the first position, but in this case with the highest number of responses (74%). There is a high level of agreement in prioritising stakeholders according to Technological factors. Given the margin of error in the sample, the only uncertainty is that the Government could step up to the same position as Regulators. However, this does not change the overall ranking as the Government has fewer responses (15%). Finally, Pressure groups and Consumers close this ranking.

3.4.3.5 Legal factors

The importance distribution of Legal concerns per wave energy stakeholder group and the most frequently ranked stakeholders are presented in Figure 3.11.

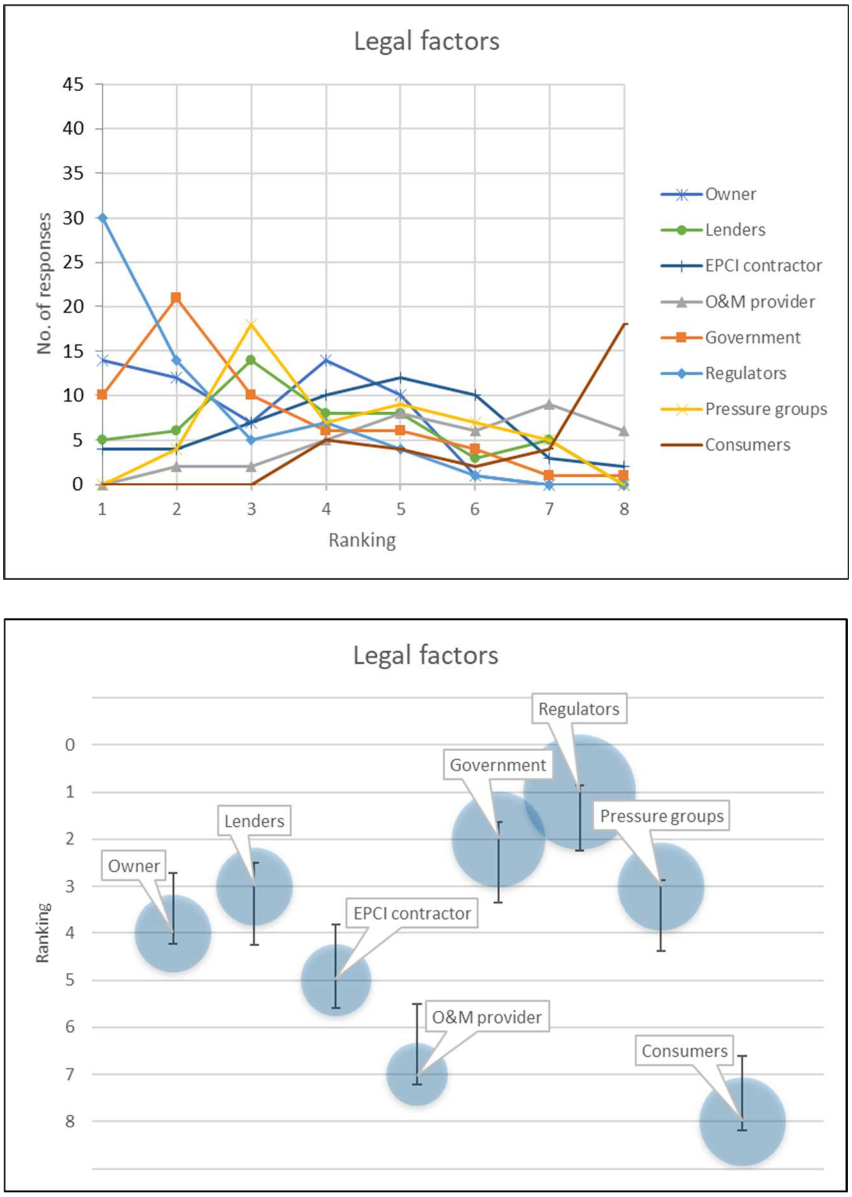


Figure 3.11: Legal Concerns for the Wave Energy Stakeholders.

Regulators present the highest priority with 49% of responses and Consumers with the lowest with 30% of responses. There is a significant level of agreement in the ranking of stakeholders despite the margin of error in the sample. The only uncertainty remains with the position of the Owner, which can be swapped from four to one.

3.4.3.6 Environmental factors

Finally, the importance distribution of Environmental concerns per wave energy stakeholder group and the most frequently ranked stakeholders are presented in Figure 3.12.

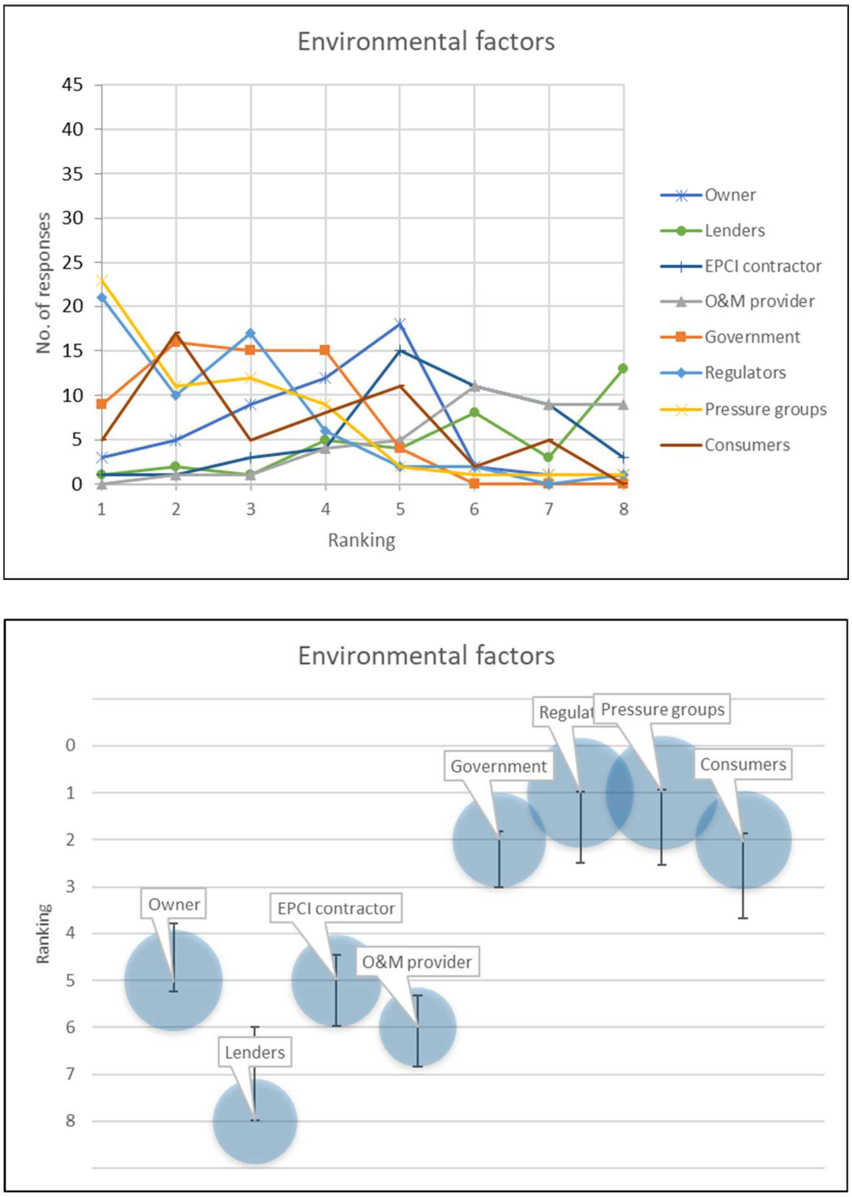


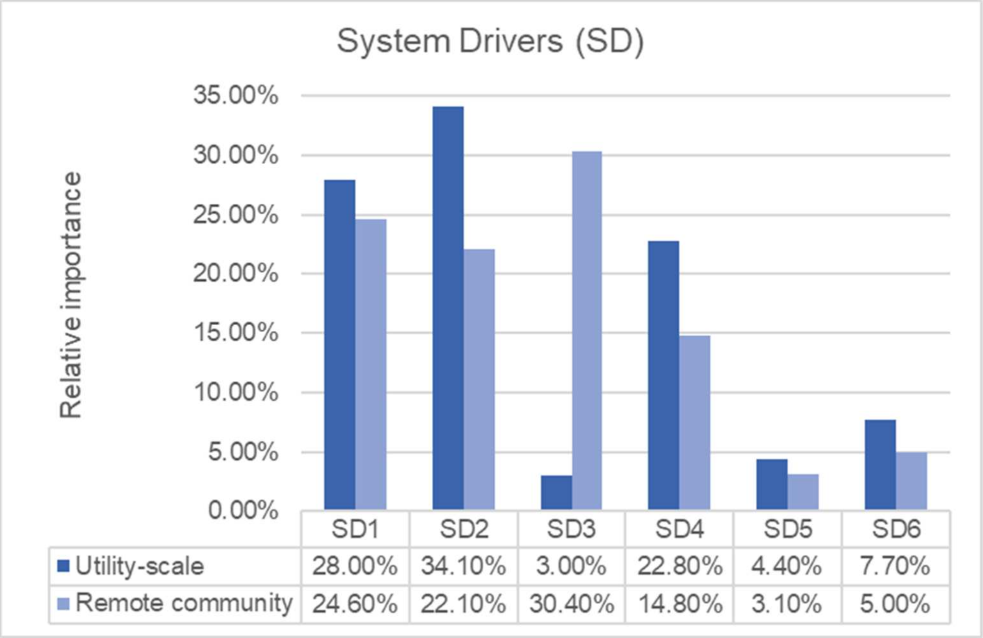
Figure 3.12: Environmental Concerns for the Wave Energy Stakeholders.

Pressure groups and Regulators share the first position with 38% and 34% of responses, respectively. Lenders are ranked last. The overall ranking is not sensitive to the margin of error except for the Government, which can take either the third or fourth position. However, the Government accounts for fewer responses (26%) than the Consumers (28%), which make the obtained prioritisation still reliable.

3.4.4 Prioritisation of SDs

According to the survey results, the ranking of wave energy drivers considerably differs between the two application markets. Economic factors are the primary motivations for developing utility-scale generation projects, whereas Social factors drive the remote community generation market. This result is in line with the market characterisation presented in section 3.3.2 and the qualitative feedback collected from the consultation to wave energy representatives. In other words, utility-scale generation is a very competitive market, whilst the social demand for clean energy and public acceptance drive powering remote communities.

The application of AHP provides more granularity to compare this outcome. The weights resulting from pairwise comparisons are reliable since the Consistency Ratio yields a satisfactory value below 0.1 in both cases. As shown in Figure 3.13, the Economic, Political and Technological factors are significant drivers in the utility-scale generation, accounting for almost 85% of the total ratings. However, in powering remote communities, more drivers come into play. Economic, Political and Technological factors are still important, but Social factors dominate. Altogether, they account for 92% of the total ratings.



	SD1	SD2	SD3	SD4	SD5	SD6
■ Utility-scale	28.00%	34.10%	3.00%	22.80%	4.40%	7.70%
■ Remote community	24.60%	22.10%	30.40%	14.80%	3.10%	5.00%

Figure 3.13: Relative importance of SD for the application market.

Wave energy utility-scale projects are not at the commercial stage, as they require technological development to demonstrate the necessary reliability and cost-effectiveness. This circumstance creates important barriers to accessing the required financial and insurance support. Hence, public funding is needed to develop wave energy to the point that the private sector can pick it up. In this sense, a key political driver is long-term revenue support from governments. Additionally, investment decisions may hinge on available political targets concerning climate change, energy transition and security of supply. Consequently, utility-scale development of wave energy technologies will largely depend on attractive economic support and a favourable political framework.

In contrast, the maturity of existing wave energy technologies may be sufficient to provide energy at a smaller scale in a remote community project. Remote communities already bear a high energy cost, opening the way to make wave energy technologies competitive with other energy sources. In this sense, the growing energy demand and social acceptance of the local communities are crucial drivers. Moreover, local populations are much more engaged and have a closer appreciation of nearby environmental and economic benefits. The economic and political factors score second in a remote community market application, and the social concerns highly determine them.

Technological factors are second for the utility-scale projects and third for the remote community generation. This reflects that technology maturity is somehow assumed to be in place before any significant technology roll-out can be conceived. Besides, grid infrastructure may be critical but needs stronger pushes in the economic, political and social drivers since it is out of the hands of the technology developers.

Surprisingly, the legal and environmental factors are considered to have minor importance for both markets, and the social factors score last in the utility-scale market when it is the major motivation for a remote community market.

Legal and environmental aspects are generally perceived as barriers instead of drivers. Many procedures are partially in place and data gathered on the potential environmental impacts are limited or poorly validated because of the short deployment times of current technologies. It will be important to address these uncertainties in the future. However, it is considered that if wave technology is proven to work, then the legal and permitting side will eventually follow. Factors relating to competing uses of resource areas might also impact decision-making. Stricter environmental protection will speed up the transition to renewables for energy companies. The legal factor is usually equalised once the political factor is in place and sets the legal environment.

The previous results point out that each application market is a central issue but also that drivers are somehow interlinked. Finance is connected to a suitable political framework. Limited support will delay technology maturity, but if the technology is proven, the legal side will follow. The political factors will contribute to setting the legal framework. Environmental concerns may be the motivator for political and social factors. Finally, job creation is a political aspect but can also improve social acceptance.

3.4.5 Prioritisation of SHs

In the stakeholder domain, the wave energy problem is expressed in terms of stakeholders' expectations. The different importance ranking of these stakeholders for each key driver and market application will hence determine the system requirements for developing wave energy technologies that are tailored to each specific use.

According to the survey results, two broad clusters of stakeholders arise. On the one hand, the Owner, Lenders, EPCI contractor and O&M provider are the most important actors for the Economic and Technological factors. On the other hand, the Government, Regulators, Pressure groups and Consumers are mainly connected to Political, Social, Environmental and Legal factors. This result is in line with the few references in the literature [111], [112] and the qualitative feedback collected from the consultation to wave energy representatives.

Political factors are of primary concern to the Government and Regulators. It is worth noting that although the Political drivers are directly steered by the Government and Regulators, the Pressure groups and the Consumers also have a certain degree of influence on the Government.

Economic and Technological factors share a similar profile of stakeholders' concerns. The ranking starts with the Owner followed by the Lenders, EPCI contractor and O&M provider. However, the Government is slightly more concerned with Economic drivers than Technological ones. At the current stage of development, Economic and Technological drivers are crucial for both Owners and Lenders as their return on capital is at stake. EPCI contractors and O&M providers will try to reduce their exposure due to technology immaturity.

Social and Environmental drivers are more connected to the public and therefore are vital for the Government, Regulators, Pressure groups and Consumers. These four stakeholders score high for the Environmental drivers. However, Consumers and Pressure groups stand out in the case of Social drivers. Lastly, Legal factors are driven by those who can support and define the boundaries of the legal framework, namely Regulators, the Government and Pressure Groups.

These results show that the Owner and the Government are lead players in the two stakeholder clusters. We have seen earlier Economic and Political factors dominate utility-scale generation, whilst powering remote communities is mainly motivated by Social drivers. Accordingly, it can be inferred that the development of wave energy technologies will be primarily influenced by the needs of the Owner and the Government for utility-scale and remote community projects, respectively.

This research has some limitations, as pointed out during the discussion of the key drivers of wave energy projects. The prioritisation of concerns contains a certain degree of uncertainty due to the sample size and corresponding margin of error. A different sample can reduce Lenders' concerns about Political factors and Environmental factors. Similarly, Regulators, the Government and the Owner can have greater concerns about the Economic, Social and Legal factors, respectively.

The qualitative responses in the wave energy representatives' survey help to establish the interrelationship of SHs with SDs. In the proposed method, QFD is adopted to prioritise survey results into SH weights for each application market and SDs. The use of QFD provides further insight into the qualitative results presented in section 3.4.3. The resulting SH relationships with each SDs are converted into numerical coefficients using the importance rating scale shown in Table 3.6.

Table 3.6: Importance rating scale [204].

Rating	Impact
0	None
1	Weak
3	Moderate
5	Strong
7	Very strong
9	Extremely strong

QFD results confirm that the development of wave energy technologies will be primarily influenced by the needs of the Owner (19%) for utility-scale generation and the Government (17%) for remote community projects. Additionally, it was concluded that the Owner, Lenders, EPCI contractor and O&M provider are slightly more influential in the utility-scale application. This behaviour is reversed for the Regulators, Pressure groups and Consumers in the remote community generation.

From Figure 3.14, it can be concluded that the Government has the same importance for both markets. It is the second-ranked SH in the utility-scale market. On the other hand, the Owner scores second (15.5%) after the Government for the remote community generation. Both the Owner and Government play a fundamental role in both markets. The relative weights of the different stakeholder groups for each market will determine the global merit and final suitability of wave energy technologies in the qualitative assessment.

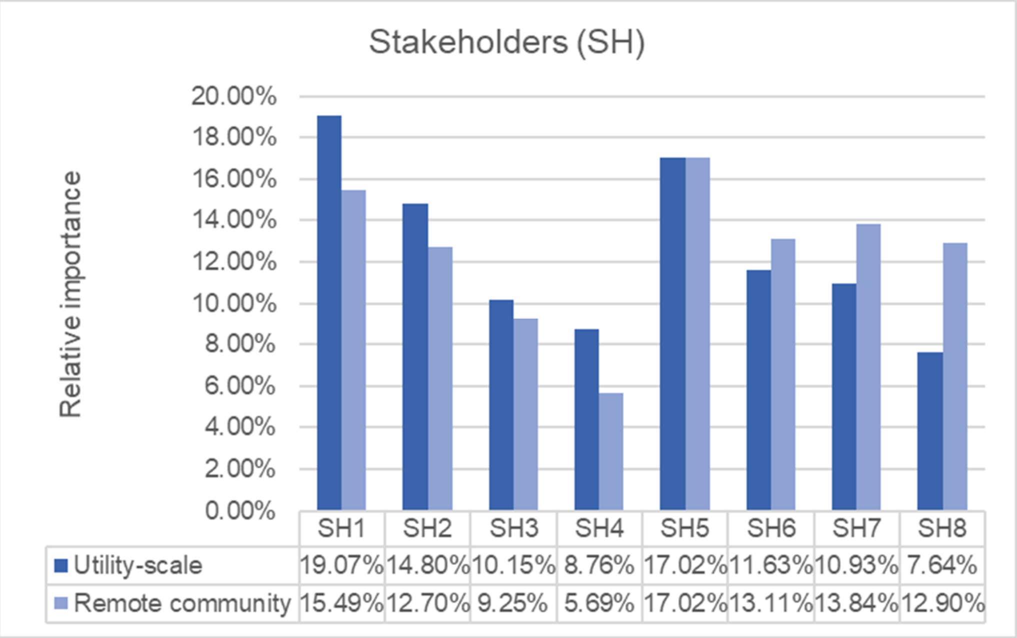


Figure 3.14: Relative importance of SH for the application market.

3.5 Conclusions

Developing cost-effective wave energy technologies is a complex and lengthy process in which many decisions must be taken. A firm foundation for developing a successful technology that meets the stakeholders' expectations requests an early definition of systems requirements and a clear understanding of the potential impact/dependencies of the overarching context where the technology will operate.

The system context comprises multiple external forces that may influence decision-making. This report has analysed the relative importance of key drivers and stakeholders influencing the development of wave energy technologies in two power markets, namely utility-scale generation and powering remote communities. The assessment of external forces has been carried out through a survey of international wave energy representatives of a varied mix of both geographical origins and backgrounds.

Results from this prioritisation exercise suggest some interesting global trends. The ranking of wave energy drivers considerably varies for the utility-scale generation market and the powering remote community's counterpart. Economic and Political factors are the primary motivations for developing utility-scale generation projects, whereas the Social drivers stand out in a remote generation market. Besides, two broad clusters of stakeholders arise.

On the one hand, the Owner, Lenders, EPCI contractors and O&M providers are the most important actors for the Economic and Technological factors. On the other hand, the Government, Regulators, Pressure groups and Consumers are mainly concerned with Political, Social, Environmental and Legal factors. Moreover, the Owner and the Government are lead players in each stakeholder cluster. The implication is that the development of wave energy technologies will be mostly determined by the needs and concerns of the Owner and the Government for utility-scale and remote community projects, respectively.

These results are consistent with recent ocean energy literature, such as OceanSET's latest annual report [205], OEE 20230 Vision [206] or IRENA's recommendations [207], and the qualitative feedback collected from consultations with representatives of wave energy stakeholders. As one technology developer expressed it: "*We need technological maturity, but to finance that we need political support (public finance) and economical support (private finance)*".

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CHAPTER 4 FORMALISING SYSTEM REQUIREMENTS

> “Keep your eyes on the stars, and your feet on the ground”
>
> *Theodore Roosevelt (1850 – 1919)*

4.1 Overview

This chapter aims to a structured inventory of the goals that should guide the search for solutions. The wave energy specification captures all critical and prioritized Stakeholder Requirements (SRs) at the highest level. The specification then moves on to the Functional Requirements (FRs). Finally, Technical Requirements (TRs) specify the technological concerns that must be considered to properly implement the system in physical components and assemblies.

Section 4.2 introduces the specific methods and tools used in this step of the methodology. Functional analysis is employed to formalise the wave energy requirements. For the external analysis, which focuses on the system user and the identification of its service functions, the Octopus diagram is utilised. On the other side, service functions are converted into internal and technical functions using the Functional Analysis and System Technique (FAST). When aggregating merit, the underlying functional relationships are captured using the Logical Scoring of Preference (LSP).

Section 4.3 develops the specific wave energy system requirements. A solution space is bound by hierarchical and interconnected requirements. In order to satisfy the end-user or stakeholder needs, the SRs pinpoint which particular system characteristics are required. FRs outline what must be done by the system to attain the SRs. TRs are also referred to as design requirements because they are dependent on the design solution. Design Parameters (DPs) define the real space that is available for developing solutions.

Section 4.4 describes the practical implementation of this step. System requirements common to wave energy market applications are ranked based on the QFD approach. Results are presented in three hierarchical levels.

Finally, section 4.5 summarises the chapter and discusses some partial findings from this novel methodology that might be of interest to the wave energy sector.

4.2 Methods and Tools

4.2.1 Functional Analysis

Functional analysis is a structured approach to identifying and correlating the functions that a system must perform during its lifetime [85]. The Wave Energy System is the entity under consideration, which can comprise a variety of components, assemblies or subsystems acting together to achieve a common goal. It interacts with a set of External Systems using its interfaces. Finally, as we saw in the previous chapter, the Context is the wider environment where the system is placed. Figure 4.1 depicts the different interactions among the Wave Energy System, External Systems and Context.

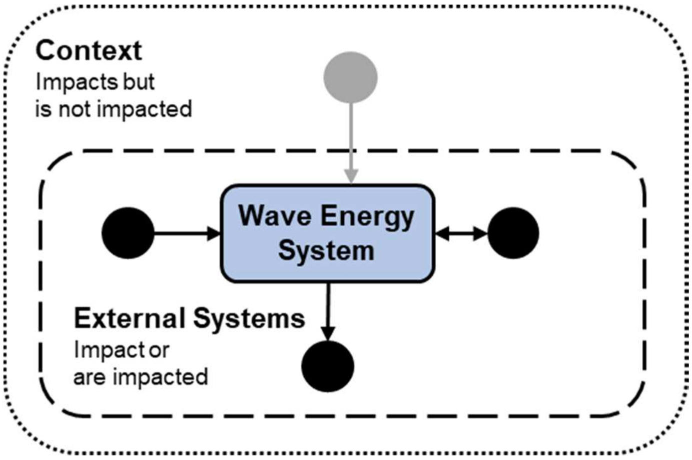

Figure 4.1: Wave Energy System, External Systems and Context (adapted from [62]).

There are two main types of functional analysis with complementary aims. The external analysis, focused on the system user and the identification of its service functions, helps to visualise the interactions of the Wave Energy System with the External Systems. On the other hand, the internal analysis, focused on the system designer, transforms service functions into internal and technical functions.

External Analysis

The Octopus diagram (see Figure 4.2) is one of the most useful tools provided by the APTE method [208] that displays the interactions of the Wave Energy System with the External Systems. It considers the system as a “black box”. For each of the relevant lifecycle phases, the External Systems are analysed concerning the Wave Energy System. An arrow is used to show three different categories of connections:

1. The System allows one External System (no. 1) to modify the status of another one (no. 2),
2. The System modifies the status of the External System (no. 3), and
3. The System is modified by the External System (no. 4).

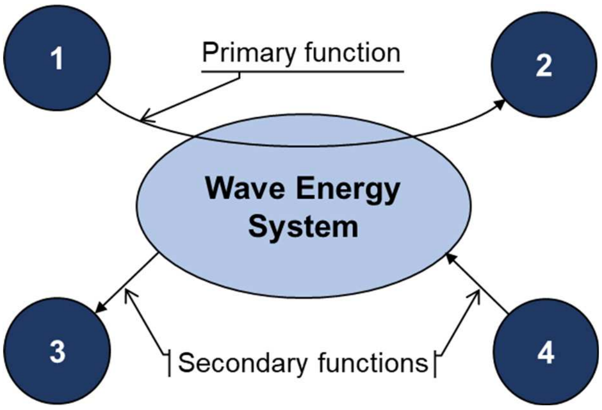

Figure 4.2: Octopus diagram.

Primary functions bind together two External Systems, whereas secondary functions connect just one.

The external functional analysis provides a general overview of the service functions of the Wave Energy System. However, this method cannot be used to examine internal system functionality.

Internal Analysis

For the internal analysis, the Function Analysis System Technique (FAST) is used. FAST was introduced by C. W. Bytheway, an engineer at Unisys, in 1960 [158]. The FAST diagram is a hierarchical representation that translates high-level functions into lower-level functions that must be performed by the system. It is built from left to right in the logic of "why" to "how". Any function to the left is a higher-level function since reading the FAST diagram in the "why" direction leads to the primary function. Conversely, any function to the right of another function is a lower-level function and represents a means that is needed (how) to achieve the function being addressed. The level of detail expands until it terminates at an actionable level. An actionable or measurable level of detail is one on which an engineer can begin the development work.

The main output of FAST is the identification of the basic functions through the decomposition of the higher-level functions. The basic functions help define or refine the functional requirements of the system, as each basic function can be rewritten as a functional requirement.

Functions in FAST are designated with a verb in the infinitive form. The method leans on an interrogative technique as described next:

1. Identify the primary functions and place them to the left.
2. For each primary function, ask the question, "How is this function to be achieved?" Place those functions that answer this question to the right of the primary function.
3. Repeat step 1 until an actionable level function is identified.

4. Verify the structure of the FAST diagram by starting at the lowest-level functions on the right and asking the question, "Why is this function included?" The function to the immediate left of the function being considered should answer this question.

Responses to each question can be single, multiple (using AND connector) or optional (using OR connector).

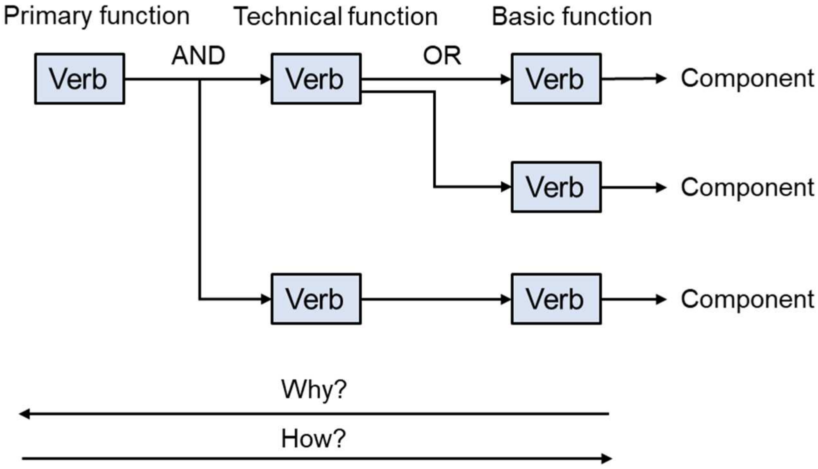

Figure 4.3: Function hierarchy in a FAST diagram

4.2.2 Logical Scoring of Preference (LSP)

The aggregation concept is a common feature of multi-criteria analysis methods. Even though tools such as AHP or QFD can be used to derive weightings for the various evaluation criteria, combining the lower-level evaluation criteria into an aggregated score is not a simple task. For instance, the TPL methodology [133] introduces three different ways of combining the lowest level scores (i.e. arithmetic mean, geometric mean and multiplication with normalisation) and four degrees of flexibility ranging from high flexibility to none.

The Logical Scoring of Preference (LSP) method proposed by Dujmovic [159] is used here to capture the underlying functional relationships and add more granularity to the aggregation step by allowing the definition of the degree of simultaneity of the requirements to be combined from the total disjunction to full conjunction [209].

Conjunction in LSP means that the output utility is predominantly affected by the value of the smallest input, calling for simultaneous high input values. The geometric and harmonic means, respectively, are examples of conventional operators that provide increasing levels of simultaneity. Conversely, disjunction means that the output utility allows the replaceability of low-value inputs. The square mean is an example of partial replaceability. Neutrality, which is the perfect balance between conjunction and disjunction, is denoted in LSP by the weighted arithmetic mean. When combining mandatory and optional inputs or sufficient and optional inputs, conjunctive or disjunctive partial absorption is used, respectively. The intensity of the simultaneity or replaceability can be continuously adjusted by selecting different operators as shown in Figure 4.4. Weightings in LSP are adjusted using QFD [76].

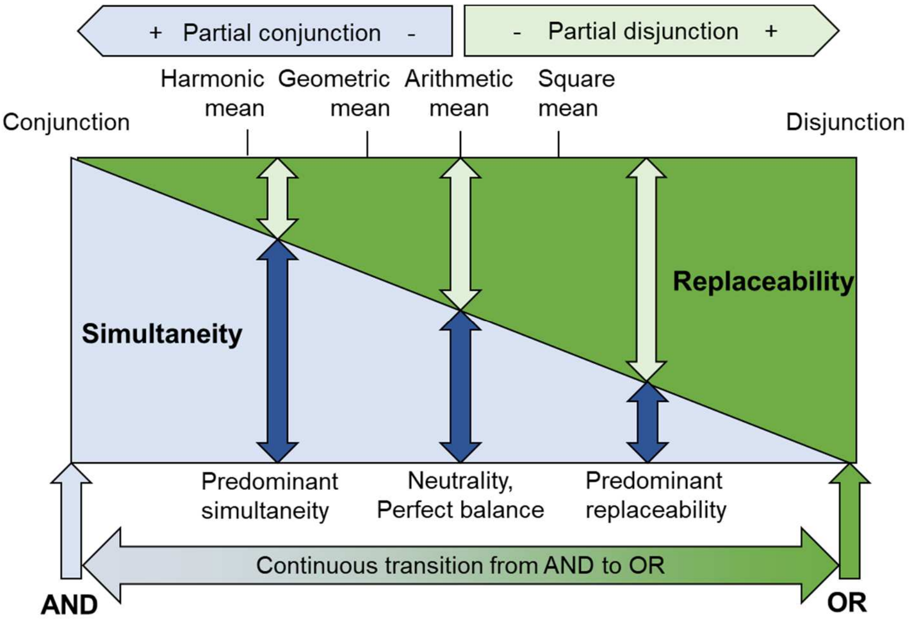

Figure 4.4: Degrees of simultaneity/replaceability of logic operators (adapted from [159]).

Following this approach, the evaluation criteria can be aggregated sequentially into higher hierarchical levels accounting for the degree of simultaneity of the different attributes until the final overarching merit is obtained. The overall suitability can be interpreted as the qualitative degree of satisfaction with all specified requirements. This suitability, s_0, is computed from the next level of evaluation criteria, s_i, as follows:

$$s_0 = \left(\sum_{i=1}^{m} w_i \cdot s_i^d \right)^{\frac{1}{d}}; \quad \sum_{i=1}^{m} w_i = 1, \qquad i = 1,2,\dots,m \tag{7}$$

where m is the number of evaluation criteria, w_n are their weightings, and d is a coefficient that depends on the degree of simultaneity. Values of d range from $-\infty$ for pure conjunction to $+\infty$ for pure disjunction. Special cases of weighted power mean for m=2 are shown in Table 4.1.

Table 4.1: Special cases for weighted power mean m=2 [210]

Aggregator	s_0	d
Maximum	$max\ (s_1, s_2)$	$+\infty$
Square mean	$\sqrt{w_1 s_1^2 + w_2 s_2^2}$	2
Arithmetic mean	$w_1 s_1 + w_2 s_2$	1
Geometric mean	$(s_1)^{w_1} \cdot (s_2)^{w_2}$	0
Harmonic mean	$\frac{1}{w_1/s_1 + w_2/s_2}$	-1
Minimum	$min\ (s_1, s_2)$	$-\infty$

Additional values of *d* are provided in Table 4.2 for other alternatives of partial conjunction and disjunction. The 'Andness' column represents the degree of conjunction.

Table 4.2: Generalised conjunction-disjunction. Values of d [159]

Aggregator	**Symbol**	**Andness**	**m=2**	**m=3**	**m=4**	**m=5**
Extreme disjunction	D	0.0000	+∞	+∞	+∞	+∞
Very strong disjunction	D++	0.0625	20.630	24.300	27.110	30.090
Strong disjunction	D+	0.1250	9.521	11.095	12.270	13.235
Medium strong disjunction	D+-	0.1875	5.802	6.675	7.316	7.819
Medium disjunction	DA	0.2500	3.929	4.450	4.825	5.111
Medium weak disjunction	D-+	0.3125	2.792	3.101	3.318	3.479
Weak disjunction	D-	0.3750	2.018	2.187	2.302	2.384
Square mean	S	0.3768	2.000	-	-	-
Very weak disjunction	D--	0.4375	1.449	1.519	1.565	1.596
Arithmetic mean	A	0.5000	1.000	1.000	1.000	1.000
Very weak conjunction	C--	0.5625	0.619	0.573	0.546	0.526
Weak conjunction	C-	0.6250	0.261	0.192	0.153	0.129
Geometric mean	G	0.6667	0.000	-	-	-
Medium weak conjunction	C-+	0.6875	−0.148	−0.208	−0.235	−0.251
Medium conjunction	CA	0.7500	−0.720	−0.732	−0.721	−0.707
Harmonic mean	H	0.7726	−1.000	-	-	-
Medium strong conjunction	C+-	0.8125	−1.655	−1.550	−1.455	−1.380
Strong conjunction	C+	0.8750	−3.510	−3.114	−2.823	−2.606
Very strong conjunction	C++	0.9375	−9.060	−7.639	−6.689	−6.013
Extreme conjunction	C	1.0000	−∞	−∞	−∞	−∞

4.3 Wave Energy System Requirements

4.3.1 Background

The previous chapter analysed the external forces influencing wave energy technology development due to the key role they play in establishing further requirements. The hierarchical formulation of wave energy requirements is built upon these results.

QFD is used to produce traceable mappings between the environmental, stakeholder, functional and technical domains as represented in Figure 4.5. The Stakeholder Requirements (SRs) are translated into several prioritised Functional Requirements (FRs) and Design Parameters (DPs) that the wave energy system should meet. This way, the functional analysis produces a complete and unambiguous definition of the design problem space.

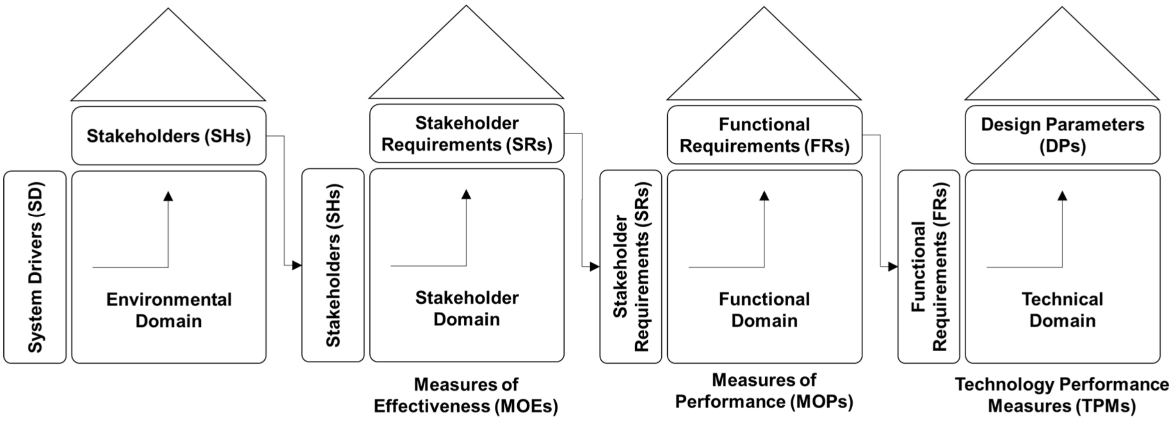

Figure 4.5: Approach to building Wave Energy System Requirements.

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.

To carry out this analysis, it is necessary to delimit the scope of the wave energy system. Most commonly, technology developers identify the system of reference with their Wave Energy Converter (WEC), whereas suppliers consider it to be one of its main constituents, such as the Power Take-Off (PTO) or the mooring system. However, it is more appropriate and unbiased to designate the wave energy farm as the baseline system for the global assessment of technologies since this is the final product that can meet the market need for sustainable, affordable, and secure energy. Moreover, this definition is fully consistent with the system analysis conducted by Babarit et al. for wave energy [118].

4.3.2 Stakeholder Requirements (SRs)

The mission statement of a wave energy system is presented in [118] for a utility market application. This overarching goal is reformulated and generalised here to other electricity generation markets as follows:

> "The wave energy farm converts ocean wave energy into consumable power"

Starting with this mission statement, the roles and expectations of the different stakeholder groups have been structured from various literature sources such as [116], [117], [118], and [211]. They are summarised in Table 4.3.

Table 4.3: Stakeholder roles and expectations.

Id	Stakeholder	Roles	Expectations
SH1	Owner	Initiate the project and design the farm Provide equity Set return on investment targets Manage project risks Sell electricity to consumers	Competitive profitability Low project risks Access to affordable credit Stability of policy framework Assess performance levels Competitive cost of electricity Predictable generation Match consumer demand
SH2	Lenders	Provide debt Set interest rate Assess financial risk	Low revenue risks Maintain reputation
SH3	EPCI contractor	Manage farm construction and installation Provide insurance during construction Select suppliers Manage end-of-life recycling	Select the best components and systems Avoid cost overruns and delays Well-understood and manageable risks
SH4	O&M provider	Provide spare parts and services Perform (un)scheduled maintenance Provide insurance during the operation Select service suppliers	Reliability of assets during the project's lifetime Avoid cost overruns and delays Well-understood and manageable risks Safety at sea
SH5	Government	Develop and implement sectoral policies Review compliance Provide investment and generation incentives	Economic development Efficient use of public resources Compliance with regulation Socio-economic benefits
SH6	Regulators	Establish permitting requirements Review project use of ocean space Provide concession	Compliance with regulation Maintain reputation
SH7	Pressure groups	Lobby for or against the project Improve the well-being of the community	Acceptable environmental impact No affection for other activities Socio-economic benefits
SH8	Consumers	Set power quality requirements Purchase generated electricity	Competitive cost of electricity Predictable generation

Underlying all stakeholders' expectations, there is the need to make wave energy competitive and acceptable for the targeted market, or expressed in another form, wave energy must address the energy trilemma, namely energy security, sustainability and affordability [212].

With this in mind, Stakeholder Requirements (SRs) and Measures of Effectiveness (MOEs) have been identified through an iterative process of distilling stakeholders' expectations until arriving at the condensed list as shown in Table 4.4.

Table 4.4: Stakeholder Requirements and Metrics.

Id	Stakeholder Requirement (SR)	Measure of Effectiveness (MOE)
SR1	Convert wave energy into consumable power	Capacity Factor (CF) [59]
SR2	Operate when needed	Availability Factor (AF) [142]
SR3	Reduce upfront costs	Capital Expenditure (CAPEX) [59]
SR4	Reduce annual costs	Operational Expenditure (OPEX) [59]
SR5	Prevent business risks	Fixed Charge Rate (FCR) [213]

It is worthwhile noting that the way SRs are elicited greatly facilitates the definition of MOEs. A closer look at the upper system metrics reveals parallelism with the simplified LCOE equation [214].

$$LCOE = \frac{CAPEX \times FCR + OPEX}{8{,}766 \times P \times CF \times AF} \tag{8}$$

where

- *CAPEX*, Capital Expenditure, represents all capital costs associated with the farm development, manufacturing, installation and decommissioning at the end of the project life.
- *FCR*, Fixed Charge Rate, is the annual return, i.e. the fraction of *CAPEX* which is needed to meet investor revenue requirements.
- *OPEX*, Annual Operating Expenditure, include all routine maintenance, operations, and monitoring activity.
- 8,766 is the average total hours in a year.
- *P*, Rated Power, is the nominal installed capacity of the farm.
- *CF*, Capacity Factor, is the gross annual power generated by the wave energy farm as compared to its rated output at 100% availability.
- *AF*, Availability Factor, is the percentage of the time that the wave energy farm is available to provide energy to the grid. By convention, the zero production periods (i.e the wave resource lies below or above certain limits) are counted against the *CF* but not against the *AF*.

As can be seen, the numerator accounts for the annuitized lifetime costs and the denominator is the net energy production per year.

In the proposed method, QFD is used to prioritise the SRs. To maintain traceability, the importance ranking of SRs for each application market was obtained in connection to the SHs. The same importance rating scale previously shown in Table 3.6 is used to derive SH–SR relationships.

Additionally, LSP is used to aggregate the MOEs sequentially accounting for the degree of simultaneity of the different attributes until a final measure of suitability is obtained, which can be interpreted as the global degree of satisfaction of the SRs.

Figure 4.6 presents the aggregation logic of the MOEs into this Global Merit (GM). The weights above each arrow, w_i, represent the relative importance ratings of the SRs. The Geometric mean (G) and Arithmetic mean (A) operators were chosen to combine attributes with a multiplicative and additive nature, respectively.

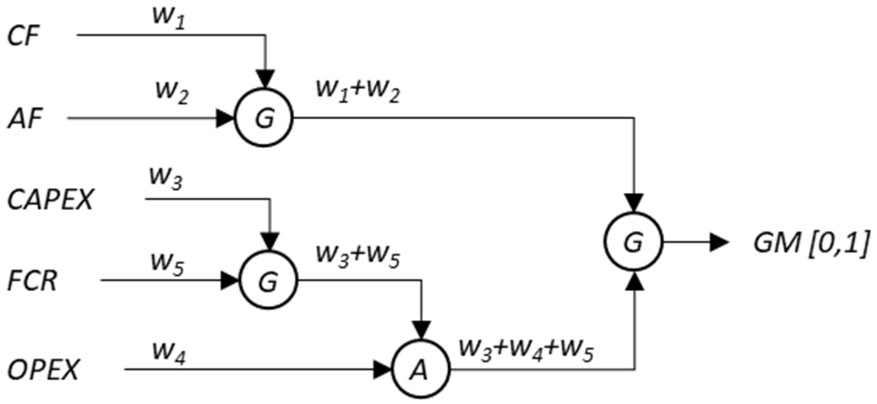

Figure 4.6: Aggregation of MOE.

LCOE is the most common highest-level metric used to assess wave energy options [142]. However, the reader should bear in mind that the GM of a wave energy option might differ from the preference obtained using the numerical LCOE values since the aggregation logic also accounts for the relative importance expressed by the stakeholders, the underlying degree of simultaneity and the flexibility allowed to the various requirements, all of them qualitative aspects.

CAPEX and OPEX vary largely for prototype technologies. Based on the OceanSET Third Annual Report [205], a CAPEX of €5m per MW and an OPEX of €500,000 (i.e. 10% of CAPEX) can be considered as threshold values for a zero utility, respectively.

The simplified LCOE expression uses the Fixed Charge Rate (FCR):

$$FCR = \frac{r}{[1-(1+r)^{-y}]} \tag{9}$$

where r is the discount rate and y is the project lifetime in years. For pre-demonstration projects with a maximum lifetime of 10 years, the discount rate can be as high as 15% [215] leading to a maximum FCR of 20% (zero utility). On the other hand, mature technologies with long lifetimes (>25 years) can achieve an FCR of just 5% with low discount rates of 3% (i.e. very low borrowing and inflation rates).

The CF will generally increase with the higher wave energy flux. Figure 4.7 presents an illustrative plot of the upper CF bound for various wave energy levels, based on estimates of Babarit et al. [216] for eight different WECs at five sites along the Atlantic coast of Europe. This reference is useful to set the maximum CF utility at 50%.

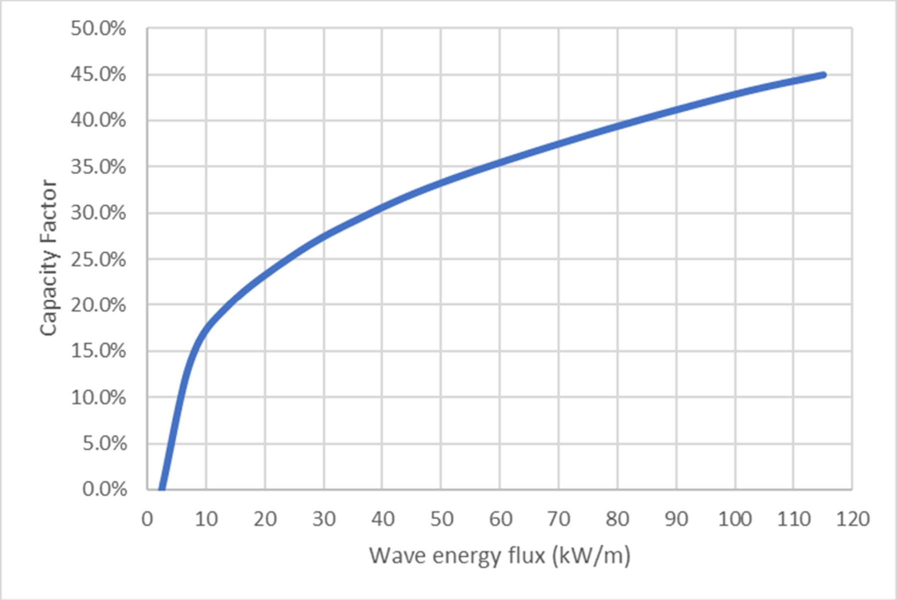

Figure 4.7: Fundamental relationship between the CF and the wave energy level (adapted from [217], Supplemental Information).

Finally, according to the World Energy Council's Performance of Generating Plant Committee [218], 80% of the gap in the best achievable AF is due to suboptimal O&M management practices. This is supported by OceanSET reporting an average AF of 78% for 13 wave energy projects [205]. Moreover, Greaves and Iglesias [3] identified an operational availability threshold of 75% for marine renewable energy devices.

4.3.3 Functional Requirements (FRs)

Functional Requirements (FRs) are the bridge between the stakeholders and technical teams, and they should be elicited in all phases of the system lifecycle [81]. Functional analysis is used to identify what functions the wave energy system should perform, their logical structure and interactions to satisfy SRs efficiently.

Whilst the engineering system exists only for its usage, all life phases must be considered since they add important constraints to the system design. Figure 4.8 shows the typical lifecycle of a wave energy system and the independent entities to which it is physically or virtually linked, that is the External Systems. Stages have been adapted from [118].

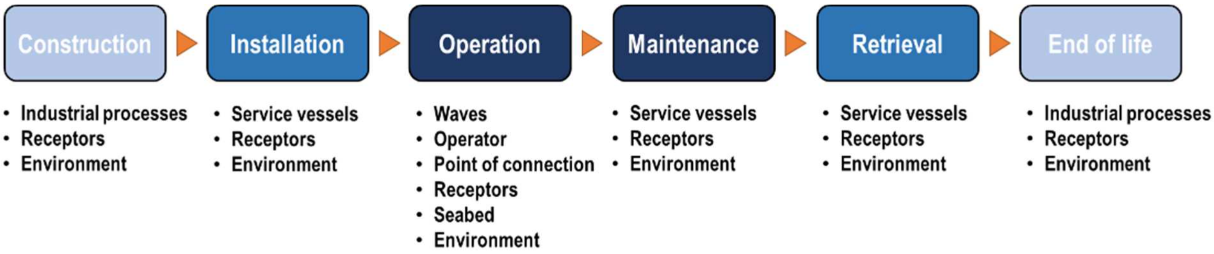

Figure 4.8: Lifecycle of the wave energy system and entities.

The construction phase encompasses all manufacturing, transport and assembly activities performed onshore. Similarly, the end-of-life phase includes reusing, recycling or safely disposing of the parts that make up the wave energy system. The installation, maintenance and retrieval phases comprise the offshore transport. Additionally, maintenance involves inspection, repair, or replacement [219]. Minor repairs can be performed on-site. For major repairs and replacements, the wave energy system might be brought to shore and may require specific industrial processes, as for the construction and end-of-life phases. Finally, the operation is the most important phase in the system lifecycle since it is the only one that directly adds value to the end-users. The operation phase includes the standby, normal, malfunction and survival modes of the wave energy devices.

Firstly, the external analysis of the wave energy farm is carried out to provide a general overview of the service functions of the wave energy system. The Octopus diagram is used to display the interactions of the wave energy system with the external systems.

During its operational phase (Figure 4.9a), the wave energy system interacts with two External Systems, namely the Waves and the Point of connection where the converted energy is consumed. Accordingly, the primary function of a wave energy system is stated as follows:

F_p: Convert wave energy into consumable power

This primary function is precisely elicited as the mission statement presented earlier. The remaining operational functions are secondary:

F_{s1}: Operate when needed

F_{s2}: Control energy capture

F_{s3}: Transfer loads to the seabed

F_{s4}: Reduce the severity of environmental threats

F_{s5}: Avoid risks to receptors

These secondary functions connect the wave energy system with the Operator, Seabed, Ocean Environment and Receptors, respectively.

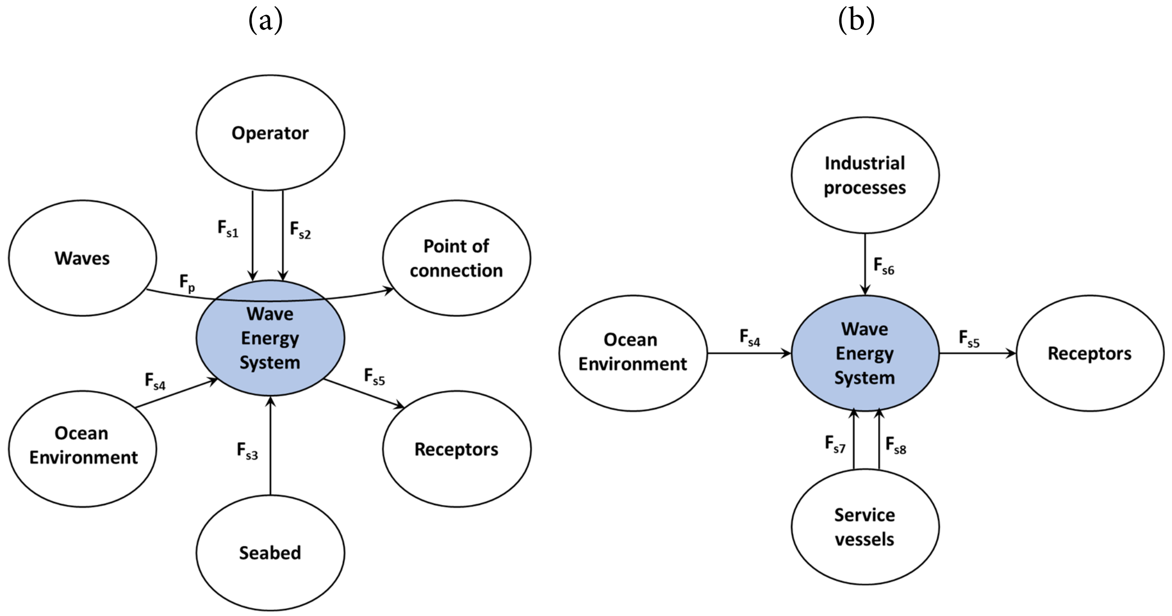

Figure 4.9: Octopus diagram for the operation phase (a) and rest of phases (b).

The rest of the phases, which add constraints to the system design, have been merged into a single diagram for convenience (Figure 4.9b) leading to three additional secondary functions.

F_{s6}: Manufacture by industrial processes

F_{s7}: Install by service vessels

F_{s8}: Maintain by service vessels

These new functions connect the wave energy system with the Industrial processes (F_{s6}) and Service vessels (F_{s7} and F_{s8}). Note that F_{s4} and F_{s5} are present in all life phases of the system.

For the internal functional analysis, the FAST diagram is used to translate the high-level functions into lower-level functions that must be performed by the wave energy system.

Figure 4.10 presents the functional decomposition of the wave energy system into FRs (first level) and TRs (second level). The service functions from the external analysis and the SRs are included for the sake of traceability. It can be noted that the resultant FAST diagram organises the functions into consistent levels of detail and engineering domains. Service functions mainly belong to the functional domain (F_{s5}, F_{s6}, F_{s7}, F_{s8}), but also some to the technical domain (F_{s2}, F_{s3}, F_{s4}) and even the stakeholder domain (F_{s1}).

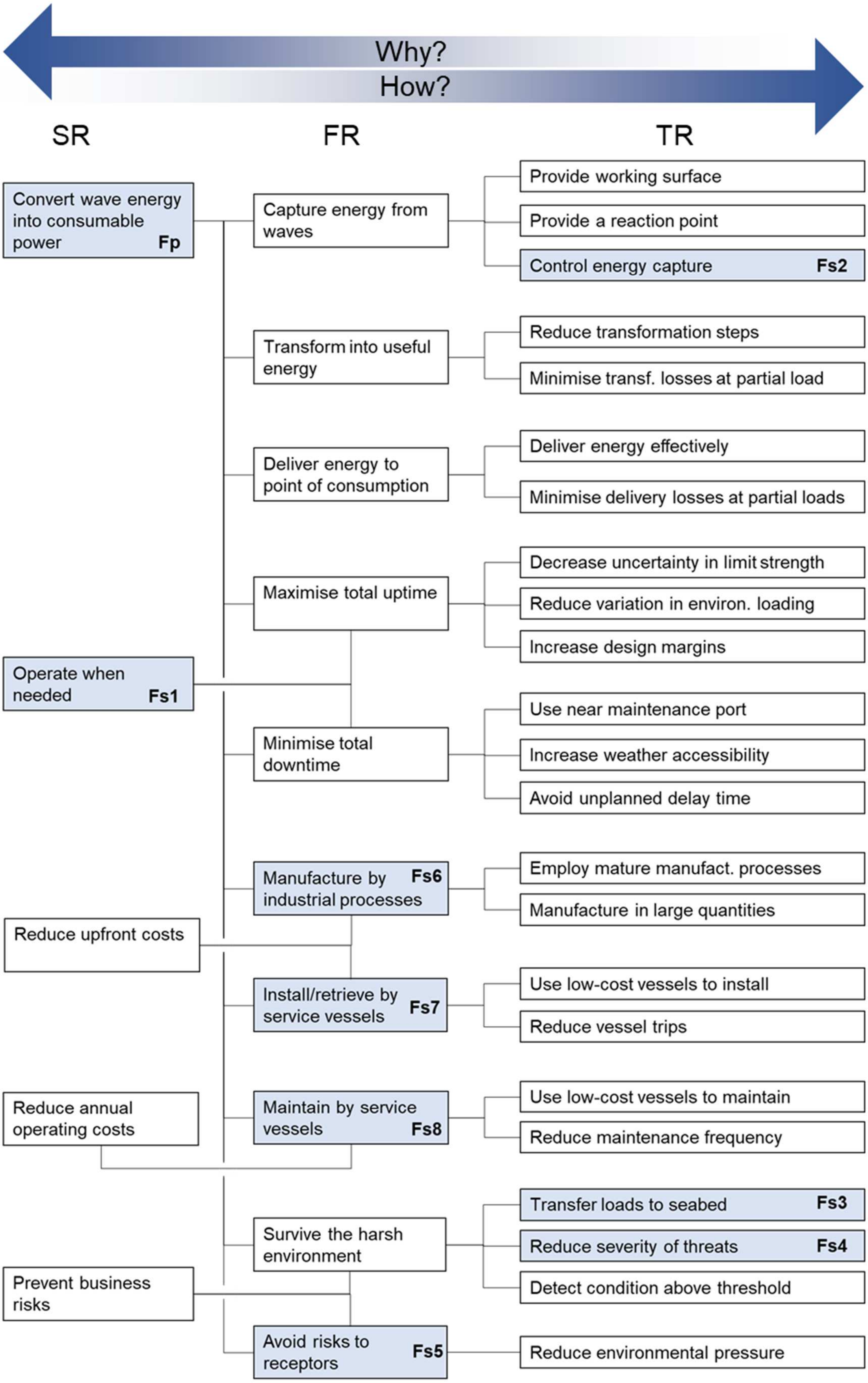

Figure 4.10: FAST diagram for the Wave Energy System.

It is also worthwhile mentioning that the TPL assessment method [133] also provides an analysis of requirements including various levels of functions. The top-level functions are directly linked to the SRs and the system mission. The next breakdown level compares with the FRs, whereas the lower levels should be related to the TRs. The functional tree is not developed to the same depth in all its branches which makes it difficult to apply the design domains method. Moreover, the combination of individual weightings is not traced in the various domains but is assigned through expert judgement.

The FAST diagram has been used to identify the FRs. Measures of Performance (MOPs) are allocated to specifically gauge the capabilities of a design solution. They are assigned to each requirement to enable the technology-agnostic assessment of wave energy alternatives objectively. The wave energy system has ten main FRs as shown in Table 4.5.

Table 4.5: Functional Requirements and Metrics.

Id	Functional Requirements	Measures of Performance (MOP)
FR1	Capture energy from waves	Normalised Capture Width (C_{wn}) [220]
FR2	Transform into useful energy	Transformation Efficiency (η_t) [142]
FR3	Deliver energy to point of consumption	Delivery Efficiency (η_d) [221]
FR4	Maximise total uptime	Reliability (MTTF = $1/\lambda$ *) [142]
FR5	Minimise total downtime	Maintainability (MTTR = $1/\rho$ **) [142]
FR6	Manufacture by industrial processes	Manufacturability (MANEX) [142]
FR7	Install/retrieve by service vessels	Installability (INSTEX) [142]
FR8	Maintain by service vessels	Repairability (REPEX) [142]
FR9	Survive the harsh environment	Survivability (SURV) [142]
FR10	Avoid risks to receptors	Environmental Impact Score (EIS) [222]

* λ = failure rate, ** ρ = repair rate.

Once again, QFD has been employed to prioritise FR in the proposed method. Since SRs are only coupled to a reduced number of FRs (1 to 3 max), the relative importance ratings of FR have been directly established from literature analysis. The same importance rating scale shown in Table 3.6 is used to derive SR–SH relationships.

LSP is applied to combine the MOPs into the immediately higher hierarchical level, i.e. MOEs. Figure 4.11 presents the aggregation logic of the different MOPs. The weights above each arrow, w_i, represent the relative importance ratings of the FRs.

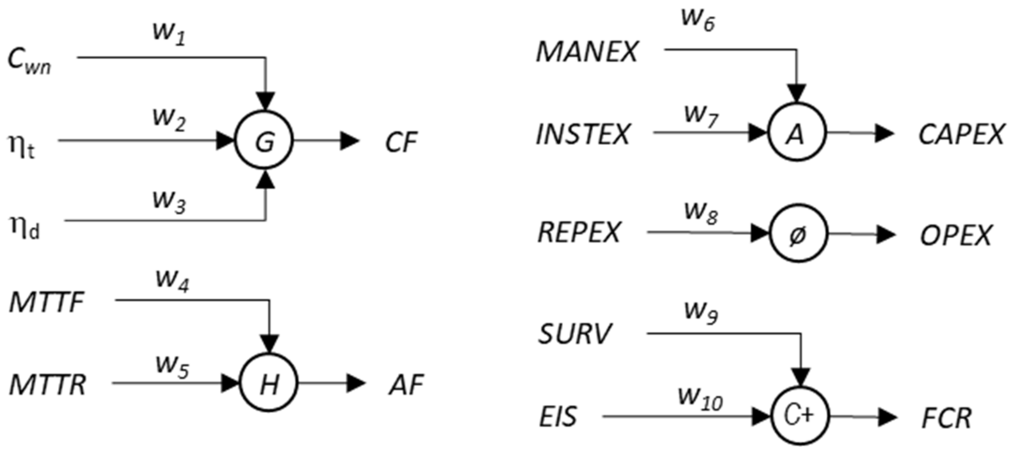

Figure 4.11: Aggregation of MOP.

Converting wave energy into consumable power (SR1) requires capturing, transforming, and delivering the energy. These functions are characterised by the Normalised Capture Width[3] (C_{wn}), Transformation Efficiency (η_t) and Delivery Efficiency (η_d) respectively. The efficiency ratings have a multiplicative nature and therefore are combined using the weighted Geometric mean (G).

Operating when needed (SR2) entails maximising the total uptime and minimising the total downtime. They are characterised by the Mean Time to Failure (MTTF) and the Mean Time to Repair (MTTR). These metrics are combined into the system Availability Factor (AF) employing the Harmonic mean (H) which calls for a higher degree of simultaneity as per Eq. (10).

$$AF = \frac{MTTF}{MTTF + MTTR} \tag{10}$$

Assuming an average number of 8 failures a year for the wave energy system (similar to recent estimations for floating offshore wind [223]), the MTTR and MTTF for a 75% AF should be close to 15 days and 46 days respectively.

Reducing upfront costs (SR3) involves both manufacturing and installation. The neutral Arithmetic mean (A) is used in this case as the different cost centres (i.e. MANEX & INSTEX) can be compensated. Installation costs typically fall in the range of 8% to 17% of the CAPEX [178], with lower values for wave energy deployments consisting of a larger number of units. A value of 10% is selected as the threshold for the minimum utility.

Reducing annual costs greatly depends on the maintenance strategy selected. If preventive and/or predictive maintenance strategies can be implemented, these costs can be broken down into scheduled and unscheduled costs. However, the functional analysis has not split

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[3] Percentage of the ideal value of the Capture Width.

it into different functions since both paths lead to the same technical requirements. Thus, the repairability metric (REPEX) is directly matched to the operational costs (OPEX).

Finally, preventing business risks requires surviving the harsh ocean environment and avoiding risks to receptors. They are characterised by the Survivability[4] (SURV) and the Environmental Impact Score[5] (EIS). The strong conjunction operator (C+) is employed to penalise a low utility value for each FR.

As mentioned before, the reader should bear in mind that the utility assigned to each MOP might differ from the values estimated with numerical methods, since the aggregation logic also accounts for the relative importance expressed by the stakeholders, the underlying degree of simultaneity and the flexibility allowed to the various requirements.

4.3.4 Technical Requirements (TRs)

The technical domain describes the physical embodiment to achieve the wave energy system functions. Whilst FRs specify what the system must do, Technical Requirements (TRs) define the practical issues that must be considered to successfully implement the system functions in physical parts and assemblies. Therefore, TRs are dependent on the design solution.

Again, FAST has been used to identify the TRs (see Figure 4.10). The wave energy system comprises 23 main TRs as shown in Table 4.6. Associated Technology Performance Measures (TPMs) can be used to demonstrate the successful delivery of these requirements.

Capturing energy from waves (FR1) requires providing a working surface (TR1), a reaction force (TR2) and controlling energy capture (TR3). These requirements are characterised by the Area of the hydrodynamic object (S), the Maximum permissible PTO load (F_{PTO}) and the Relative bandwidth[6] (B_r) respectively. The neutral Arithmetic mean (A) is used to aggregate S and B_r which are replaceable and later combined with F_{PTO} through the Geometric mean (G).

The area of the hydrodynamic object perpendicular to the body oscillation creates a swept volume), which incidentally determines the upper bound of wave energy absorption [224]. Secondly, the maximum permissible PTO force limits the total absorbed energy concerning the unconstrained case [225]. Finally, a wide capture bandwidth will mean higher energy absorbed in the full range of the wave spectrum [224].

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[4] Likelihood of experiencing an event beyond expected design conditions without sustaining an unacceptable level of damage or loss of functionality.

[5] Numerical value of the environmental pressure created by physical stressors in the wave energy system and modulated by the sensitivity level of receptors.

[6] Ratio of the frequency interval for 50% of the maximum power capture. $B_r=(\omega_h-\omega_l)/(\omega_h+\omega_l)$

Table 4.6: Technical Requirements and Metrics.

Id	Technical Requirements	Technical Performance Measures (TPM)
TR1	Provide working surface	Area of the hydrodynamic object (S) [40]
TR2	Provide a reaction force	Maximum permissible PTO force (F_{PTO}) [225]
TR3	Control energy capture	Relative bandwidth (B_r) [224]
TR4	Reduce transformation steps	No. of conversion steps (n_c)
TR5	Minimise transf. losses at partial loads	Conversion load factor (LF_c)
TR6	Deliver energy effectively	No. of aggregation levels (n_a)
TR7	Minimise delivery losses at partial loads	Delivery load factor (LF_d)
TR8	Decrease uncertainty in limit strength	Technology class (TC) [226]
TR9	Reduce variation in environ. loading	Load shedding capability (L_s)
TR10	Increase design margins	Safety factor (SF)
TR11	Use near maintenance port	Travel time (t_t)
TR12	Increase weather accessibility	Waiting time (t_w)
TR13	Avoid unplanned delay time	Logistic time (t_l)
TR14	Employ mature manufact. processes	Cycle time (t_c)
TR15	Manufacture in large quantities	Unit cost (UC_m)
TR16	Use low-cost vessels to install	Install vessel charter cost (UC_i)
TR17	Reduce vessel trips	No. of installation trips per device (n_i)
TR18	Use low-cost vessels to maintain	Service vessel charter cost (UC_s)
TR19	Reduce maintenance frequency	No. of service trips per device (n_s)
TR20	Transfer loads to the seabed	Maximum permissible foundation load (F_f)
TR21	Reduce the severity of threats	Load shedding capability (L_s)
TR22	Detect conditions above the threshold	Detection level (D)
TR23	Reduce environmental pressure	Farm density (FD)

Transforming the energy from the wave into useful energy (FR2) needs reducing the transformation steps (TR4) and minimising transformation losses at partial loads (TR5). These requirements are characterised by the Number of conversion steps (n_c) and Load factor (LF_c). The multiplicative nature calls for a combination with the Geometric mean (G).

The maximum conversion efficiency is achieved when the PTO works at its nominal capacity. However, wave energy systems are mostly operated at partial load which means higher losses. Figure 4.12 shows an illustrative example of a PTO system with 100% maximum efficiency at full load. Since actual efficiency will be lower than 100% [227], the addition of a greater number of transformation steps will effectively decrease the PTO utility.

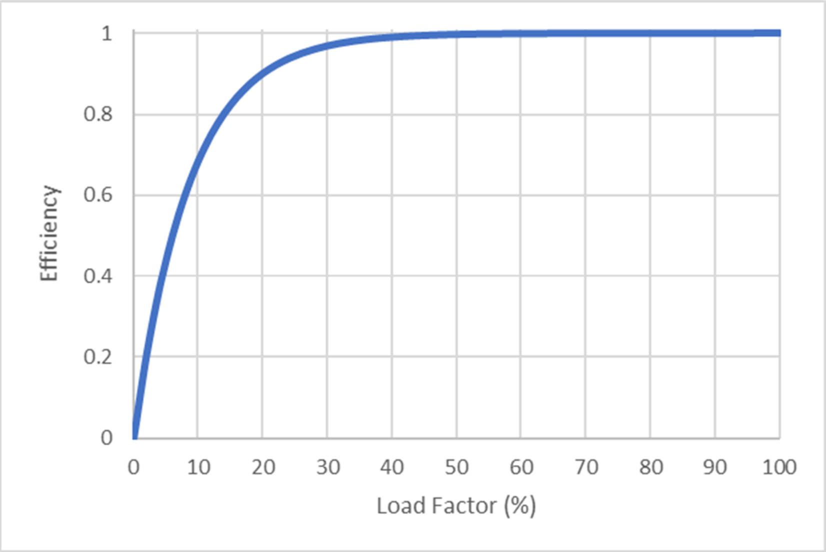

Figure 4.12: Illustrative relationship between the LF and efficiency.

Similarly, delivering energy to point of consumption (FR3) requires delivering energy effectively (TR6) and minimising delivery losses at partial loads (TR7). These requirements are characterised by the number of delivery aggregation levels (n_d) and load factor (LF_d). The TPMs are also aggregated through the Geometric mean (G) operator.

Failures occur when the system's stress exceeds its design strength. Maximising the total uptime (FR4) requires decreasing the uncertainty in limit strength (TR8), reducing the variation in environmental loading (TR9) and increasing design margins (TR10). These requirements are characterised by the Technology class (TC), the Load shedding[7] capability (L_s) and the Safety factor (SF) respectively. The three TPM are partially replaceable and thus the neutral Arithmetic mean (A) is used to combine them.

Table 4.7: IEC Technology Classes [226].

Application Area	**Technology Status** Validated TRL 7-9	 Limited Field History TRL 4-6	 New or Unproven TRL 1-3
Known	1	2	3
New	3	3	4

Technology classes [226] involve increasing levels of uncertainty, ranging from class 1 "No new technical uncertainties" to class 4 "Demanding new technical risks". Technology validation contributes to reducing the uncertainty in the variation of the system strength as indicated in Table 4.7. Besides, load shedding reduces the adverse effect of

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[7] Load shedding is a property of wave energy devices enabled through hydrodynamic control to reduce the impact of extreme environmental loads and increase survivability.

environmental loads. A third strategy involves using higher safety factors to increase design margins as depicted in Figure 4.13.

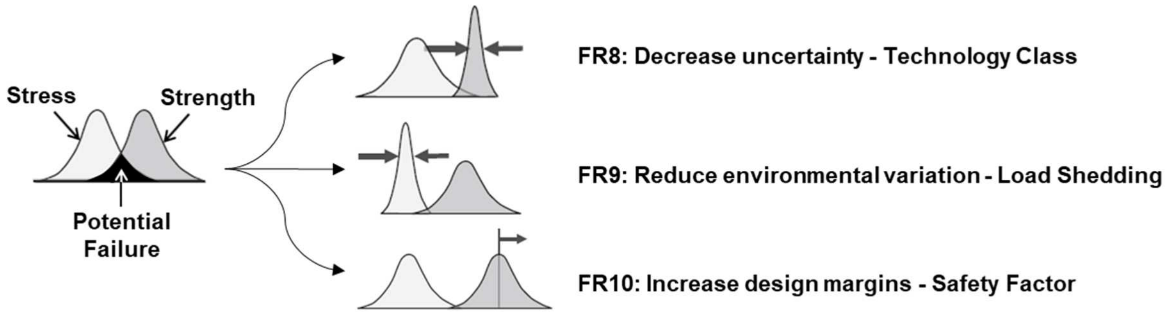


Figure 4.13: Strategies to minimise failures (adapted from [228]).

Minimising total downtime (FR5) demands using near maintenance port (TR11), increasing weather accessibility (TR12) and avoiding unplanned delay time (TR13). These requirements are characterised by Travel time (t_t), Waiting time (t_w) and Logistic time (t_l) respectively. In turn, t_w depends on the site accessibility and the service time required to perform the maintenance operation. Again, the three TPM are partially replaceable and thus the neutral Arithmetic mean (A) is used to combine them.

Manufacturing by industrial processes (FR6) requires employing mature manufacturing processes (TR14) and manufacturing in large quantities (TR15). These requirements are characterised by the Cycle time (t_c) and the Unit cost (UC_m). These two attributes are more replaceable than the perfect balance and thus the weak disjunction (D-) is used for their aggregation.

UC_m depends on the investment costs incurred for the manufacturing tooling, the variable cost of manufacturing each unit and the number of units. In general, replicative processes have higher investment costs and lower variable costs [229]. The Unit cost is given by Equation (11) with displays a characteristic hyperbolic form.

$$UC_m = \frac{C_f}{m} + C_v \tag{11}$$

where C_f is the fixed cost, C_v is the variable cost and m is the number of units.

Installing and retrieving by service vessels (FR7) demands using low-cost vessels (TR16) and reducing the number of vessel trips (TR17). These requirements are characterised by the Install vessel charter cost (UC_i) and the No. of trips per device (n_t). The multiplicative nature requests a combination with the Geometric mean (G).

Likewise, maintaining by service vessels (FR8) requires using low-cost vessels (TR18) and reducing the maintenance frequency (TR19). These requirements are characterised by Service vessel charter cost (UC_s) and the No. of trips per device (n_t). The multiplicative nature also calls for aggregation through the Geometric mean (G). Long-term agreements for one or several years can significantly reduce vessel charter rates compared with the spot market [230]. The no. of trips per device depends on the MTTF.

Surviving the harsh environment (FR9) needs transferring loads to the seabed (TR20), reducing the severity of threats (TR21) and detecting conditions above the threshold (TR22). These requirements are characterised by the Maximum permissible foundation load (F_f), the Load shedding capability (L_s) and the Detection level (DL). Load shedding and detection require a certain degree of simultaneity and the Geometric mean (G) operator is used to combine them. The resulting utility is aggregated through the Arithmetic mean (A) as they can compensate for each other.

Last but not least, avoiding risks to receptors (FR10) demands reducing the environmental pressure (TR23). The EIS metric is directly matched to the Farm density (FD) as the principal stressor. Figure 4.14 summarises the aggregation logic for the different TPMs.

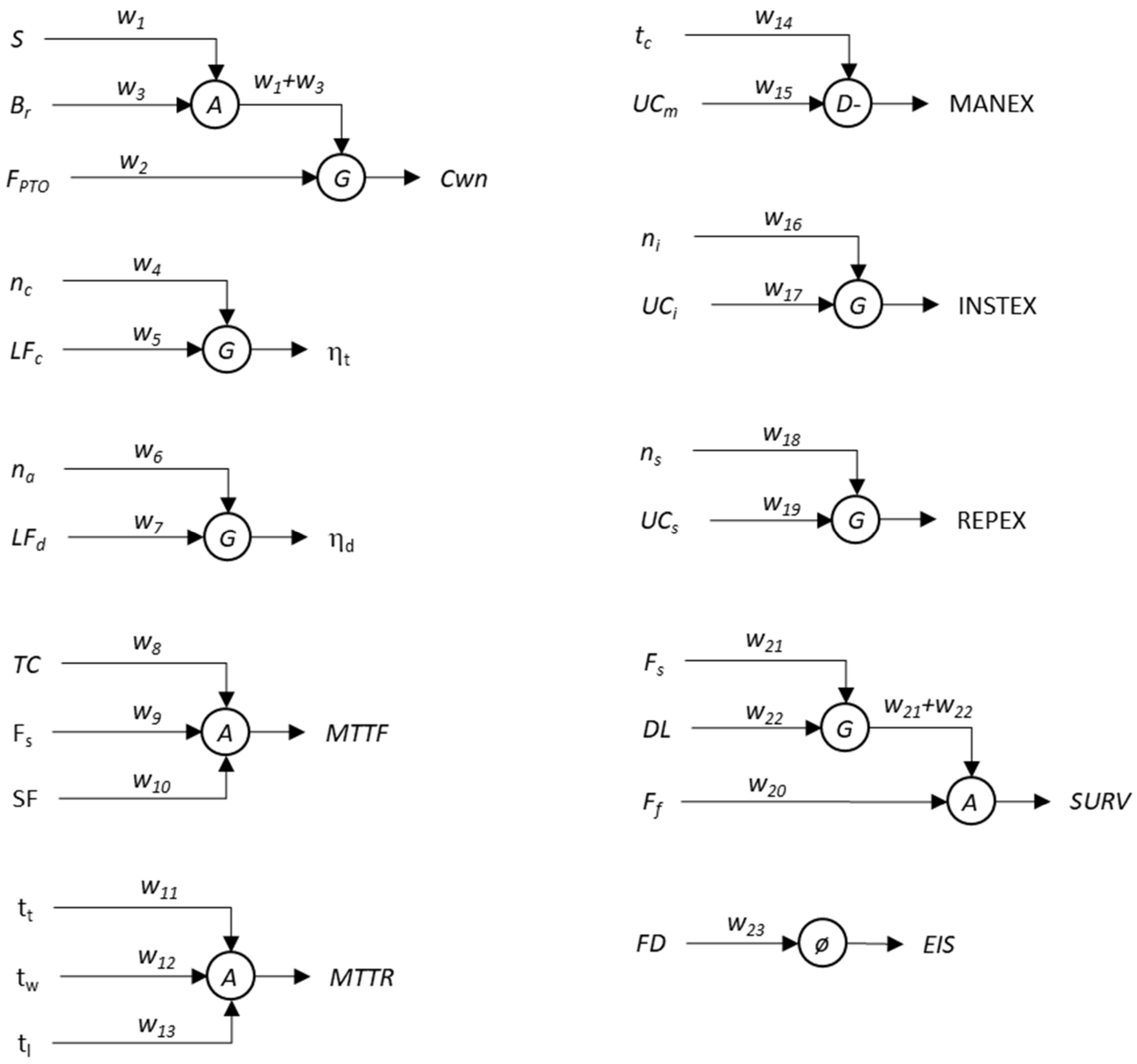


Figure 4.14: Aggregation of TPM.

4.3.5 Design Parameters (DPs)

The large number of TRs results in a QFD matrix difficult to manage. To begin with, ranking a multitude of requirements is simply beyond human cognitive capability. Besides, the analysis of the information contained in the QFD matrix becomes much more challenging. Finally, TRs may not be independent, as can be observed in the list of TPMs which share some commonalities.

To avoid this problem, TRs are mapped to the design parameter space. Design Parameters (DPs) are used in Axiomatic Design [84] to characterise the physical attributes of a system. Given that one DP can be shared by two or more TRs, the technical domain analysis can be greatly simplified. This transformation is also supported by factor analysis [231], a mathematical technique for simplifying the relationship among a large number of correlated variables by a lower number of underlying variables called factors.

DPs should be selected so they are independent of one another. To enforce factor independence, a selection from TRIZ technical parameters [232] was considered. The 39 technical parameters identify the most widely used and important features of technical systems (see Appendix C: List of TRIZ 39 Technical Parameters). Altshuller extracted these a priori characteristics after studying over 400,000 worldwide patents [233].

DPs should be also defined at the same level of abstraction as FRs. To avoid, as far as possible, coupled designs, the same number of DPs and FRs should be considered. A list of 10 DPs from the relevant common parameters from TRIZ has been mapped to the TRs as shown in Table 4.8.

Table 4.8: Mapping of Technical Requirements (TRs) to Design Parameters (DPs).

Id	Design Parameters	TRIZ no.	Technical Requirements
DP1	Area of moving object	5	TR1, TR23
DP2	Strength	14	TR2, TR10, TR20
DP3	Duration of action by moving object	15	TR8
DP4	Loss of energy	22	TR5, TR7
DP5	Loss of time	25	TR11, TR12, TR13
DP6	Quantity of substance	26	TR15, TR16, TR18
DP7	Adaptability	35	TR3, TR9, TR21
DP8	Device complexity	36	TR4, TR6
DP9	Difficulty of detecting and measuring	37	TR22
DP10	Productivity	39	TR14, TR17, TR19

4.4 Practical Implementation

4.4.1 Prioritisation of SRs

The practical implementation of the proposed methodology yields the relative importance of SRs plotted in Figure 4.15. The complete outcomes of the QFD ranking for the two market applications can be consulted in Appendix B: Prioritisation Matrices.

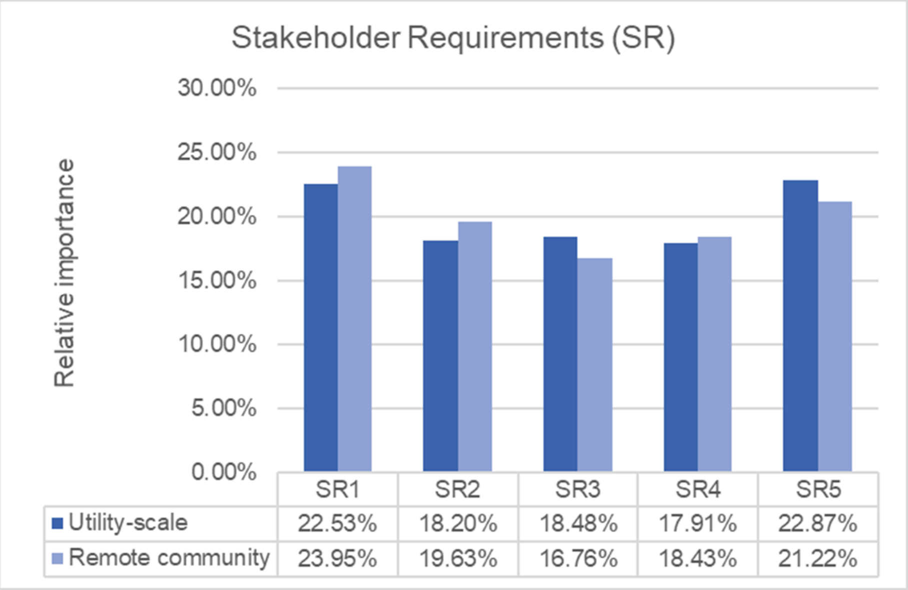


Figure 4.15: Relative importance of SRs for the application market.

It can be observed that the SRs have a relatively similar importance for the two application markets under consideration, with a variability below 10%. The conversion of wave energy into consumable power (SR1), the continuous operation (SR2) and the reduction of annual costs (SR4) have a greater influence on remote community generation. Alternatively, the utility-scale generation market puts more emphasis on the prevention of business risks (SR5) and the reduction in upfront costs (SR3). This qualitative assessment assigns weights above the average importance rating (20%) to SR1 and SR5 for both markets, but with a reversed ranking as presented in Table 4.9. It is worth noting that the standard deviation of weightings for the five SRs is below 3%.

Table 4.9: Ranking of Stakeholder Requirements (SRs).

Rank	Utility-scale	Remote community
1	Prevent business risks	Convert energy into consumable power
2	Convert energy into consumable power	Prevent business risks
3	Reduce upfront costs	Operate when needed
4	Operate when needed	Reduce annual costs
5	Reduce annual costs	Reduce upfront costs

SRs prioritisation reinforces the conclusions drawn from the analysis of the wave energy context in the previous chapter. The Economic concerns of the Owner have the greatest influence on the importance ratings of the SRs for the utility-scale market, whereas the Political concerns from the Government mainly drive the SRs for the remote community generation.

The aggregation of SRs' utility into global merit provides an additional perspective. Figure 4.16 shows the impact of changes in one MOE utility while the rest maintain the highest score for each application market.

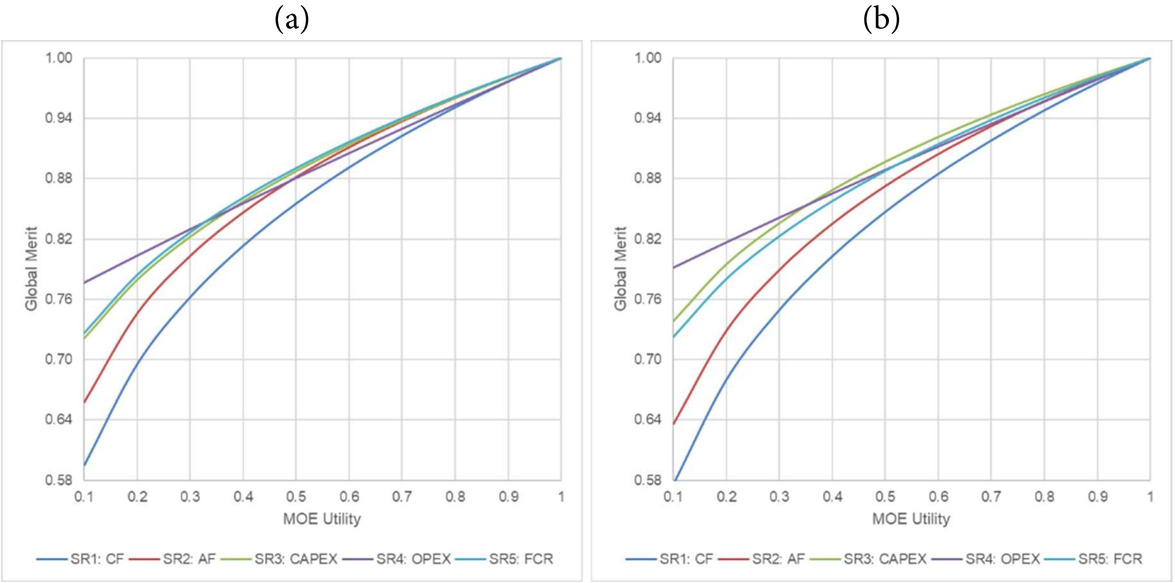


Figure 4.16: Sensitivity of Global Merit to MOE Utility for each market application: (a) Utility-scale generation; (b) Powering remote communities.

In both market scenarios, the conversion of wave energy into consumable power (SR1: CF) has the greatest influence on the Global Merit followed by operating when needed (SR2: AF). When deriving the Global Merit, the logical preference operators used for combining the MOEs have a stronger influence than their corresponding weightings. The Geometric mean penalises low utility values. This logical operator is applied twice consecutively to combine SR1: CF and SR2: AF.

Then it follows the reduction in upfront costs (SR3: CAPEX) and prevention of business risks (SR5: FCR). Their influence is however swapped for each application market. Finally, the less sensitive MOE to changes in the utility is the annual costs (SR4: OPEX). This is due to the fact the utility is combined through the Arithmetic mean, which is a neutral operator. OPEX has the least influence until it reaches medium utility, where it becomes more predominant, particularly for the utility-scale generation market.

4.4.2 Prioritisation of FRs

Figure 4.17 depicts the results from the practical implementation of the methodology in the functional domain. Likewise, the complete outcomes of QFD ranking for the two market applications can be consulted in Appendix B: Prioritisation Matrices.

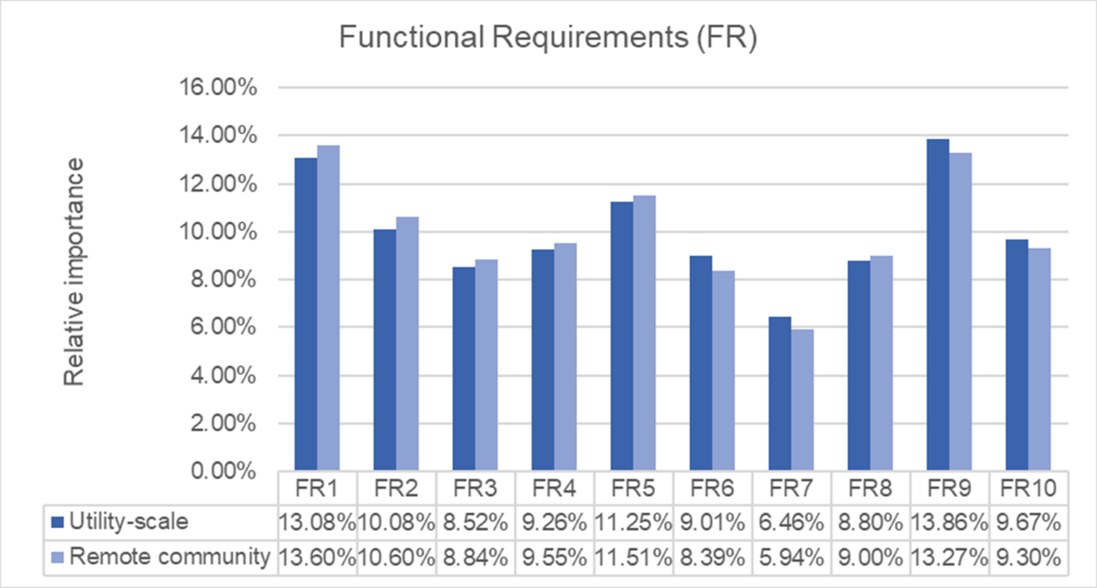


Figure 4.17: Relative importance of FR for the application market.

FRs have relatively equal importance for the two application markets under consideration, with a variability lower than 9%. The functions contributing to each SR follow the same pattern as before. However, we can appreciate that capturing (FR1) and transforming (FR2) wave energy, minimising total downtime (FR5) and surviving the harsh environment (FR9) are the most relevant requirements, all of them above the average importance rating (10%) for both markets. The full ranking of FRs is shown in Table 4.10.

Table 4.10: Ranking of Functional Requirements (FRs).

Rank	Utility-scale	Remote community
1	Survive the harsh environmental	Capture energy from waves
2	Capture energy from waves	Survive the harsh environmental
3	Minimise total downtime	Minimise total downtime
4	Transform into energy	Transform into energy
5	Avoid risks to receptors	Maximise total uptime
6	Maximise total uptime	Avoid risks to receptors
7	Manufacture by industrial processes	Maintain by service vessels
8	Maintain by service vessels	Deliver energy to point of consumption
9	Deliver energy to point of consumption	Manufacture by industrial processes
10	Install by service vessels	Install by service vessels

Surviving the harsh environment (FR9) is ranked first for the utility-scale market followed by capturing wave energy (FR1), whereas these FRs are swapped for the remote community generation. It is worth noting that the standard deviation of weightings is slightly above 2% indicating that this ranking may be altered with small changes in the stakeholder preference.

The proposed method differs from the TPL scoring methodology [133] as the latter considers that most of the capabilities have equal influence. For instance, the same weights are assigned to equivalent pairs of requirements FR6 and FR7, FR2 and FR3, and FR4 and FR5. The traceability of design information and requirements through the different domains offers a more objective way to account for those differences without assuming either a flat distribution or any other arbitrary distribution of weights.

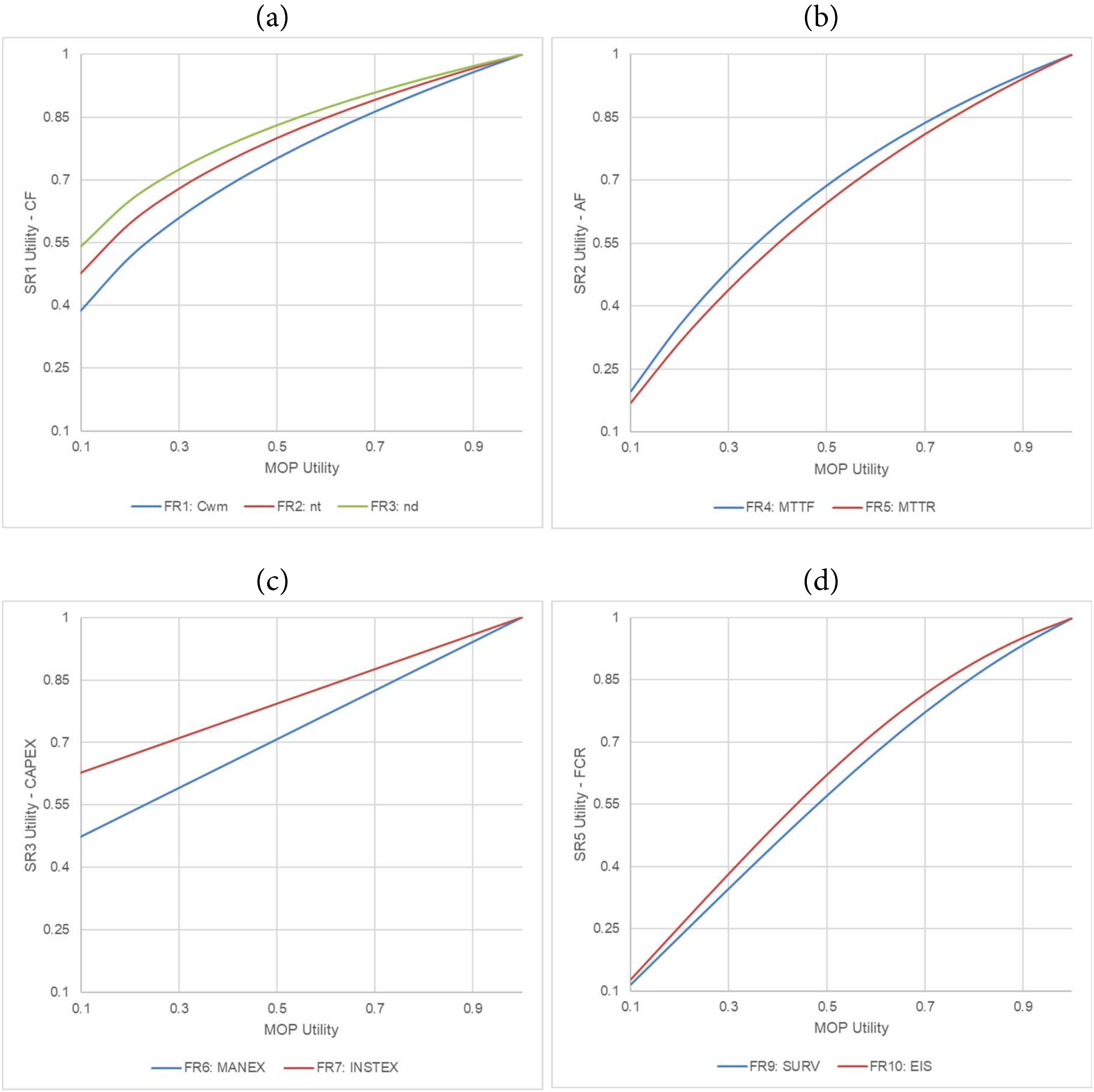


Figure 4.18: MOE Sensitivity for Utility-scale Generation: (a) Convert wave energy; (b) Operate when needed; (c) Reduce upfront costs; (d) Prevent business risks.

The aggregation of FRs' utility into stakeholder value provides additional insights. Figure 4.18 shows the impact of changes in one MOP utility while the rest maintain the highest score for the utility-scale market. Due to the low variation of weightings, the changes in utility are insignificant between the two applications considered.

Capturing energy from waves (FR1: C_{wn}), minimising total downtime (FR4: MTTR), manufacturing by industrial processes (FR6: CAPEX) and surviving the harsh environment (FR9: SURV) have the greatest influence in their respective MOE. However, FR4 and FR9 have the widest utility variation as a result of the logical operator chosen (harmonic mean and strong conjunction respectively).

Figure 4.19 depicts the sensitivity of Global Merit to each FR for both market scenarios. In line with the ranking of FRs, the installation by service vessels (FR7) has a lesser impact on the Global Merit. Low utility values for transforming (FR2) and delivering (FR3) energy have a bigger impact on the Global Merit than manufacturing (FR6). The impact of capturing wave energy is kept between manufacturing (FR6) and maintenance (FR8) for a wider range of utility values, particularly for the remote community generation which has a higher weighting. Finally, low utility values for minimising downtime (FR5), surviving the harsh environment (FR9), avoiding risks to receptors (FR10) and maximising uptime (FR4) have the greatest influence on the Global Merit. As the utility of these MOPs increases, maintenance (FR8) becomes more penalising for the Global Merit. As can be seen in Figure 4.19, the sensitivity to low MOP utility is longer maintained for the remote community generation.

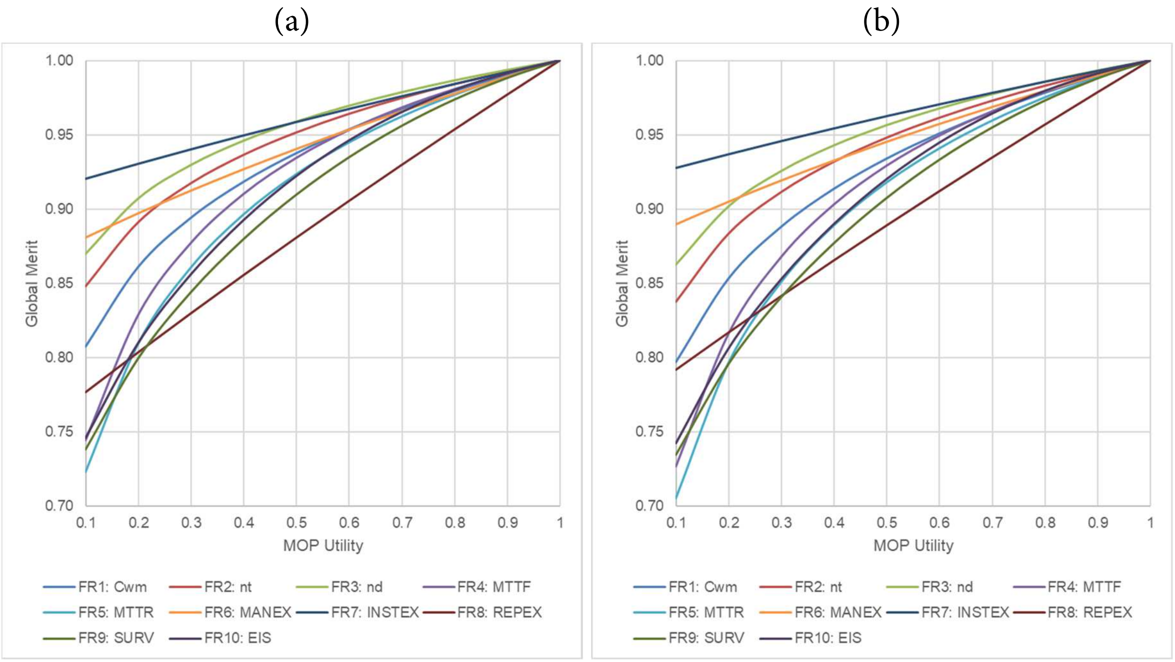


Figure 4.19: Sensitivity of Global Merit to MOP Utility for each market application: (a) Utility-scale generation; (b) Powering remote communities.

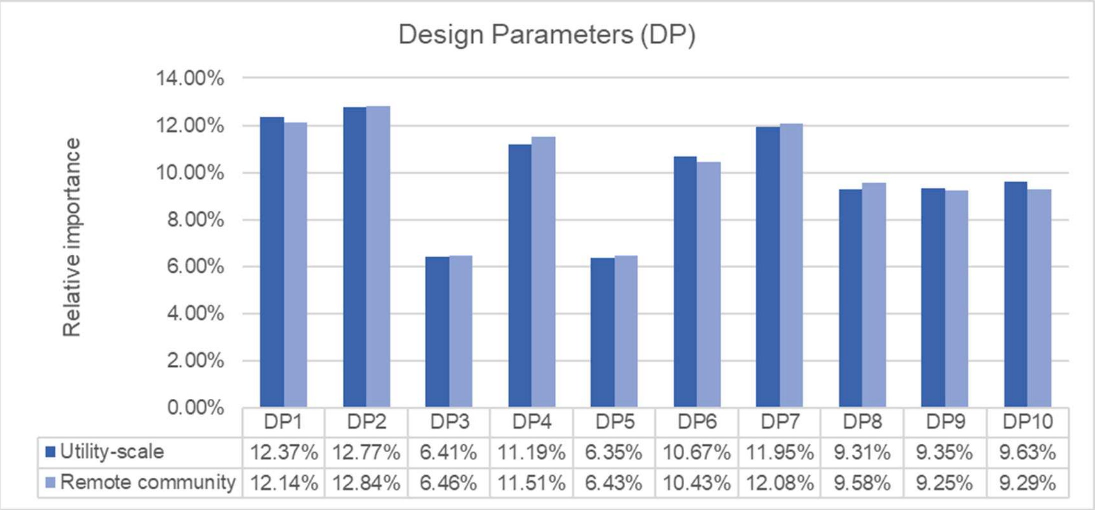
4.4.3 Prioritisation of DPs

As said before, the large number of TRs results in a QFD matrix difficult to manage. The ranking of 23 requirements is simply beyond the human cognitive capability and, if it were possible, the interpretation would become much more challenging.

Supported by the stakeholder and functional domain results, it can be assumed that the importance of the weightings would be minor and that the two markets considered will yield quite similar relative importance. Moreover, logical operators which require higher conjunction will influence more the Global Merit. Taking as reference the sensitivity analysis of FRs with values greater than 0.3 (Figure 4.19), we can anticipate that the following TPMs will be key for achieving high merit:

- The Unit service vessel cost and Number of trips for REPEX.
- Load shedding and Detection level for SURV.
- The Farm density for EIS.
- Travel, Waiting and Logistic times for MTTR.
- Technology class, Load shedding and Safety factor for MTTF.
- Maximum permissible load for Cwn.

Figure 4.20 shows the results from the practical implementation of the methodology for the mapping of Design Parameters (DPs). The complete outcomes of the QFD ranking for the two market applications can be consulted in Appendix B: Prioritisation Matrices.



	DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10
■ Utility-scale	12.37%	12.77%	6.41%	11.19%	6.35%	10.67%	11.95%	9.31%	9.35%	9.63%
■ Remote community	12.14%	12.84%	6.46%	11.51%	6.43%	10.43%	12.08%	9.58%	9.25%	9.29%

Figure 4.20: Relative importance of DPs for the application market.

Again, DPs have relatively equal importance for the two application markets under consideration, with a variability lower than 4%. The top priority DPs, all of them above the average importance rating (10%), are the Strength (DP2), Area of moving object (DP1), Adaptability (DP7), Loss of energy (DP4) and Quantity of substance (DP6). The full ranking of FRs is shown in Table 4.11, which remains the same for the two market applications.

Table 4.11: Ranking of Design Parameters (DPs).

Rank	Utility-scale & Remote community
1	Strength
2	Area of moving object
3	Adaptability
4	Loss of energy
5	Quantity of substance
6	Device complexity
7	Productivity
8	Difficulty of detecting
9	Loss of time
10	Duration of the action

We can observe that the three top-ranked design parameters, namely Strength (DP2), Area of moving object (DP1) and Adaptability (DP7), are related to the primary stakeholder requirement, converting wave energy into consumable power (SR1). Moreover, they also contribute to operating when needed (SR2) and preventing business risks (SR5). This result is consistent with Figure 4.16 in section 4.4.1 since these were the most sensitive MOE. Loss of energy (DP4) is linked to transforming (FR2) and delivering (FR3) energy, both of which are connected to SR1. Finally, Quantity of substance (DP6) contributes to manufacturing (FR6), installing (FR7) and maintaining (FR8), which are linked with the other two stakeholder requirements.

4.5 Conclusions

The creation of a standard framework for wave energy technologies constructed around the notion of design domains assists in the organization of data on requirements and metrics to make system validation and verification easier. This common framework can be applied to different levels of system aggregation, technology maturity and markets ensuring a consistent and fully traceable assessment. By repeating the domain mapping process and adding additional layers to the requirements hierarchy, traceability offers flexibility to adapt this framework to rapidly changing market conditions and stakeholder priorities or to focus the analysis on particular wave energy sub-systems, assemblies or components.

The LSP technique allows for greater granularity in the formulation of the aggregation logic and enables the seamless combination of mandatory, sufficient and optional metrics. This method can amalgamate disparate attributes and criteria expressed by a variety of units, orders of magnitude and qualities, as has been evidenced by the aggregation of MOE, MOP and TPM. However, this is a qualitative assessment that may diverge from the preference obtained using the numerical LCOE values since the aggregation logic also takes into account the relative importance indicated by the stakeholders, the underlying degree of simultaneity, and the flexibility granted to the various requirements, all of which are qualitative aspects.

The requirements of the Owner for utility-scale power and the Government for remote community initiatives drive the development of wave energy systems. However, when the three-level hierarchy of system requirements is examined, the application market's influence on the development of wave energy technologies is greatly reduced.

Converting wave energy (SR1) and preventing business risks (SR5) are the highest-ranked Stakeholder Requirements. The former scores first for the remote community market, whilst the latter does for the utility-scale generation. However, when assessing the Global Merit, low utility values of converting wave energy (SR1) penalise to the greatest extent both market applications.

Capturing wave energy (FR1), Surviving the harsh environment (FR9), minimising downtime (FR5) and transforming energy (FR2) are the highest ranked Functional Requirements for both market applications. FR1 is first for the remote community and second for the utility-scale application. FR9 swaps the ranking for the two markets considered. Low utility values of FR9 and FR5 penalise more significantly the MOE utility and consequently the Global Merit.

Finally, when analysing the technical domain, we can observe that the top-ranked design parameters are connected to converting wave energy (SR1), operating when needed (SR2) and preventing business risks (SR5), through the corresponding FRs and TRs.

CHAPTER 5 GUIDING THE DESIGN DECISIONS

> “When nothing is sure, everything is possible”
>
> *Margaret Drabble (1939 – now)*

5.1 Overview

This chapter seeks to provide a holistic assessment of wave energy technology performance to guide design decisions throughout the various development stages, select the most suitable option for a particular market application, and identify the challenges to meeting system requirements.

Section 5.2 introduces the specific methods and tools used in this step of the methodology. Value functions are used to analyse the fundamental relationships between the system requirements and the utility provided, therefore assisting in the assessment of wave energy capabilities. On the other hand, the allocation of design targets to the lower-level assessment criteria avoids any unfeasible combination at the same time it enables benchmarking and tracking progress.

Section 5.3 develops the assessment of wave energy capabilities. The qualitative assessment is based on the Global Merit (GM) introduced in the previous chapter. Commercial Attractiveness (CA) enables a more objective comparison of wave energy technologies when the technology meets or exceeds the system requirements. Technical Achievability (TA) assesses the risk of technology development, as well as the time and effort required to attain desired performance.

Section 5.4 describes the practical implementation of this step using six sample scenarios of theoretic wave energy technologies. First, the qualitative assessment based on the quantification of the GM is presented. Second, the performance benchmark of the CA and TA is discussed.

Finally, section 5.5 summarises the chapter and discusses some partial findings from this novel methodology that might be of interest to the wave energy sector.

5.2 Methods and Tools

5.2.1 Value Functions

Value functions are used to convert design attributes into a quantitative measure of the decision-maker preference [234]. This way, the selection between disparate alternatives is greatly objectivised and facilitated.

Linear numeric relationships are not always the best method of assigning preferences. Nonlinear value functions enable a more accurate representation of preferences by grasping the underlying fundamental relationships, risk-avoidance attitudes, constraints and/or optimal values. However, creating a specific value function for each design attribute may be challenging. Instead of facing this activity on a case-by-case basis, an alternative approach is to model different curve shapes based on the variation of a limited number of parameters.

A set of generic value functions are suggested in [235] based on five parameters, making it possible to generate linear, concave, convex and S-shaped functions. These curve families can have either a growing or a decreasing value. Similarly, the concept design analysis method in [236] proposed a series of nonlinear functions for maximisation, minimisation, optimisation and avoidance of design attributes. The maximisation and minimisation functions introduce the concept of neutral point (n), that is, the design attribute which yields a value of 0.5. In contrast, the optimisation and avoidance functions defined the neutral point (n) as the design attribute where the value is 1 or 0, respectively. For the latter functions, the concept of tolerance (t), the design attribute $x \pm t$ yielding a value of 0.5, is also introduced.

The curve families described before can be grouped into three possible categories of generic value functions. The reader should note that the use of the terms maximisation and minimisation is not intended in the extract mathematical sense, but to denote that increasing values of a certain design parameter maximise and minimise the utility provided.

Maximisation/minimisation type

The value that provides the highest utility lies on one side of the design parameter range. Concave and convex curves show risk-avoiding and risk-seeking attitudes which delimit where the threshold will be placed. A typical example of a convex value function is the efficiency of a generator. When its load factor is low, the efficiency is close to zero. However, the efficiency steeply improves as the load factor increases.

The following equation defines this family of value functions and is represented in Figure 5.1. Base 2 is taken for convenience.

$$v(x) = B\left[1 - 2^{-c\left(\frac{x - x1}{n}\right)^{p}}\right] \tag{12}$$

where

- *x2* and *x1* are the maximum and minimum abscise values for the maximisation type; however, these values are swapped for the minimisation type.
- *n* is the neutral point (utility is 0.5).
- *p* is the shape factor. For this family of curves, *p* = 1.
- *c* takes a value of 1 for convex curves and -1 for concave ones.
- *B* is the scaling factor to maintain the function in the interval [0,1].

$$B = \left[1 - 2^{-c\left(\frac{x2 - x1}{n}\right)^{p}}\right]^{-1} \tag{13}$$

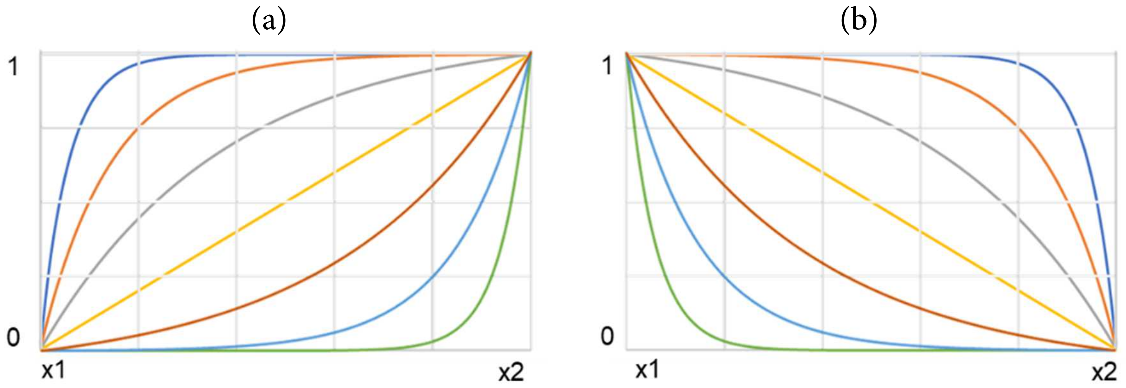


Figure 5.1: Maximisation (a) and minimisation (b) value functions.

The linear value function is a special case of the above where the increase of the parameter lends equal improvement in utility. Linear functions are created when the parameter *c* is equal to zero.

Saturation/Constraint type

S-shaped functions are used to represent a saturation point or a constraint. The utility will decrease sharply if the parameter is below its threshold value for the saturation-type function. Conversely, for the constraint type, the utility will steeply increase if the parameter is above its threshold value. The curve slope will determine the tolerance to the threshold. An example of a saturation value function is environmental pressure. The environmental pressure remains low until a certain stressor level, but it will rapidly increase if surpassed.

The same equation defines the saturation-type function as the maximisation and minimisation functions, Eq. (12), but the parameters vary. The shape factor, *p*, is now greater than one and *c* takes a value of 1. Values up to 3 produce soft slopes, whereas values greater than 3 produce sharper slopes. The neutral point (*n*) represents the threshold value in this case. The scaling factor, *B*, maintains the function in the interval [0,1].

This family of value functions is represented in Figure 5.2.

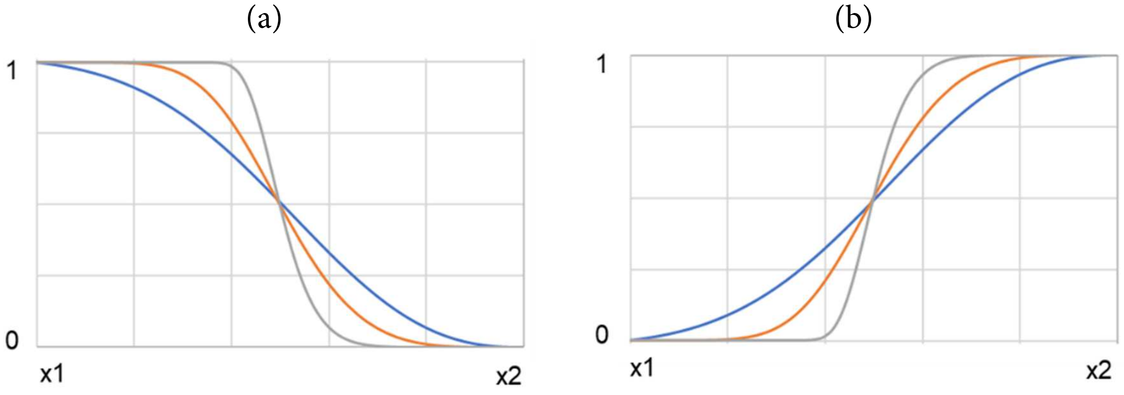


Figure 5.2: Saturation (a) and constraint (b) value functions.

Optimisation/avoidance type

This function is used when the design parameter should either converge to (optimisation) or avoid (avoidance) a specific value. The curve tolerance determines the design parameter threshold. An example of an optimisation-type utility function is the capture width ratio of a wave energy converter. The maximum value is obtained at the resonance frequency and the tolerance is related to the bandwidth of its response. Similarly, resonance frequencies might create an extreme response that needs to be avoided to ensure appropriate survivability.

This family of value functions is defined by the following equations respectively and is represented in Figure 5.3:

Optimisation
$$v(x) = \frac{1}{1 + \left(\frac{x - x_1 - n}{t}\right)^2} \tag{14}$$

Avoidance
$$v(x) = 1 - \frac{1}{1 + \left(\frac{x - x_1 - n}{t}\right)^2} \tag{15}$$

where n is the neutral point value of 1 or zero respectively, and t is the tolerance value. When the design attribute equals one of the tolerance values, the optimisation function has a value of 0.5.

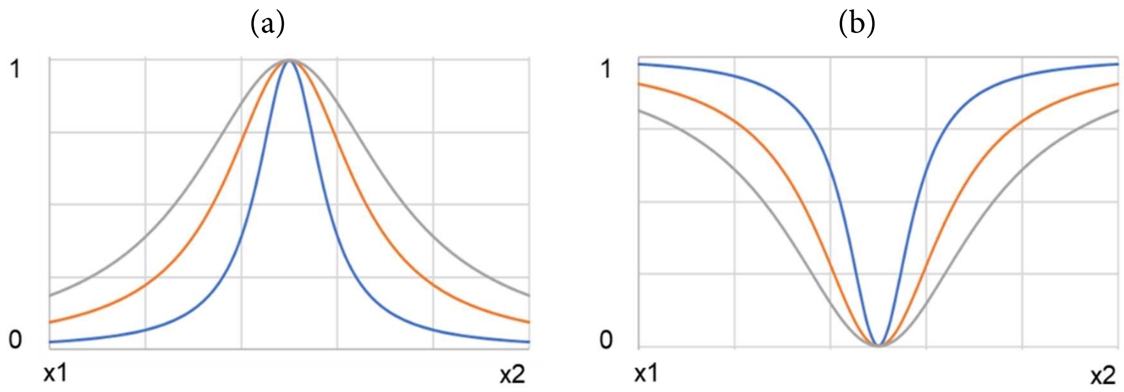


Figure 5.3: Optimisation (a) and avoidance (b) value functions.

5.2.2 Allocation of Targets

Once wave energy requirements and assessment criteria have been identified, the natural next step is to allocate performance targets to clarify what should be aimed for. Four sets of values may coexist within the range of the assessment criteria (Figure 5.4):

- **Benchmark**: achievable range from the technology spectrum known.
- **Threshold**: acceptable value within the state-of-the-art.
- **Target**: desirable value that might exceed the state-of-the-art.
- **Ideal**: highest possible value; theoretical or fundamental limits.

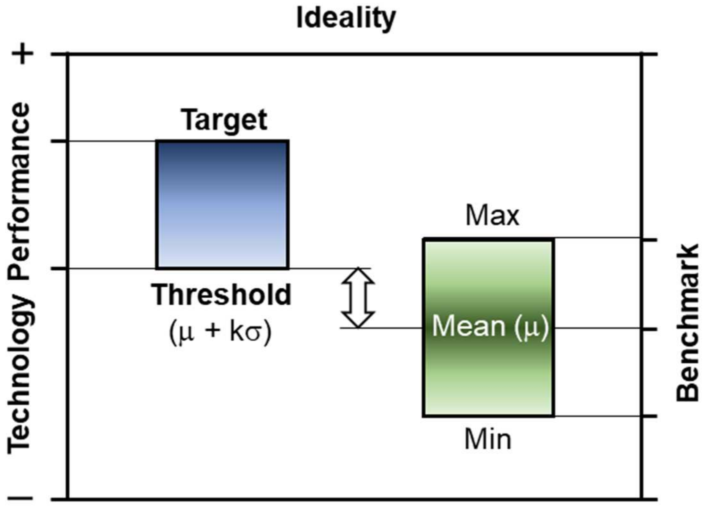


Figure 5.4: Deriving threshold metrics from benchmark data

Providing individual target values for each metric may be arduous. Whereas the overall technology performance (i.e. highest level in the hierarchy of metrics) is relatively easy to specify, a plurality of combinations may be feasible at lower hierarchy levels. Reverse LCOE or inverse TPL analysis [237] may be used to allocate target values to the next level of metrics supported by the mathematical expression that binds them. Having set the higher-level metric, all independent lower-level metrics but one can be freely allocated. By way of illustration, in [145], the maximum CAPEX of a wave energy technology with a certain annual energy production is determined to reach the target LCOE.

In this allocation, respecting the theoretical or fundamental limits that cannot be surpassed is paramount. For instance, physical limits for power capture, such as the Budal upper bound [224] and the maximum capture width [238], should be respected.

Underperformance in an intermediate metric can create an issue at a higher level and, therefore, should be thoroughly checked. However, it may be compensated by other metrics with better scores at the same level, due to the existence of multiple solutions in the allocation for group criteria targets.

Allocation of target values will significantly depend on the specific technology option being considered. However, target values for the technology's most innovative aspects should preferably be above the maximum benchmark values. Otherwise, investors may not be willing to take the risk. On the other hand, target values not essential for the innovation can be within the achievable range from the technology spectrum known.

A threshold value can be suggested whenever guidance on the possible maximum and minimum range of values can be obtained from the state-of-the-art. According to Chebyshev's inequality [239], no more than $1/k^2$ of the benchmark values can be k or more standard deviations (σ) away from the mean (μ) for any probability distribution and any constant k greater than 1. This probabilistic statement can be written as follows:

$$Pr(|X - \mu| \geq k\sigma) \leq \frac{1}{k^2} \tag{16}$$

with X being the performance variable under consideration with mean value μ and standard deviation σ.

The probability that benchmark values lie outside the interval (μ - $k\times\sigma$, μ + $k\times\sigma$) does not exceed $1/k^2$ (see Figure 5.4). For example, to identify a threshold value within 75% of benchmarks, the value of $k = 2$ can be obtained by solving $0.75 = 1 - 1/k^2$.

Literature review such as [240] is quite helpful to synthesise the range of values that might be considered for key assessment criteria. Practical Capture Width Ratios (CWR) for heaving devices result in a mean value of 17.5% and a standard deviation of 12%. Assuming $k = 2$, the suggested threshold CWR should be set at 41.5%. Other useful literature sources provide relationships between the availability and resource level [241], the absorbed power and displaced volume [242], or the steel mass and total WEC volume [243].

In the lack of benchmarks in the existing literature, commercial values in known akin applications could also be considered reference values to establish the targets.

5.3 Assessment of Wave Energy Capabilities

5.3.1 Background

Staged development processes are employed in many engineering sectors to ensure that technologies are developed in a controlled manner, therefore managing risk and uncertainty [244]. A staged development process defines suitable evaluation metrics that should be monitored throughout technology development, and thresholds for these metrics that must be met to demonstrate successful progress [245]. With clear evaluation metrics, progress can be quantified, and the development process guided to produce the desired outcome. Moreover, by identifying the weakest and strongest areas of the technology, the development efforts can be allocated more appropriately, and more cost-effective designs can be produced through various design iterations.

The previous chapter presented a common evaluation framework for wave energy technologies based on three levels of metrics. Satisfaction of wave energy requirements is expressed at different hierarchical levels through MOEs, MOPs and TPMs. Furthermore, aggregating system requirements into a final figure, or Global Merit (GM), enables a qualitative assessment of the overall suitability of the wave energy technology.

Evaluation of technology performance is inherently a continuous activity [63]. As the wave energy technology matures, however, the purpose of this assessment will shift from strategic evaluation and feasibility studies to funding authorisation, budgeting and project control.

Notably, most wave energy assessments carried out to date have been based on projected data and were not derived from direct open-sea deployment experience [246]. The reliance on projected figures leads to further uncertainties in the assessment process, which can be substantial depending on the stage of technology development, the degree of innovation, the data quality of assumptions, and the level of detail in the assessment. To the best of our knowledge, the quantification of the assessment uncertainty is a topic that has not been addressed in wave energy.

The earlier the stage of technology development is, the lower the accuracy can be achieved during the evaluation due to the limited knowledge. Many evaluation areas may not have been adequately addressed at the initial maturity level where the concept is formulated (i.e. TRL1). They will require taking numerous assumptions leading to significant uncertainties. However, the accuracy of these estimates will be progressively refined in subsequent development stages. Thus, the uncertainty band will narrow.

The value assigned to the assessment criteria of a wave energy technology should be supported by evidence of the activities carried out at each development stage [142]. For instance, the H2020-funded DTOceanPlus project proposes a series of activities a technology developer must complete at each main development stage [156].

The state-of-the-art values in wave energy or any other closed-related sector application could be used as a reference for a holistic evaluation. Nevertheless, until it becomes feasible to collect practical evidence on the metrics, they will be obviously taken as control values; if the technology solution diverges much from its target, the overall performance might be compromised.

It can be easily inferred that the larger the gap from the expected targets, the greater the challenges ahead, which can compromise the technological feasibility for market entry. The development trajectory must ensure that each identified challenge is addressed at the earliest stage since the same performance gap will be harder to overcome at the next TRL.

5.3.2 Performance Ratio (PR)

System performance needs to be measured against a specified reference to provide a quantitative assessment. QFD considers a particular step to benchmark how the system requirements are currently satisfied. Besides, awareness of best practices in wave energy helps to assign acceptable, achievable and desirable ranges for system requirements, as mentioned in section 5.2.2 for the capture width [240]. These target values enable benchmarking of the relative performance of wave energy technologies in a quantitative manner.

Evaluation criteria targets divide technology performance into two separate regions. There is a region of acceptable performance where the technology meets or exceeds the specified reference for the corresponding metric. By contrast, unacceptable performance occurs when the technology falls short concerning this reference value [247]. Any wave energy developer aims to reach the acceptable performance region for all mandatory metrics.

Notwithstanding the metric under consideration, evaluation criteria can present two different performance behaviours. Whereas some metrics in the evaluation hierarchy must decrease to meet the established target (see Figure 5.5), other metrics display an increasing performance pattern (see Figure 5.6). M1 to M5 stands for measured values at each development stage.

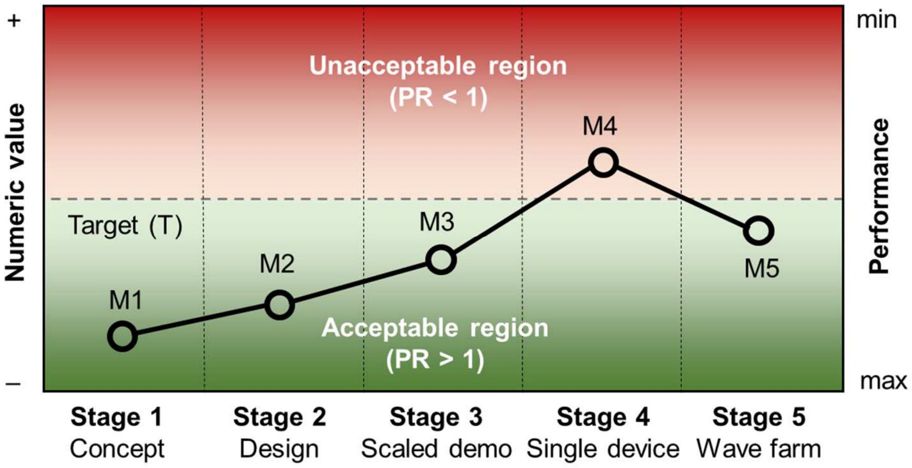


Figure 5.5: Metric exhibiting a decreasing performance behaviour (lower is better).

Let us define the Performance Ratio (PR) to overcome this opposing behaviour. For metrics that exhibit decreasing performance (i.e., lower is better), the PR_i is calculated as follows:

$$PR_i = \frac{T_i}{M_i} \tag{17}$$

where T_i and M_i are the target and measured performance values, respectively, for the evaluation criteria *i*. Typical examples of this category of metrics are the Levelized Cost of Energy (LCOE), Mean Time to Repair (MTTR) and Waiting time (t_w).

Alternatively, for metrics that show an increasing performance pattern (i.e., higher is better), the PR_i is calculated by reversing this quotient, which accounts for the percentage that the measured performance exceeds the target value.

$$PR_i = \frac{M_i}{T_i} \tag{18}$$

Some examples of this category of metrics are the Availability Factor (AF), Mean Time To Failures (MTTF) and Relative bandwidth (B_r).

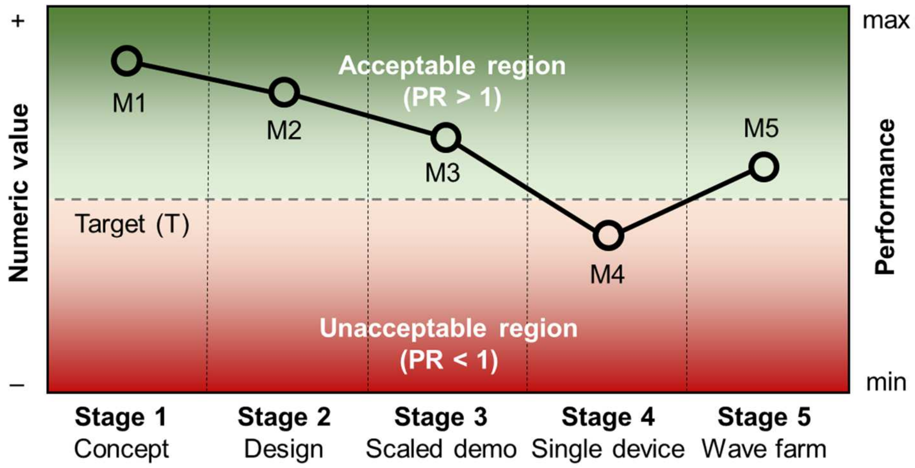


Figure 5.6: Metric exhibiting an increasing performance behaviour (higher is better).

The outcome of performance benchmarking for a wave energy concept estimates how close or far the technology is to achieving its previously established technical goals. A $PR_i \geq 1$ means that the wave energy technology is in the acceptable performance region for the evaluation criteria *i*. Conversely, a $PR_i < 1$ denotes an unacceptable performance for this evaluation criteria.

Technologies with all mandatory requirements in the acceptable performance region can be benchmarked regarding their Commercial Attractiveness (CA). Otherwise, the Technical Achievability (TA) should be investigated.

5.3.3 Commercial Attractiveness (CA)

Commercial Attractiveness (CA) is a broad concept encompassing various aspects ranging from economic profitability to stakeholder acceptability and size of the market opportunity.

In wave energy, CA has been defined as the ratio of the target LCOE value to the calculated one to explore concepts beyond the existing technologies [248]. Note that this ratio fits perfectly within the generic PR definition from Eq. (*22*) & (*23*), but in this case applied to the Levelised Cost of Energy (LCOE), which is the most common high-level affordability metric.

The assessment of CA is also mentioned in the International Evaluation Framework for Ocean Energy Technologies [142], this time comprising both the cost of energy and sustainability aspects such as environmental and social acceptance. The guideline, however, neither provides any metric for sustainability nor a procedure for the computation of the CA.

To take into consideration the qualitative aspects beyond mere affordability (i.e. stakeholders' preference), the proposed methodology will define CA as the product of the Global Merit (GM), derived from the qualitative assessment, and the Performance Ratio (PR), resulting from the quantitative estimations of the LCOE, whenever $PR \geq 1$. The previous statement can be written as follows:

$$\text{If } PR \geq 1 \qquad CA = GM \times PR; \qquad else \qquad CA = 0 \tag{19}$$

The Geometric mean (G) operator is chosen to combine these attributes to prevent compensation. This definition has the advantage of enabling an objective comparison of wave energy technologies in various markets presenting dissimilar energy prices and responding to different stakeholder demands and priorities.

Although CA is mainly a useful concept for comparing the affordability of wave energy systems, it can be equally applied to the partial evaluation of lower-level design attributes in wave energy technologies, such as MOEs, MOPs or TPMs. It only requires substituting the GM for the partial utility of the performance metric under consideration resulting from the QFD analysis.

Figure 5.7 exemplifies the concept of CA for assessing two illustrative wave energy options. Whereas the single quantitative assessment will rank Option 2 on top of Option 1, the qualitative assessment reverses this order of preference. The hatched area (PR < 1) highlights the need to improve some wave energy capabilities.

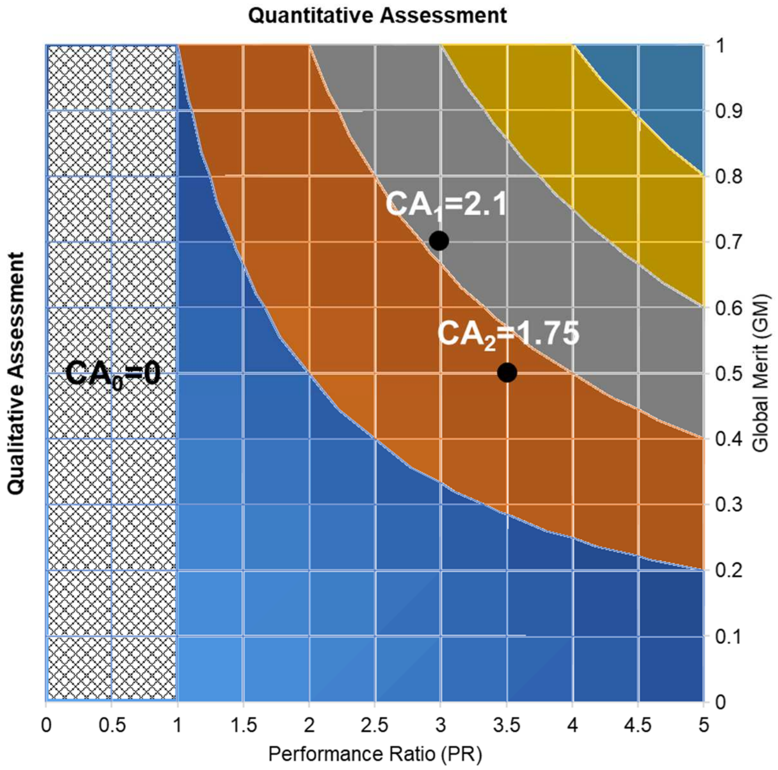


Figure 5.7: Commercial Attractiveness (CA).

5.3.4 Technical Achievability (CA)

For wave energy technologies that cannot meet one or more of the mandatory requirements and, therefore, technological improvements are needed, the Technical Achievability (TA) concept is introduced. It measures the technology development risk, time or effort to meet the target performance. This concept is particularly useful when guiding technologies with long development times such as wave energy.

TA has been formulated in [248] for power performance and subsystem cost metrics. Improvement factors and learning rates are used to assess the degree of effort needed. Likewise, the reverse LCOE engineering method [6] was proposed to explore the limits of the technical parameters of wave energy technologies. This is a unidimensional analysis in which all partial evaluation criteria are fixed. The cost reduction is investigated to achieve a PR = 1.

This methodology proposes an alternative but more comprehensive definition that can be used to assess wave energy performance at any hierarchical level. The TA definition has been adapted from [249], where it is used to support decisions of new defence technologies through their development lifecycle based on performance assessment.

TA combines the Performance Ratio (PR) and Degree of Difficulty (DD) as shown in Equation (20). In this expression, DD effectively measures the risk probability, whilst the unmet performance (1 – PR) measures the risk severity or importance.

$$TA = \frac{PR}{1 + (1 - PR) \times DD} \tag{20}$$

Table 5.1 presents the DD levels and their corresponding numerical values. The risk levels are based on [249]. However, the assigned numerical values have been resized to a 9-point scale for consistency with the QFD ranking methods. The lower bound (0) indicates no risk in meeting the performance requirement, and success is guaranteed. Conversely, the upper bound (9) means that it is impossible to meet this requirement. Intermediate levels denote different degrees of difficulty.

Table 5.1: Technical Difficulty (adapted from [249]).

Level	Degree of Difficulty (DD)	Value
1	Very low uncertainty (certain feasibility)	0
2	Moderate uncertainty	1
3	High uncertainty	3
4	Very high uncertainty (fundamental breakthrough)	9

Figure 5.8 illustrates four achievability curves for different DD levels. For instance, the TA of one technology with very low uncertainty and PR = 0.6 (point a) is analogous to a technology with a PR = 0.94 (point c) and very high uncertainty, which requires a fundamental breakthrough. Similarly, a technology with very high uncertainty but the same PR = 0.6 (point b) will severely decrease its TA to 0.13.

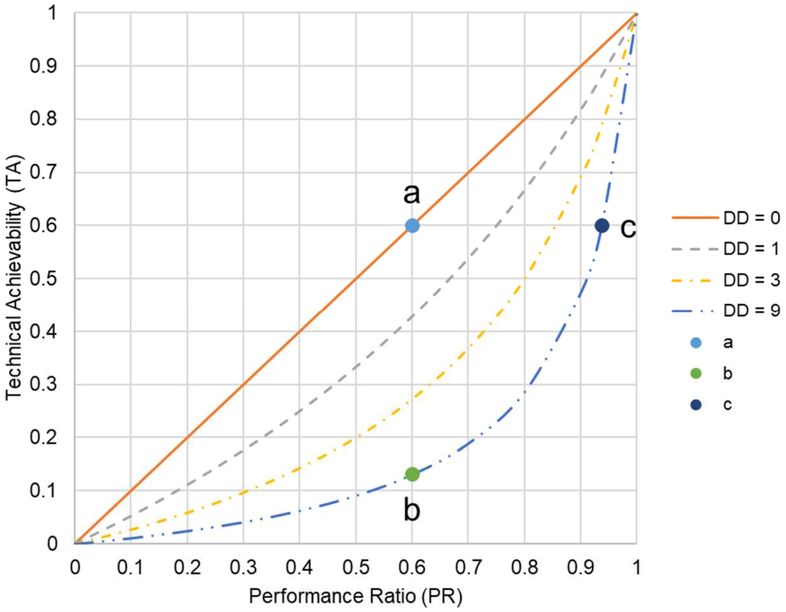


Figure 5.8: Technical Achievability (TA).

Assigning the DD level to the system requirements of a wave energy technology under development may seem entirely subjective and challenging. Despite the difficulties, too little time spent in the early design phases can lead to gaps in understanding the problem requirements, limited opportunities for novel concept generation and wasted time and money developing a concept that cannot perform well enough to become a viable solution [17].

In practical terms, the ability of new technology to meet its performance targets will depend on its innovation capability and it is limited by fundamental limits (ideality). In the early stages, emerging technologies will have significant improvement potential. In contrast, mature technologies in the later development stages will have limited improvement potential. Thus, DD indicates the Learning Rate (LR) needed to achieve a PR = 1.

Different learning mechanisms have been described in the literature, as will be further discussed in CHAPTER 6. However, in the context of technology development, technological learning refers to the rate at which new knowledge is effectively acquired to improve its performance.

As technology development progresses, new knowledge is acquired, the sources of variability for the various evaluation criteria are pinned down, and the uncertainty of the estimates is narrowed. This phenomenon is known as the “cone of uncertainty”. Defined initially for software development [250], this concept has been used in Project Management for decades to describe uncertainty reduction as engineering systems evolve.

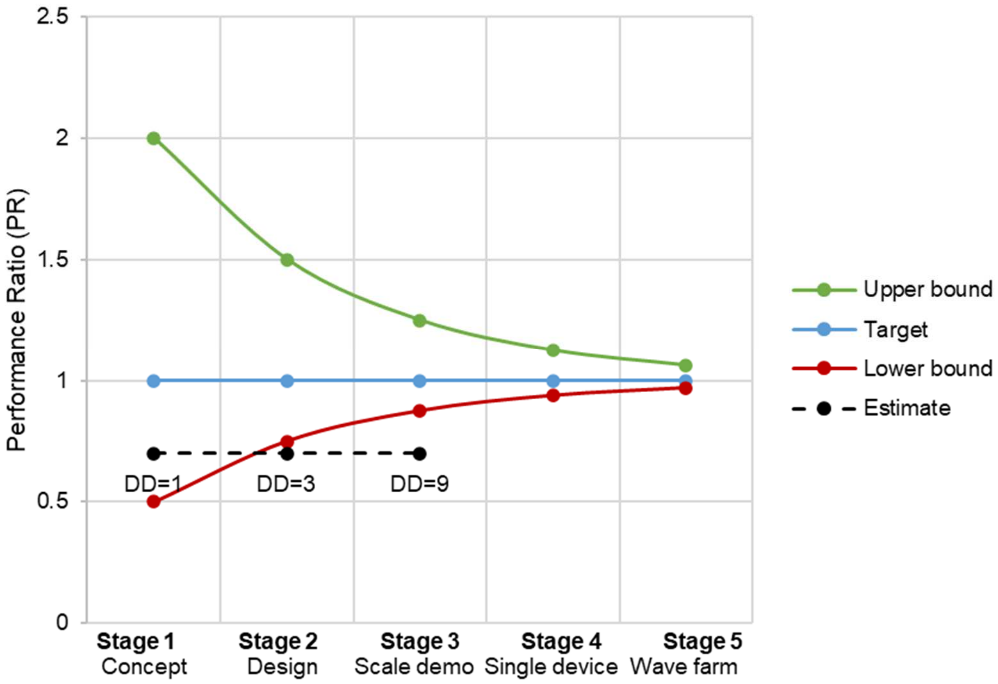


Figure 5.9: Cone of uncertainty and DD levels.

At the concept stage, the initial estimate is based on minimal information. This estimate is a rough order of magnitude, whose variance can be as much as 100% depending on the source of evidence. Then the variance will be progressively diminished in subsequent phases until the technology is finally deployed and there is no uncertainty remaining. The cone of uncertainty delimits the upper and lower bounds for five development stages as illustrated in Figure 5.9.

All the estimations with PR < 1 that lie within the cone of uncertainty would be assigned a low DD. However, the same estimation should increase its DD if the PR does not improve. For instance, a PR = 0.7 can be assigned a DD level 1 at concept design (Stage 1) but increased to 3 in the design phase (Stage 2) or even rated 9 for later stages. The innovation capability is limited as the technology matures. Therefore, the PR should be penalised with a higher DD at later design stages.

Conversely, an early TRL opens the room for improvements through innovation. Weber [151] expresses the same underlying idea in the generic WEC development trajectories displayed over a TRL-TPL matrix. Fundamental system changes are only feasible and affordable at low TRLs. Cost reduction and improved performance for mature technologies are mainly limited to learning by doing and economies of scale.

5.4 Practical Implementation

5.4.1 Benchmark Cases

The practical implementation of the proposed methodology is showcased with six illustrative cases of hypothetical wave energy technologies. These benchmark cases are defined with an identical installed capacity (1 MW) but different combinations of MOE, leading to a plurality of LCOE values.

The numerical values for the different evaluation criteria are summarised in Table 5.2. The LCOE is calculated using Equation (8), presented in the previous chapter.

Table 5.2: Illustrative benchmark cases.

Eval Criteria (MOE)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
P (MW)	1	1	1	1	1	1
CF (%)	30	25	50	40	20	25
AF (%)	95	97	99	98	92	85
CAPEX (M€)	1	1.2	3	3	1.9	3.5
OPEX (k€)	45	92	150	210	114	140
FCR (%)	8	10	9.4	10.2	11	9.3
LCOE (€/MWh)	50	100	100	150	200	250

Case 1 represents a high-performing wave energy technology in all evaluation criteria. It leads to the lowest LCOE of 50 €/MWh, which could compete in cost terms with traditional energy sources even without additional subsidies.

Case 2 and Case 3 involve two wave energy options that reach the same LCOE of 100 €/MWh through alternative performance paths. Whereas Case 2 has a moderately low-capacity factor coupled with competitive lifetime costs, Case 3 displays the highest net energy production but also carries high CAPEX and OPEX costs. Depending on the innovation potential of these technologies, they could have scope for further energy cost reduction.

Case 4 explores a wave energy technology that cannot compensate for the high lifetime costs despite the significant net energy production. Hence, Case 4 leads to an LCOE of 150 €/MWh. The EU's SET Plan implementation plan for Ocean Energy [226] establishes a target LCOE of 150 €/MWh by 2030 and 100 €/MWh by 2035 for wave energy technologies.

However, the two last benchmark cases have an LCOE beyond the EU's SET Plan implementation plan targets. Case 5 has a very low-capacity factor and moderately high costs, which results in an LCOE of 200 €/MWh. Finally, Case 6 has the highest investment costs and lowest availability resulting in the least affordable option, which leads to the highest LCOE of 250 €/MWh.

5.4.2 Global Merit (GM)

A value function is defined for each MOE to compare the different wave energy options. The function is normalised considering maximum (1) and minimum (0) utility values as shown in Table 5.3. Maximum and minimum bounds to the MOE have been assigned examining wave energy literature, as described in section 4.3.2.

Table 5.3: Stakeholder Requirements and Utility.

MOE	Min = 0	Max = 1	Value Function
CF (%)	0%	≥50%	Maximisation type, Convex
AF (%)	≤75%	100%	Maximisation type, Concave
CAPEX (M€)	≥5 M€	0 M€	Minimisation type, Concave
OPEX (k€)	≥500 k€	0 k€	Minimisation type, Convex
FCR (%)	≥20%	≤5%	Constraint type

CF is modelled with a maximisation type value function. It has a slightly convex shape: this reflects the increasing difficulty of improving utility as the CF gets closer to its maximum value. The neutral point is set to 17.5%, the average value reported for heaving point absorbers in [240]. Figure 5.10-a) depicts the function and the values for the six benchmark cases.

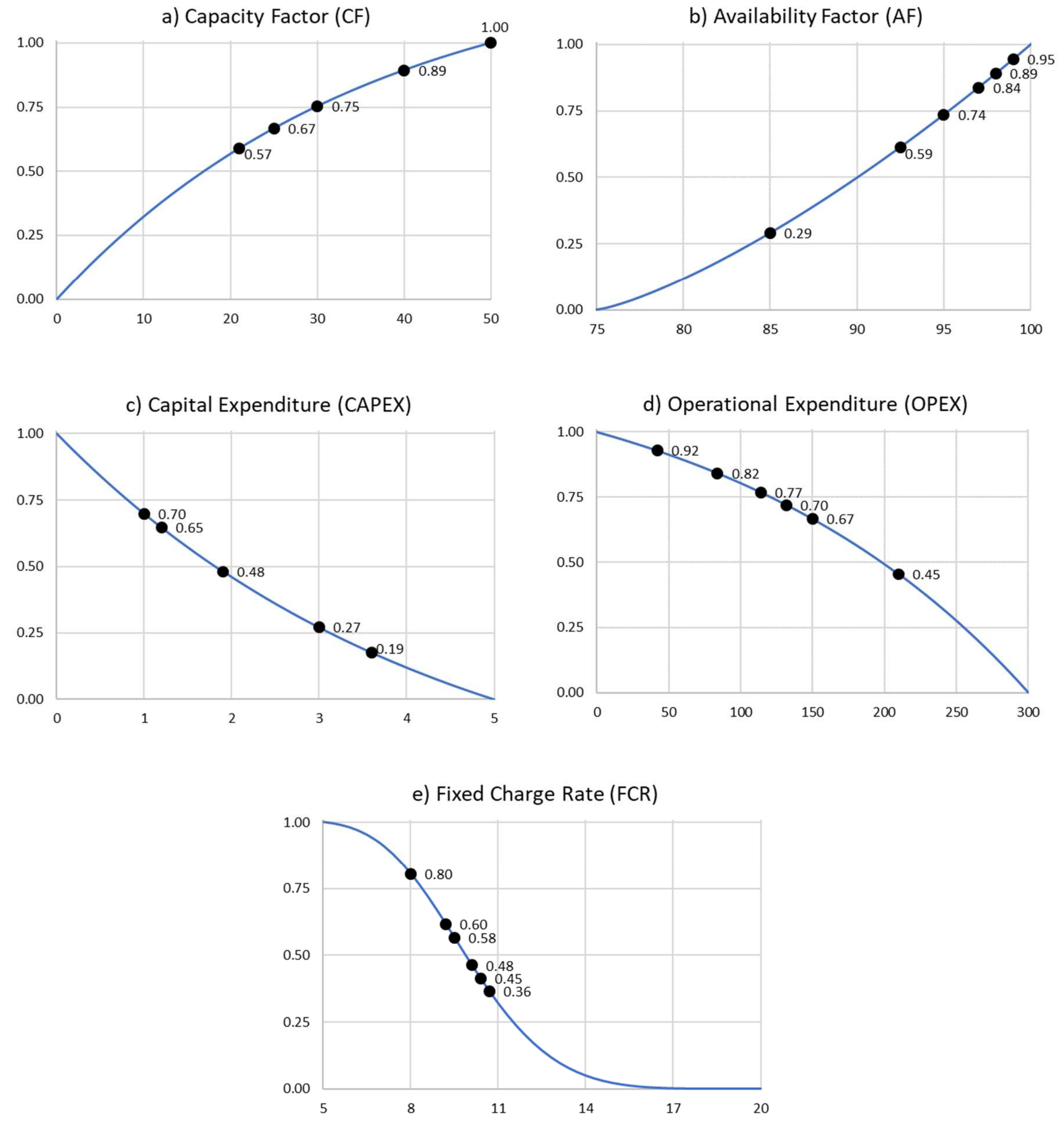


Figure 5.10: Value functions for the six benchmark cases.

AF is also modelled with a maximisation type value function. In this case, a concave shape is used to penalise wave energy options with large repair times since downtime will also reduce the total annual energy produced. The neutral point is set to 90%, as most power plants are expected to achieve high energy availability [218]. Figure 5.10-b) depicts the function and the values for all benchmark cases.

CAPEX is modelled with a minimisation type value function. The concave shape reflects the risk aversion to higher upfront capital investment. The neutral point is set to 1.8 M€/MW, as this is the average range of cost expected from the reverse LCOE engineering performed in [168] to achieve a target LCOE of 100 €/MWh. Figure 5.10-c) depicts the function and the values for the benchmark cases.

OPEX is also modelled with a minimisation type value function. In this case, the convex shape favours low operational costs. Annual OPEX is often assumed to be a percentage of CAPEX, with values ranging from an optimistic 2% to a pessimistic 8%. In this case, the neutral point is set to 198 k€, i.e. approximately 4% of the maximum CAPEX, a commonly used value in ocean energy renewable studies [180]. Figure 5.10-d) depicts the function and the values for the six benchmark cases.

Finally, FCR is modelled through a constraint-type value function with a soft slope. Discount rates for energy projects commonly range between 3% and 15%, depending on the sector, country and perceived risks [251]. The neutral point represents the threshold value and has been set to 10%, which corresponds to an 8% discount factor for a 20-year lifetime project. However, this value may be revised in the medium term if the interest rates keep rising. Figure 5.10-e) depicts the function and the values for all benchmark cases.

Table 5.4 summarises the qualitative assessment results of each MOE for the six illustrative cases of hypothetical wave energy technologies previously defined in Table 5.2.

Table 5.4: Qualitative assessment of MOE.

MOE	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
CF (%)	0.75	0.67	1.00	0.89	0.57	0.67
AF (%)	0.74	0.84	0.95	0.89	0.59	0.29
CAPEX (M€)	0.70	0.65	0.27	0.27	0.48	0.19
OPEX (k€)	0.92	0.82	0.67	0.45	0.77	0.70
FCR (%)	0.80	0.48	0.58	0.45	0.36	0.60

The Global Merit (GM) for these six benchmark cases are presented in Table 5.5. The suitability scores are calculated for each application market using the aggregation logic implemented in the previous chapter (see Figure 4.6) and the relative importance presented in Figure 4.15. First, the weighted Geometric mean (G) is used to combine CF and AF, on the one hand, and CAPEX and FCR, on the other hand. Then, the latter is combined with OPEX through the weighted Arithmetic mean (A). Finally, the resulting values are combined again using the weighted Geometric mean (G).

Table 5.5: Global Merit (GM) of wave energy option for the application markets.

Global Merit (GM)	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
Utility-scale	0.79	0.69	0.66	0.54	0.56	0.47
Remote community	0.78	0.69	0.67	0.56	0.56	0.47

It can be noted that the small variation in the weights for the two application markets results in very similar global merits in all six case studies. This result suggests that the application market is less significant than the overall technology performance.

A large imbalance in the utility of evaluation criteria combined with the weighted Geometric mean (G) penalises the GM since this operator does not allow full compensation. This applies to Case 3 and Case 4, with high CAPEX.

In general, GM decreases as LCOE increases. Only if one of the evaluation criteria is totally removed, setting its weight to 0% may revert the conventional ranking per affordability. However, the qualitative assessment provides a way to disambiguate between technologies with different combinations of performance levels leading to the same LCOE. For instance, Case 2 has higher merit than Case 3 although they share the same cost, 100 €/MWh. This means that selecting a wave energy alternative exclusively based on either LCOE or GM might yield an unsuitable decision.

5.4.3 Evaluation of the CA

The quantitative assessment of wave energy technologies requires the allocation of performance targets to the system requirements. Let us start with affordability.

As presented before, the EU's SET Plan implementation plan for Ocean Energy establishes a target LCOE of 100 €/MWh by 2035. This target LCOE can be used as the reference price of energy for the utility-scale generation market. It comes without saying that this is an ambitious value that exceeds the state-of-the-art. As a reference, the third annual report from the OceanSET project [205] found an average LCOE of 272 €/MWh for wave energy technologies that have reached a TRL 7 or greater.

By contrast, according to the World Bank [189], the average price of energy in 30 of the Small Island Development Country States (SIDS) ranges between 160–330 €/MWh. Given these high generation costs, wave energy technologies not currently affordable in the utility-scale markets may already be cost-competitive in these remote communities. Let us assume 300 €/MWh as the reference energy price for the remote community market to illustrate the practical implementation of the methodology. This target value is in the range of the average LCOE of 272 €/MWh reported by OceanSET.

The LCOE target value divides the technology suitability into acceptable and unacceptable regions. Table 5.6 presents the Commercial Attractiveness (CA) results for the utility-scale and the remote community markets considering the 100 €/MWh and 300 €/MWh targets, respectively.

As can be seen, Cases 1–3 have a combination of MOE that yields a reasonable cost of energy for the utility-scale generation market. However, Cases 4–6 can only be compatible with the remote community market.

Table 5.6: Wave energy attractiveness.

Utility-Scale (100 €/MWh)	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
GM	0.79	0.69	0.66	0.54	0.56	0.47
PR	2.00	1.00	1.00	0.67	0.50	0.40
CA	1.57	0.69	0.66	0	0	0
Remote Community (300 €/MWh)	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
GM	0.78	0.69	0.67	0.56	0.56	0.47
PR	5.99	3.01	3.01	2.00	1.50	1.20
CA	4.70	2.08	2.02	1.11	0.85	0.56

The concept of CA allows the selection of the most suitable wave energy option when the LCOE or the GM are identical for the same market application. For instance, Case 2 & Case 3 share the same LCOE (and hence PR) but have distinct GMs. The current methodology gives a preference to Case 2 as it better fits the stakeholders' needs.

On the other hand, Case 4 & Case 5 for the remote community lead to the same GM but with different LCOEs. Other potential combinations of affordability and Global Merit can be objectively disambiguated through the examination of the CA.

Furthermore, CA allows comparing wave energy technologies across different market applications. For instance, Case 4 for remote community generation (CA = 1.11) is more attractive than Case 3 for utility-scale generation (CA = 0.66), even if the LCOE is higher.

5.4.4 Evaluation of the TA

Now let us focus on the Technical Achievability (TA) of wave energy technologies with PR < 1. This applies to Case 4 for the utility-scale market (see Table 5.2). Besides, to estimate the technical difficulty, this technology option is assumed to be in the design optimisation stage (TRL 4). Case 2 ratings are reference values to compute the PR (see Table 5.2). PR is calculated using Equation (17) for metrics that exhibit decreasing performance. Otherwise, Equation (18) is used.

When PR ≥ 1, the Degree of Difficulty (DD) is zero, as shown in Table 5.7. However, for unmet performances, the DD level was estimated using the 0-9 scale in Table 5.1. The aggregated DD for the higher-level evaluation criteria was calculated as a weighted average of individual DDs using the weightings in Figure 4.15. The TA is then computed using Equation (20).

The combined DD is rated as moderate to high (1.32) resulting in a TA of 0.46. Hence, this wave energy technology is still far from reaching its techno-economic goals.

Table 5.7: TA for the MOE in the utility-scale generation market.

Eval Criteria (MOE)	**Case 2**	**Case 4**			
	Reference	**Ratings**	**PR**	**DD**	**TA**
CF (%)	25	40	1.60	0.00	1.60
AF (%)	97	98	1.01	0.00	1.01
CAPEX (M EUR)	1.2	3	0.40	3.00	0.14
OPEX (k EUR)	92	210	0.44	3.00	0.16
FCR (%)	10	10.2	0.98	1.00	0.96
LCOE (EUR/MWh)	100	150	0.67	1.32	0.46

The assessment of the TA provides a means to concentrate the innovation efforts on improving those areas with the most significant impact on technology performance. In this practical implementation case, the development should focus on reducing the CAPEX (TA = 0.14) and the OPEX (TA = 0.16).

This analysis can be replicated at a lower hierarchical level in the functional domain to identify improvement areas among the various technological capabilities. The reverse TPL analysis [237] can be used to allocate reference values that should agree with the higher-level MOE. For instance, the CF can be derived from the product of the Capture Width, Transformation Efficiency and Delivery Efficiency. Similarly, the AF can be calculated with Equation (10). Table 5.8 displays the allocation of MOP targets and quantitative assessment for Case 4.

Table 5.8: TA for the MOP in the utility-scale generation market.

Eval Criteria (MOP)	**Case 2**	**Case 4**			
	Reference	**Ratings**	**PR**	**DD**	**TA**
Normalised Capture Width (C_{wn})	45	60	1.33	0	1.33
Transformation Efficiency (η_t)	61	70	1.15	0	1.15
Delivery Efficiency (η_d)	91	95	1.05	0	1.05
Reliability (MTTF)	850	1,010	1.19	0	1.19
Maintainability (MTTR)	26	21	1.28	0	1.28
Manufacturability (MANEX)	1.1	2.6	0.41	3	0.15
Installability (INSTEX)	0.1	0.4	0.31	3	0.10
Repairability (REPEX)	92	210	0.44	3	0.16
Survivability (SURV)	8.5	8.7	1.02	0	1.02
Environmental Impact Score (EIS)	3.5	3.7	0.96	2.5	0.87

Again, the cost metrics (i.e. MANEX, INSTEX and REPEX) pose the greatest uncertainty in achieving a suitable technology performance in this practical implementation example. Environmental impacts are also identified as another potential area of attention.

As mentioned in Section 5.3.4, the DD may also be defined by fundamental limits. Table 5.9 presents the list of MOP and possible factors that may restrict innovation capability. It can be noted that the fundamental limits are defined either by attributes of the system design or the External Systems that interact with it. For instance, the deployment site defines the wave energy resource and the distance to the point of connection. Similarly, the service vessels available in the area dictate the charter cost. The technology developer cannot modify the attributes of the External Systems but select the most appropriate locations, thus constraining the total addressable market of the technology.

Table 5.9: Degree of difficulty factors for FR.

MOP	**Factors**
Normalised Capture Width (Cwn)	Wave energy resource at the deployment site
Transformation Efficiency (ηt)	No. of transformation steps
Delivery Efficiency (ηd)	Distance to the point of connection
Reliability (MTTF)	No. of components in series
Maintainability (MTTR)	Time of maintenance operation
Manufacturability (MANEX)	Cost of raw materials
Installability (INSTEX)	Cost of vessels
Repairability (REPEX)	No. of trips
Survivability (SURV)	Safety class
Environmental Impact Score (EIS)	Environmental pressure

Other fundamental limits are related to the design of the wave energy device. The number of transformation steps in the PTO, the complexity of the product with components connected in series or the safety class are examples of attributes over which the technology developer has full control. Discontinued technologies such as “WaveBob” or “Pelamis”, with proven components but complex PTOs [252], should have had extremely high component reliability to meet appropriate system reliability. With five components in a series, the individual reliability should be 98% to achieve system reliability of 90% (i.e. 0.98^5). The same could be said for PTO efficiency. The number of transformation steps will restrict the capability of the technology to meet the given thresholds.

5.5 Conclusions

The comprehensive assessment of wave energy technology performance provides a tool to guide design decisions throughout the various development stages, select the most suitable option for a particular market application, and identify the remaining challenges to achieving system requirements. A staged evaluation ensures that technologies are developed in a controlled manner, therefore managing risk and uncertainty.

Value functions are employed to investigate the link between system needs and utility offered, therefore assisting in the assessment of the suitability of wave energy capabilities.

The allocation of design targets to lower-level assessment criteria avoids any unfeasible combination at the same time it enables benchmarking and tracking progress.

To meet the needs of the development stage, the modelling approach, threshold, and target values should be carefully selected. Allocating evaluation criteria is a difficult task, but thresholds may be recommended by looking at current benchmarks and targets set while taking into account both the most innovative aspects of the technology and theoretical bounds. Estimating the threshold values for the major design parameters of a physical embodiment can be supported by fundamental relationships.

Commercial Attractiveness (CA) enables comparing more objectively wave energy technologies when the technology fulfils or surpasses the system requirements. CA is a useful concept for the overall comparison of the affordability of wave energy systems. However, it can be equally applied to the partial evaluation of lower-level design attributes in wave energy technologies, such as MOEs, MOPs or TPMs.

Technical Achievability (TA) provides an indication of the risk, time, or effort required for technology development to achieve the desired performance. This concept is particularly helpful when guiding complex technologies like wave energy that takes a long time to develop. The TA combines the Performance Ratio (PR) and Degree of Difficulty (DD). The task of assigning a DD level to the wave energy requirements when the technology is under development may seem highly subjective and difficult. However, this effort can be assisted by the “cone of uncertainty” concept, which has been used in Project Management for decades.

Awareness of the existing performance gap will facilitate decision-making and help focus the innovation efforts to overcome the technology development challenges. Although the expected accuracy range will reduce as wave energy technology advances to later stages of development, it is crucial to remember that decisions must always be made with a certain amount of uncertainty.

Due to the slight difference in the weights for the two application sectors, the actual application of this technique to six sample scenarios of hypothetical wave energy technologies produced relatively identical Global Merits (GMs). This finding shows that the performance of the technology as a whole is more important than the application market. The quantitative calculation of LCOE and the qualitative evaluation of GM often have a significant inverse relationship, meaning that GM declines as LCOE rises.

When the LCOE or the GM are identical for the same market application, Commercial Achievability (CA) enables choosing the best wave energy option. Additionally, CA enables comparisons between wave energy technologies for different market applications.

Last but not least, the evaluation of Technical Achievability (TA) offers a way to focus innovation efforts on enhancing those areas having the greatest influence on technology performance.

CHAPTER 6 ESTIMATING FUTURE TECHNOLOGY COSTS

> "The goal of forecasting is not to predict the future but to tell you what you need to know to take meaningful action in the present"
>
> *Paul Saffo (1954 – now)*

6.1 Overview

This chapter aims to improve the accuracy, consistency, and usefulness of projected cost predictions for emerging wave energy technologies. Beginning with the current breakdown of wave energy costs, this novel method assigns uncertainty ranges based on the accuracy of the estimation used to calculate the first-of-a-kind cost of the mature technology. The LCOE of the commercial technology is then projected using component-based learning rates once a given capacity has been installed through a number of projects.

Section 6.2 introduces the specific methods and tools used in this step of the methodology. Propagation of uncertainties is employed to factor in contingencies and accuracy ranges in the combination of engineering estimates. Besides, the learning curve method is applied to account for future cost reductions due to cumulative experience.

Section 6.3 describes the implementation of the novel three-step approach: (1) combining current bottom-up and top-down approaches to produce the current cost breakdown, (2) assigning uncertainty ranges, based on the estimation accuracy used, to determine the first-of-a-kind cost of the commercial technology, and (3) using component-based learning rates and the upper bound from (2) to account for optimism bias.

Section 6.4 illustrates the practical implementation of the method for calculating cost projections of wave energy technologies with the assistance of one of the Reference Models (RMs). Specifically, the Reference Model 5, a floating oscillating wave surge converter (OWSC) designed for a wave site near Eureka in Humboldt County (California) was chosen to exemplify this method.

Finally, section 6.5 summarises the chapter and discusses some partial findings from this novel methodology that might be of interest to the wave energy sector.

6.2 Methods and Tools

6.2.1 Propagation of Error or Uncertainty

The estimation of wave energy attributes is always prone to error or uncertainty. Common causes are unknown parameters, simplified modelling or data collection inaccuracies. Therefore, an essential aspect of research is quantifying and tracking these uncertainties from input to derived quantities.

Propagation of error (or uncertainty) is a statistical calculation method used to combine uncertainties from multiple variables to another quantity. It is based on a set of simple mathematical rules. The standard deviations are used to calculate the resulting uncertainty. Furthermore, covariances are avoided under the hypothesis of independent variables.

The general formula for error propagation of independent variables is given:

$$\delta q = \sqrt{\left(\frac{\partial q}{\partial x}\delta x\right)^2 + \cdots + \left(\frac{\partial q}{\partial z}\delta z\right)^2} \tag{21}$$

where q is a function that depends on the estimated quantities, $x, \ldots, z$ and their associated uncertainties, $\delta x, \ldots, \delta z$.

The workflow for error propagation involves the following:

1. The identification of the uncertain variables in the techno-economic expression for cost estimation.
2. Taking partial derivatives with respect to each of the variables identified in the previous step.
3. Multiplying the partial derivatives by the associated uncertainty to calculate the error contribution from each variable.
4. Adding the contributions in quadrature.
5. The global error is the square root of the summation.

Uncertainty can be represented using a probability distribution. Figure 6.1 shows the probability density function for the normal and lognormal distributions. Whereas the normal distribution is symmetrical, the lognormal is a right-skewed curve. This graph is used to illustrate some definitions used in this chapter. Note the difference in the mean (×), mode (○) and median (+) values for the lognormal distribution. Also, note that the area bounded by the P10 and P90 (light-shaded) represents the range for an 80% confidence level.

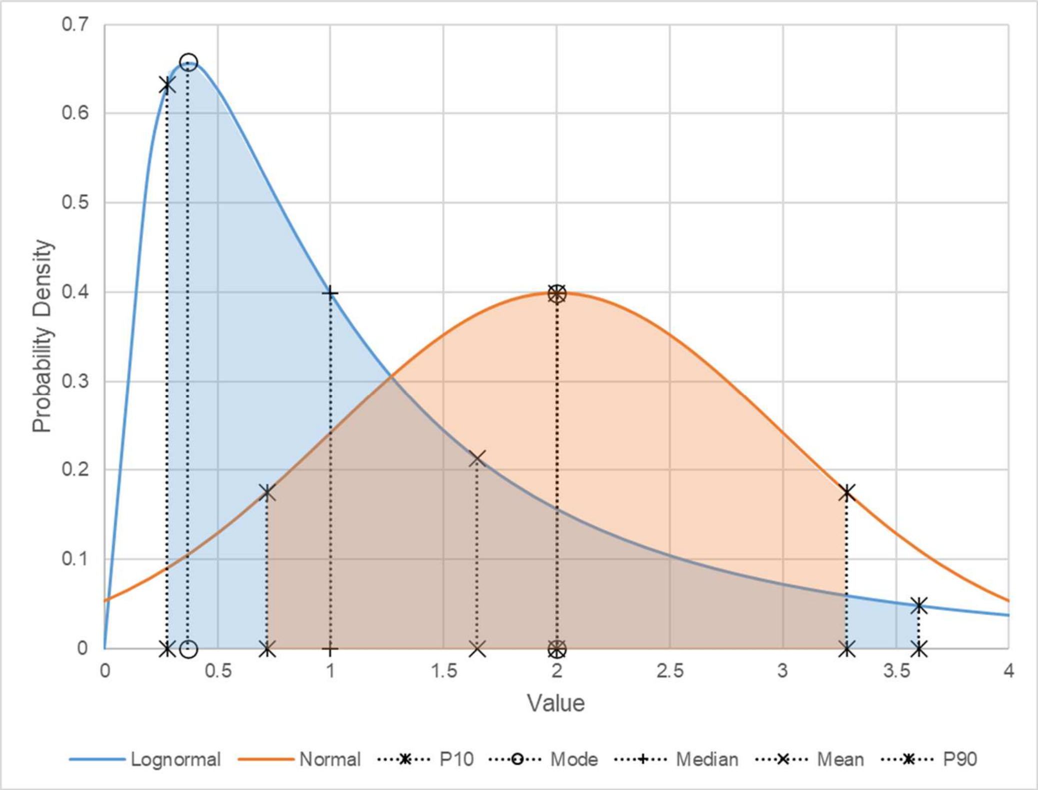


Figure 6.1: Probability representation of uncertainty and main statistical properties.

6.2.2 Technological Learning

Different learning mechanisms have been described in the literature, such as in [24], [253] and [254]. The most important mechanism is **technological learning**. Other learning factors may include:

- **Economic learning**: shifting production to low-wage countries,
- **Social learning**: as stakeholders become more familiar with the collaboration, they increase trust in one another, and
- **Financial learning**: as banks and investors gain confidence in new technology, they reduce the expected interest rates.

These exogenous factors significantly impact cost estimation, but unfortunately, they can only be accounted for within the initial assumptions or through sensitivity analysis.

Technological learning is an endogenous factor that encompasses different sources of learning: 1) Learning by research in the early stages due to R&D investments; 2) Learning by doing during the production stage due to the higher efficiency of manufacturing processes; 3) Learning by using in the initial stage of introduction of the technology into the market; and 4) Learning by interaction in the technology diffusion, which incidentally reinforces the previous factors. Scale effects are also part of the technological learning mechanism, both upsizing (i.e. the increase in rate power) through technology redesign leading to lower unit costs and economies of scale (i.e. mass production) through standardisation, allowing upscaling of production facilities.

The learning curve method is the most applied approach. The commonly used formulation originates from empirical observations across diverse energy technologies that often evidence a log-linear relationship between cost reductions driven by manufacturing, standardisation, the scale of production and use, and cumulative installed capacity or production [255]. In the simplest form, it can be expressed as:

$$Y = aX^b \tag{22}$$

where Y is the future cost of the technology and X represents the cumulative experience (often characterised by the installed capacity in MW). The constants a and b denote the cost of the first commercial deployment and the rate of cost reduction, respectively. Note that b represents the slope in a log-log scale in Equation (22). The cost reduction associated with duplication of experience is referred to as the Learning Rate (LR).

$$LR = 1 - 2^b \tag{23}$$

The independent variable x in Equation (22) reflects all the factors that influence the cost trajectory of the technology.

Figure 6.2 illustrates the potential benefits of experience in the cost reduction of wave energy technologies. Unit cost is plotted against the deployed capacity for three different Learning Rates (5%, 10% and 20%). The starting point is the initial cost (assumed €5,000,000/MW), and the cost trajectories are plotted until 1 GW capacity is reached.

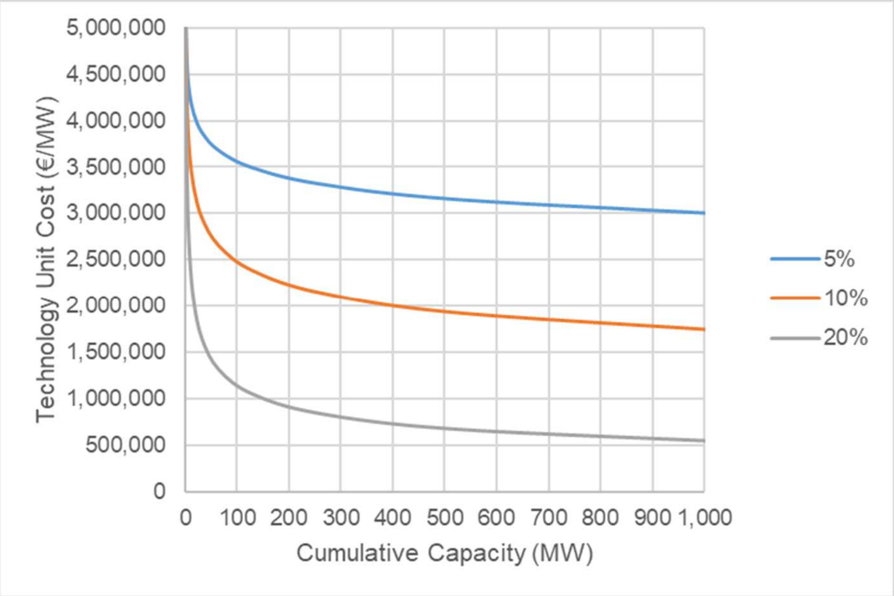


Figure 6.2: Cost reduction pathways with cumulative experience at three different Learning Rates (5%, 10% and 20%)

6.3 Future Costs of Wave Energy

6.3.1 Background

As presented in the literature review, the direct quantification of LCOE for prototype technologies produces unsuitable results. Therefore, the affordability assessment of an emerging technology requires the future projection of costs relative to the commercial technology and a first-of-a-kind commercial deployment. To be precise, this farm project should be the smallest size of a wave energy array for the LCOE to yield a meaningful value.

The proposed approach for estimating future costs of emerging wave energy technologies is an indirect method which consists of three main steps as shown in Figure 6.3:

- **Step 1**: Estimating current cost and performance based on a standardised breakdown. The emerging technology is assessed for its first-of-a-kind commercial deployment.
- **Step 2**: Cost escalation to account for uncertainties in the estimations. Uncertainty ranges (lower and upper bounds) are assigned based on the reliability of the input data. Incorporating standardised contingencies allows the cost estimation for the evolving technology regarding the same first-of-a-kind commercial deployment.
- **Step 3**: Projection of the future cost based on technology replication. Component-based learning rates are applied to the upper bound obtained in the previous step. The upper bound counterbalances the inherent optimism bias in early-stage estimates. The technology is assessed in its mature format and when it has been widely deployed.

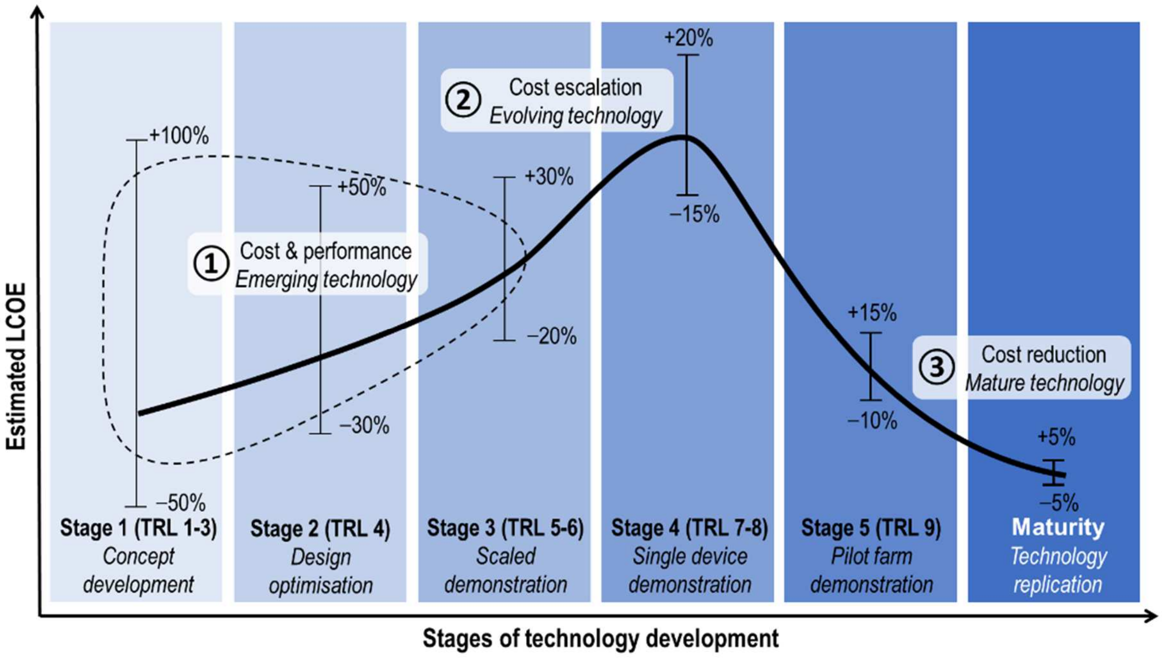


Figure 6.3: The proposed 3-step approach for estimating the future cost of an emerging wave energy technology at different stages of technology development, with an illustrative LCOE estimate and uncertainty at each stage.

The reader should note that the stages of technology development are not drawn in a time scale in Figure 6.3. Time is not evenly distributed through the development stages. More time and effort should be allocated to the initial stages, and the overall development time depends on the selected development trajectory [237].

The following sections describe each step of the proposed method.

6.3.2 Current Cost and Performance

The first step of this approach involves the bottom-up estimation of the LCOE for the emerging technology at its current state of development. Wave energy technology is decomposed into major cost centres. For emerging technologies which are at lower TRLs, this can include a simplified list of subsystems and cost centres. Further granularity (i.e. more breakdown levels) can be added as the technology moves up the TRL scale. Parametric modelling derived from experience and engineering judgement can be used to identify functional relationships between an item's physical characteristics and costs [256].

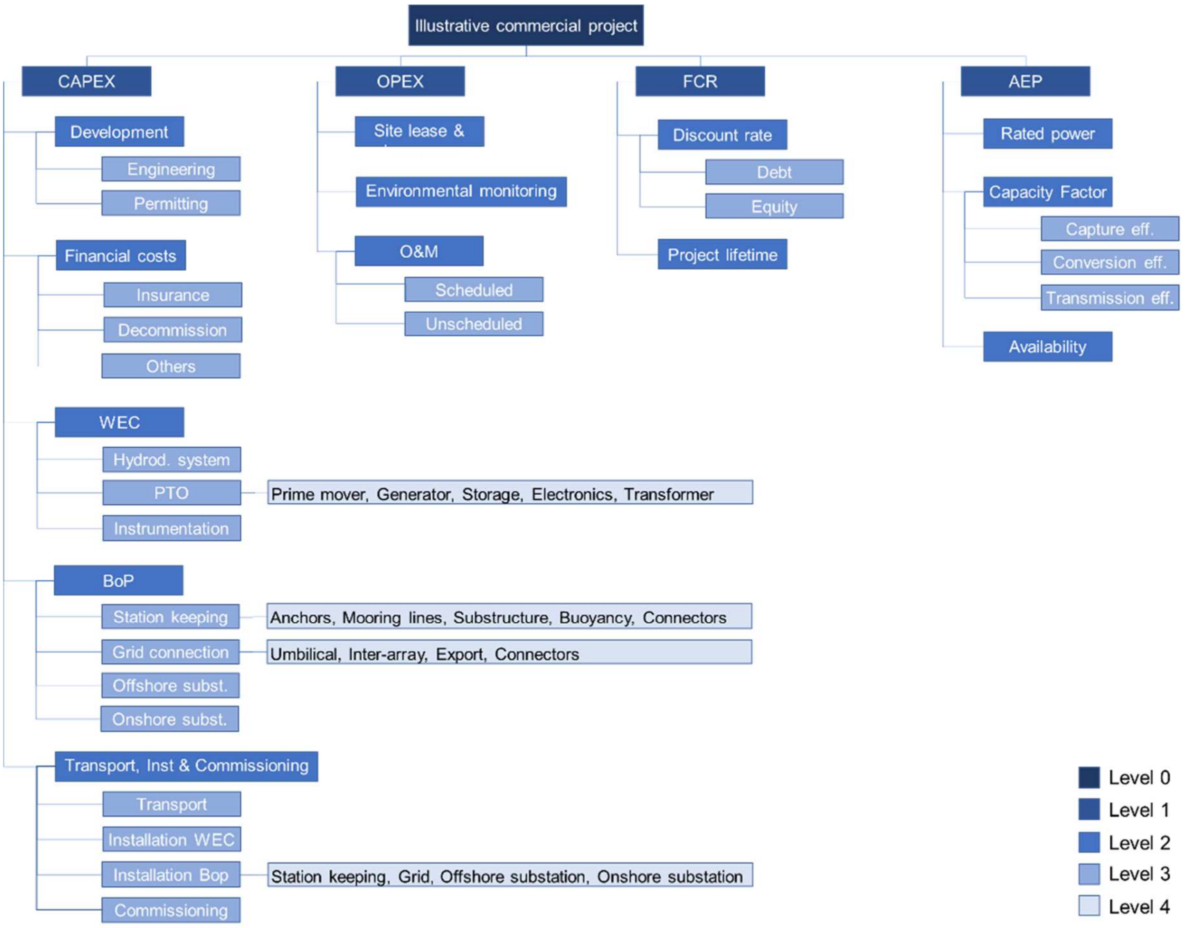


Figure 6.4: Standard cost and performance breakdown for an illustrative commercial project (adapted from [156], [227], [257], [258]).

The standardised cost and performance breakdown used in this work is shown in Figure 6.4 to the fourth level of detail. It builds upon several published guidance documents and tools such as the US Department of Energy reporting guidance [257], the BVGA study for ocean energy value chain [258], the COE Calculation Tool commissioned by the Danish Transmission System Operator [227] or the DTOceanPlus design tools [156]. These guidance documents are useful to avoid omitting any relevant cost centre.

To estimate future costs, a wave energy farm model is created which represents an illustrative first commercial project of 50 units. Considering that the rated capacity for utility-scale wave energy technologies usually ranges from 200-1,500 kW [205], this means between 10 and 75 MW. The array size lies in the capacity range used for commercial farm cost estimation [259]. The wave farm model should describe deployment site characteristics, such as wave conditions, water depth, distance to the shore and seabed type. A full description of data formats for the intended site is given in [260].

The first breakdown level fully aligns with the general LCOE equation. Due to the emerging nature of this technology, it is assumed that the annual O&M costs and energy production will remain constant during its lifetime. This is a common hypothesis in most techno-economic models and is reasonable, provided the long-term average system uptime and site resource are used to calculate energy. In this case, the simplified LCOE can be represented using a similar expression to Eq. (8) presented in CHAPTER 4 [261]:

$$LCOE = \frac{CAPEX \times FCR + OPEX}{AEP} \tag{24}$$

where *CAPEX* is the capital expenditure, *FCR* is the fixed charge rate, *OPEX* is the annual operating expenditure and *AEP* is the annual energy production, which represents the average net annual energy generated (after accounting for availability) and delivered to the grid.

A brief description of this breakdown is provided in the sections below.

CAPEX

CAPEX can be broken down into farm development costs, financial costs, and all the expenditures associated with the manufacture, installation, and commissioning of both the Wave Energy Converters (WEC) and the Balance of Plant (BoP).

Development costs comprise engineering (e.g. project management, design engineering, planning and certification) and permitting services (e.g. environmental studies, consenting and licenses). Financial costs include insurance during construction and decommissioning bonds.

The generic WEC system breakdown [56] has been used to structure the costs of WEC and BoP manufacture. The WEC contains:

- The Hydrodynamic System, comprising structural elements, ballast, and ancillary systems (e.g. navigation lights, bollards and deck crane).

- Power Take-Off (PTO), including the prime mover (mechanical, pneumatic, hydraulic or direct drive), electrical generator, short-term storage, and power electronics.
- Instrumentation, control, and safety systems, ranging from sensors, comms, control software, cooling, lubrication, firefighting and back-up power.

On the other hand, the BoP includes all the supporting infrastructure and auxiliary systems of the wave farm needed to deliver the energy other than the WEC itself [262], i.e.:

- Station Keeping, including the foundation (e.g. anchors and piles), mooring lines for compliant systems or substructure for rigid systems.
- Grid connection, comprising the umbilical, intra-array and export power cables.
- Offshore substation and switchgear

The installation and commissioning cost of the WEC and the different subsystems comprising the BoP are considered.

A basic estimate of some of these costs, such as development and financial costs, can be expressed as a percentage of total CAPEX costs. Guidance can be found in [263], where Têtu and Fernandez Chozas performed a comprehensive literature review to build a cost database for wave energy projects. However, as we will see in section 6.3.3, whenever feasible, it is much better to use more sophisticated techno-economic methods to increase the accuracy of the cost estimations.

OPEX

OPEX is usually measured on an annual basis. These costs can be broken down into Operation and Maintenance (O&M) costs, the site lease and insurance during operation. Costs related to site lease and insurance are self-evident. Insurance transfers the risks associated with replacing faulty components during the underwritten period (usually five years).

O&M costs include servicing the WECs and BoP. Depending on the ability to plan the activities, these costs can be split between:

- Scheduled maintenance, which includes periodic inspections and preventive actions.
- Unscheduled maintenance, which comprises all corrective actions to restore the operational capabilities of the farm and the logistical cost of waiting for a suitable weather window.

Again, when data is scarce, OPEX can be estimated as a percentage of CAPEX [263]. This is a basic estimate with high uncertainty. As the technology developer starts designing operational plans, techno-economic estimations based on the failure rate of components and subsystems, vessel cost, operation time and the cost of spares should be a more appropriate tool to improve the accuracy.

Financial assumptions

A key consideration for utility-scale renewable energy technologies is the impact of the availability and cost of capital on LCOE values. The two main parameters are the discount rate (a proxy of the cost of capital) and the project's lifetime.

Assumptions of discount rates are crucial for assessing wave energy technology and investment decisions. However, they are subject to a significant degree of uncertainty since the expectations and risk perceptions of investors and project sponsors differ significantly. Discount rates are often estimated using the Weighted Average Cost of Capital (WACC) [264]. The WACC gives an estimate of the cost of raising capital, which is equivalent to the approximate return required by potential creditors (debt) and investors (equity).

The simplified LCOE expression uses the Fixed Charge Rate (FCR) [213], which depends on the discount rate and project lifetime as defined per Eq. (9) in CHAPTER 4.

AEP

Calculating net AEP should closely follow the IEC's Technical Specification 62600-100 “Electricity producing wave energy converters - Power performance assessment” [138]. Assumptions regarding the wave energy resource at the intended deployment site and the numerical method for estimating performance should be documented and justified. Remarkably, the estimations should account for losses due to directionality, shallow water, array interaction effects, and WEC ancillary energy consumption needs.

Following Equations (8) and (24), the AEP is the product of the average total hours in a year (8,766), the rated power of the array (P), the capacity factor (CF) and the availability (AF).

CF represents the ratio of the energy produced by the technology continuously operating over a year compared to the energy that could have been produced at the rated power during the same period. In turn, CF can be computed as the product of the device capture efficiency (i.e. the ratio of absorbed and rated power), the conversion efficiency (i.e. the ratio of converted and absorbed power) and the transmission to grid efficiency (i.e. the ratio of grid and device output power).

AF is the fraction of time in a year that the wave energy technology can produce energy [265]. By convention, the zero production periods (i.e. wave resource lies below or above certain limits) are counted against the CF but not against the AF.

6.3.3 Cost Escalation

For commercial technologies, the costs of a farm project are commonly calculated based on quotes or published data. When costs are not readily available, they can be estimated using engineering handbooks and numerical models. However, the direct estimation method might be misleading for emerging technologies not yet built commercially due to the associated uncertainty in cost appraisals. Estimating initial costs is paramount since it will determine the additional spending required for emerging technology to be cost-competitive.

LCOE estimates of wave energy technologies can vary widely across studies depending on the external properties and the analysis methods' complexity [256]. Both aspects were highlighted in the previous step. For a correct interpretation of results, it is essential to carefully examine the underlying assumptions of farm size, deployment site characteristics, cost of capital, materials and service vessels.

The current step of the method deals with a third source of variability, namely the uncertainty of the input data for the wave energy farm model. Assigning a range with a nominal confidence band is a good practice providing much more useful information for decision-making. However, emerging technologies imply that little experience is available in the sector to assign uncertainty ranges to costs.

Several strategies can be used to allocate expected accuracy ranges into estimations based on expert judgement. Previsic [179] assigns uncertainty ranges as a double function of the stage of technology development and the source of input data for estimating wave energy technologies. Hence, estimation accuracy may vary from -30% to +80% for simplified estimations and technologies at the concept stage and from -5% to +5% for detailed estimates of mature technologies. Fernandez-Chozas [227] applies Previsic's uncertainty ranges to the AEP data for each development stage and source of performance estimates (i.e. power matrix and standard sea states). Likewise, organisations including EPRI [266], the DOE [267] and the Association for the Advancement of Cost Engineering International (AACE) [268] have defined several cost estimate classes ranging from "simplified" to "finalised". Parsons [269] performed an exhaustive review and comparison of cost contingency practices and standards to conclude that AACE represents the best industry practice. Cost estimation should require increasing levels of effort (and expense) as the technology moves from concept and preliminary design to demonstration and replication.

The ability to properly combine uncertainties from different cost factors is crucial. The individual estimates and their uncertainties can be combined statistically provided they can be calculated with statistical techniques. Rothwell [270] shows that the current engineering guidelines are consistent with contingencies equal to the standard deviation of the cost estimate. Using a lognormal probability distribution, he derives the standard deviation from an 80% confidence level since most cost estimate accuracy ranges are non-symmetric. This is because final costs are usually higher than those estimated, and there is no probability that the final cost will ever be less than zero (a possibility with the normal distribution).

Table 6.1 presents the suggested contingencies and expected accuracy ranges used by current engineering guidelines for the different types of cost estimates and the corresponding lognormal property fit of the uncertainty ranges. Statistical properties have been normalised by the mode, the most likely estimate. The median represents the 50% probability, indicating the basic uncertainty factor. The standard deviation (Std) has been adjusted with reference to the upper bound in AACE guidelines for an 80% confidence level interval. It can be noted that the statistical fit results in an Std within the range of the expected accuracy values except for the final estimate, in which it is slightly lower.

Table 6.1: Suggested contingencies and lognormal properties of uncertainty ranges normalised by mode (adapted from [270]).

Type of Estimate	**AACE**			**Statistical Properties**			
	Class	**Contingency**	**Accuracy range**	**Median**	**Mean**	**Std**	**80% Confidence**
Concept	Class 5	50%	-50% to +100%	1.159	1.249	43%	-33% to +101%
Simplified	Class 4	30%	-30% to +50%	1.068	1.104	27%	-24% to +51%
Preliminary	Class 3	20%	-20% to +30%	1.031	1.047	18%	-18% to +30%
Detailed	Class 2	15%	-15% to +20%	1.017	1.025	13%	-14% to +20%
Final	Class 1	5%	-10% to +15%	1.005	1.007	7%	-8% to +10%

Assuming the independence of each factor, the probability distributions can be combined. This is particularly simple if each distribution can be treated as lognormal. In such instances, the final distribution is also lognormal with the logarithmic standard deviation given by the square root of the sum of squares of the individual geometric standard deviations. Moreover, the error propagation technique can combine uncertainties from multiple variables in the techno-economic expressions of the wave energy LCOE model.

The final uncertainty estimation in the LCOE is not direct, but it is calculated employing its formula involving CAPEX, OPEX, FCR and AEP. These factors were derived in Step 1 using basic parametric relationships. Error propagation is used to calculate the aggregated uncertainty in a cascading manner from the lowest level of the standard cost and performance breakdown. For instance, the structural cost of the hydrodynamic system can be calculated from three techno-economic variables: the unit cost of the main raw material (€/kg), a coefficient to account for the manufacturing complexity (-), and the structural weight (kg). Ranges of uncertainty in the material unit cost (exogenous factor), maturity of manufacturing processes (suppliers' capability) and estimation of the structural weight (design accuracy) will determine the aggregated uncertainty in the estimation of the hydrodynamic system cost, in this case, the geometric mean of the standard deviations. This estimate will be combined with other capital expenditures to derive the uncertainty in the WEC, farm CAPEX and the LCOE.

6.3.4 Projection of Future Costs

The methodology's third and final step involves applying learning curves to project the future costs of wave energy technology once it has been sufficiently replicated and the estimation of uncertainties in the forecast due to learning.

Often, combinations of technological learning occur at each stage, and their contributions may change during the development of technology over time. Furthermore, single-factor learning curves do not necessarily describe the underlying cost reduction factors [255]. Some components and subsystems in wave energy farms, such as electrical infrastructure and offshore operations, are not entirely new to the market. They build on the experience gained from more mature sectors.

A disaggregated approach accounting for individual learning effects at the component level can lead to improved cost reduction estimations for emerging technologies which lack historical data. It can use past learning rates for direct comparable technologies to build a composite learning rate. In addition, it can break apart the impact of raw material (an exogenous parameter) from other cost reductions due to cumulative experience.

Learning rates in the literature for wave energy technologies mainly rely on expert judgements, expectations and assumptions. They differ widely even at the subsystem level [271]. Overall LRs range from a low 9% [272] to an optimistic 30% [168]. Component-based learning rates range from 1% to 12% [259]. Finally, SI Ocean [273] included a learning rate of 3% for the capacity factor in their LCOE projections.

Since there is little empirical evidence to establish the learning rates for WEC technologies, the component-based learning approach used in this work allocates them depending on the stage of development of the individual components. Three main categories are defined:

- **Mature components**. These technologies already established in the market have well-known characteristics and limited potential for cost reduction. Low learning rates of 0-5%. E.g. export power cables.
- **Evolving components**. These have niche market commercialisation and significant potential for cost reductions. Medium learning rates of 5-10%. E.g. prime mover.
- **Emerging components**. These have not been commercialised yet but have a high potential for cost reductions. High learning rates of 10-20%. E.g. maintenance operations.

The upper bound of learning rates is consistent with analyses such as the PelaStar cost of energy [274] and WaveBoost [275]. In these studies, the technological maturity of each major cost item is categorised as “mature,” “emerging,” or “nascent/emerging 2”, with 5%, 10% and 15-20% learning rates respectively. The lower bound refers to more conservative analyses such as NEMS [276]. Technologies classified as “conventional”, “evolutionary” and “revolutionary” are assigned 1%, 5% and 10% learning rates correlatively.

Assigning error margins to LRs is recommended to avoid overrepresentation in cost reduction estimates [277]. Forecasts are highly sensitive to uncertainties in the progress ratio (b). As in the previous step, the error can be calculated from the error propagation method [254] taking partial derivatives with regard to b in Equation (*23*):

$$\delta LR = \frac{\partial(1-2^{-b})}{\partial b}\delta b = ln2 \cdot 2^{-b} \cdot \delta b = ln2 \cdot LR \cdot \delta b \tag{25}$$

Where δb is the uncertainty in the experience parameter and δLR is the resulting uncertainty.

Technology cost reduction cannot be realised continually. There will be a bare minimum or baseline cost necessary to build a technology. As suggested in the previous section 6.3.3, segregating the price of raw materials from the estimation of manufactured component costs is a recommended strategy to prevent this situation.

6.4 Practical Implementation

6.4.1 Case Study: Reference Model 5

The application of the proposed cost estimation methodology is illustrated with the help of one of the Reference Models (RMs) for wave energy technologies [176]. The RM project team, led by Sandia National Laboratories, included a partnership between the US Department of Energy, the National Renewable Energy Laboratory (NREL) and other US laboratories. The RMs provide a non-proprietary open-source instrument for technical and economic assessment, validation of design tools and identification of cost reduction pathways and research priorities to meet the affordability targets. The wave energy models [214] reproduce three common archetypes, namely a heaving point absorber (RM3), an oscillating wave surge converter (RM5) and an oscillating water column (RM6).

The present case study is based on the RM5, a floating oscillating wave surge converter (OWSC) designed for a wave site near Eureka in Humboldt County, California. The OWSC is one of the most promising wave energy technologies in terms of its energy absorption capabilities [240]. It consists of a vertical flap facing the waves and is articulated in its lower part for rotation. The surge motion of waves creates a back-and-forth movement from which energy is extracted [2]. Several OWSC designs have been proposed, including AW-Energy's WaveRoller [36], Aquamarine Power's Oyster [278], Resolute Marine's Wave$_2$O [279] and Langlee's Robusto [280]. The floating version of OWSC tackles the potential environmental restrictions of shallow nearshore waters while opening the way to harness the higher wave energy resource in deep-water sites [281].

Figure 6.5 shows a schematic of the floating OWSC device. The flap rotates against the supporting frame to convert wave energy into electrical power from the motion induced by incoming waves. An oleo-hydraulic PTO with two rams, high-pressure accumulators, an electrical generator and corresponding switchgear transform the oscillation into electrical power. The device is tension-moored to the seabed in deep waters (50 to 100 m) through four tendons.

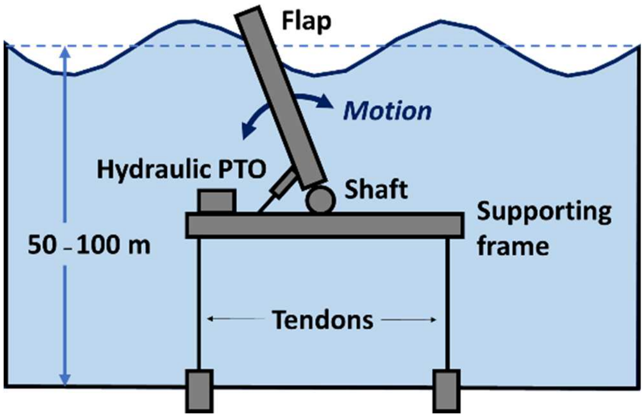


Figure 6.5: Schematic of the RM5 floating OWSC.

NREL created a techno-economic model for assessing the LCOE with multiple scenarios ranging from a single RM5 device to arrays of 10, 50 and 100 units [282]. To estimate future costs, this case study uses the cost breakdown of the 50-unit farm model, which represents the first commercial project. The RM5 has a rated capacity of 360 kW, which results in an 18 MW wave energy farm.

The array configuration is depicted in Figure 6.6. A staggered configuration with 600 m spacing between the devices to accommodate moorings is considered to avoid collisions with vessels and produce negligible hydrodynamic losses. As shown in the figure, groups of 10 devices are interconnected by umbilical cables. Electricity is then transmitted to a junction box. Intra-array cables connect the five junction boxes. Lastly, a three-phase AC export cable delivers energy to the shore. Cable landing is accomplished by using directional drilling. Close to the deployment site, there is a port with facilities well-suited for installation and maintenance activities and a 60 kV onshore substation.

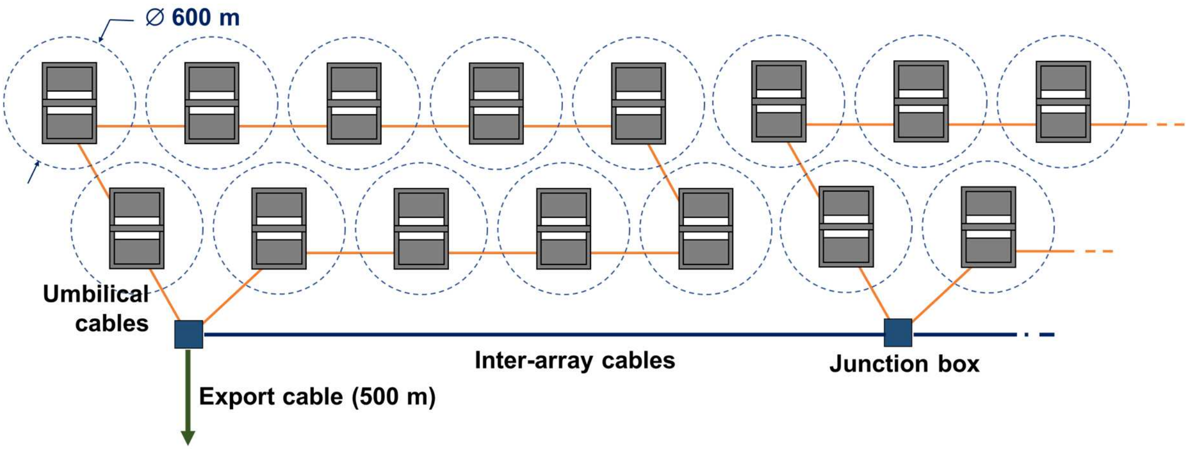


Figure 6.6: 50-unit farm array layout (not drawn to scale).

The key design parameters and main assumptions are included in Table 6.2. Further details of the RM5 design can be found in [281].

Table 6.2: Case study specifications

Category	Parameter	Specification
Site	Water depth	70 m
	Seabed	Soft sediments (sand and clay)
	Wave resource	30 kW/m, unidirectional
	Distance to shore	500 m
Device	Rated power	360 kW
	Hydrodynamic system	Flap (25 m x 19 m), shaft (∅3 m); fiberglass and steel
	PTO	Oleo-hydraulic (2 rams, HP accumulators, hydraulic motor, generator)
	Control	Optimal velocity-dependent damping per see state
Balance of Plant	Station keeping	Steel frame (45 m x 29 m), four polyester lines & suction anchors
	Grid connection	Umbilical, inter-array and export (30 kV); terminators and connectors
Array	Device spacing	600 m
Performance	Capture efficiency	37%
	Conversion efficiency	82%
	Transmission efficiency	95%
	Availability	98%
Financial	Discount rate	8.8%
	Project lifetime	20 years

6.4.2 Cost and Performance of the 50-Unit Farm

NREL's model for the 50-unit farm results in an estimated LCOE of \$0.78/kWh [282]. The proposed method yields a slightly lower estimate (\$0.72/kWh) due to the 10% contingency in CAPEX costs included in NREL's model. Contingency is a consequence of the propagation of uncertainties, which is accounted for in Step 2 (section 6.4.3).

The detailed breakdown of CAPEX and OPEX costs, financial assumptions and annual energy production taken directly from the RM5 model are presented in Appendix F: RM5 Breakdowns. This cost breakdown includes the modelling basis directly extracted from [282].

The resulting percentage contribution to the lifetime costs of the main cost centres is shown in Figure 6.7.

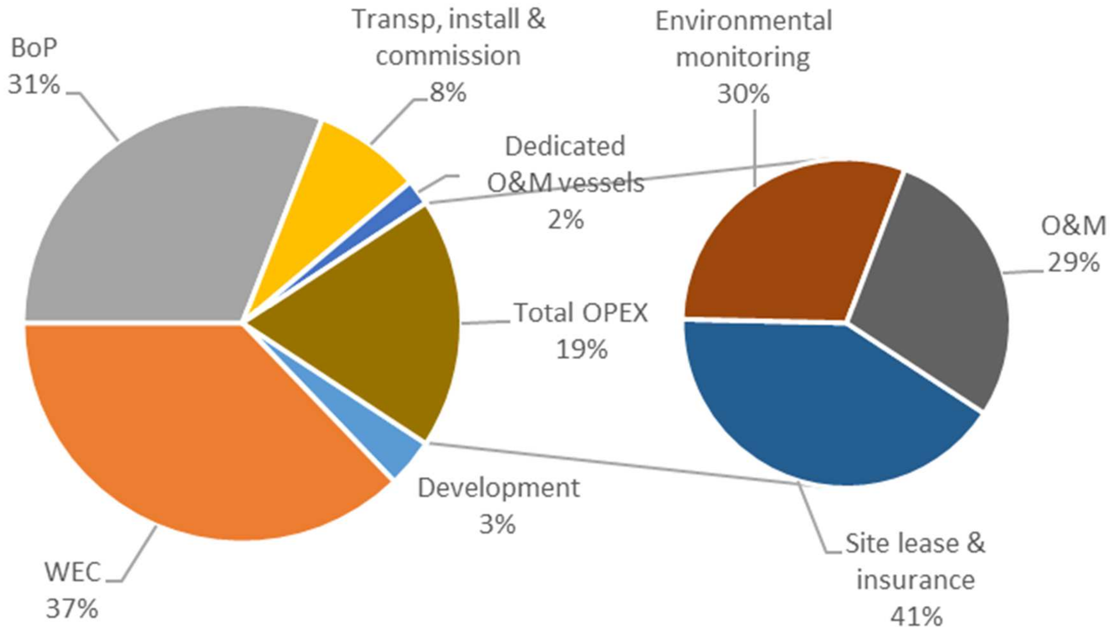


Figure 6.7: Breakdown of costs for the RM5 farm. Left: percentage of total lifetime costs; Right: distribution of OPEX costs.

As observed, WEC cost (37%) is the greatest contributor to overall lifetime costs, particularly the hydrodynamic system, due to its considerable weight (499 t). BoP cost (31%) is the second contributor to lifetime costs with particular relevance to the substructure cost (weighting 301 t), mooring lines, anchors and piles.

Total OPEX cost (19%) is the third significant contributor. In this case, the site lease, insurance and environmental monitoring have more relevance than the O&M cost. Moreover, the forecasted scheduled maintenance cost is prevalent to the unscheduled ones.

6.4.3 Cost Escalation to Account for Uncertainties

The RM5 model has inherent uncertainties regarding performance, design and economics. NREL conducted a qualitative uncertainty assessment of both design and performance [281]. Levels of uncertainty, from low to very high, were assigned to various components of the model depending on whether this facet was assessed using test/field data (low), modelled data (medium) or engineering judgment (high). Aspects not addressed were assigned a “very high” level of uncertainty.

This qualitative assessment has been mapped to AACE’s uncertainty classes and corresponding quantitative Standard Deviation (Std). Sometimes “low to medium” and “medium to high” levels of uncertainty were used. In these cases, an average value between the two adjacent classes is assumed, as shown in Table 6.3. None (0%) is only used whenever the parameter has no implicit uncertainty.

Table 6.3: Uncertainty categories, associated standard deviation and 80% confidence intervals.

Uncertainty	**AACE**	**Std**	**80% Confidence**
Very high	Class 5	43.0%	-33% to +101%
High	Class 4	27.0%	-24% to +51%
Med/High	-	22.5%	-21% to +40%
Medium	Class 3	18.0%	-18% to +30%
Low/Med	-	15.5%	-16% to +25%
Low	Class 2	13.0%	-14% to +20%
Very low	Class 1	7.0%	-8% to +10%
None	-	0.0%	–

Uncertainty is propagated upwards in the breakdown structure using the generic Equation (21) until a final LCOE is obtained. The method comprises four specific categories of functions:

- **Addition of several components** (applicable to CAPEX and OPEX cost centres). The absolute uncertainty is the geometric mean of individual absolute uncertainties.

$$\delta q = \sqrt{(\delta x)^2 + \cdots + (\delta z)^2} \tag{26}$$

- **Multiplication or division of several components** (applicable to AEP). The relative uncertainty is the geometric mean of the individual relative uncertainties.

$$\frac{\delta q}{|q|} = \sqrt{\left(\frac{\delta x}{|x|}\right)^2 + \cdots + \left(\frac{\delta z}{|z|}\right)^2} \tag{27}$$

- **Financial uncertainty** with a variable discount rate (d) and constant lifetime (y). Differentiation of the FCR with respect to the discount rate.

$$\delta q = \frac{(1+d)^{y-1}((1+d)^y + d((1+d)^y - y - 1) - 1)}{((1+d)^y - 1)^2}\,\delta d \tag{28}$$

- **Uncertainty in LCOE**. A sequential combination of multiplication (CAPEX x FCR), addition (OPEX) and division (AEP) computed with the help of Equations (26) and (27).

The detailed results are presented in Appendix F: RM5 Breakdowns. Following this procedure, the LCOE results in an upper and lower bound of $1.33/kWh and $0.50/kWh respectively. The standard deviation (Std) of the LCOE uncertainty is 38.2%, which indicates the contingency to be considered. Figure 6.8 displays the resulting uncertainties for the high-level components in the LCOE equation.

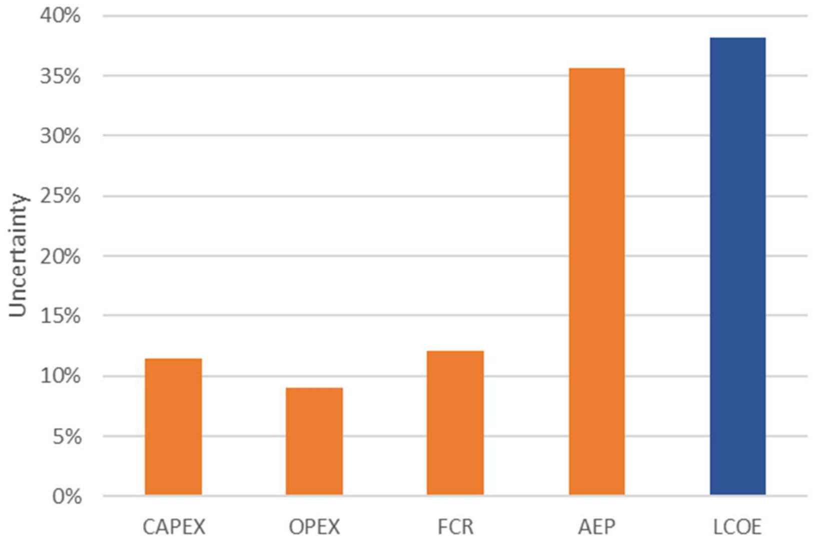


Figure 6.8: Uncertainties of the high-level components in the LCOE equation. Note that LCOE uncertainty is propagated and not simply added.

It can be noticed that the AEP is the most significant contributor to global uncertainty. The rest of the components in the LCOE [Equation (24)] are slightly above 10%, which reasonably matches the assumption above of contingency in NREL's model. For the sake of comparison, it is also worth mentioning that NREL's model estimates \$1.44/kWh for a small array of 10 units [282].

6.4.4 Projecting the Future Cost of Mature Technology

The methodology's last step involves optimising the current version of the technology through learning by doing and economies of scale (endogenous factors) leading to cost reduction. Learning is proportional to the installed capacity, impacting the CAPEX, OPEX and, to a certain extent, the AEP. Component-based learning rates are applied to the upper bound obtained in the previous step. In this case study, LCOE results are projected once 1 GW of the emerging technology has been deployed. The selection of 1 GW installed capacity allows comparison with JRC forecasts [3]. NREL's model provides component-based learning rates for the PTO. Other cost centres, only provide a qualitative indication depending on the predicted innovation potential [281]. A baseline cost has also been included marking a hard threshold beyond which no more learning would be possible. This baseline is based on the 100-unit model, corresponding to a fully commercial project.

The component-based learning rates are classified into three main categories according to the technology type as shown in Table 6.4. Learning rates of mature technologies are matched with low uncertainty, whereas evolving and emerging technologies are assumed to have medium and high uncertainties. The same standard deviations as in Table 6.3 are used.

Table 6.4: Component-based LR, uncertainty and standard deviation

Technology type	Learning Rate (LR)		Uncertainty	Std
	From	Up to		
Mature	0.0%	5.0%	Low	13%
Evolving	5.0%	10.0%	Medium	18%
Emerging	10.0%	20.0%	High	27%

Detailed results are shown in Appendix F: RM5 Breakdowns. Component-based projections are combined using the same basis in Table A.14 to derive the corresponding LRs at the immediate upper level. This process is repeated until the aggregated LR (10.6%) is finally obtained. Figure 6.9 displays the resulting LR for the high-level components in the LCOE equation. The proposed method estimates the future cost of energy at \$0.69/kWh. The suggested baseline cost is \$0.62/kWh, higher than the lower bound of \$0.50/kWh identified in Step 2. Finally, NREL’s 100-unit model estimates the same cost of \$0.69/kWh [282].

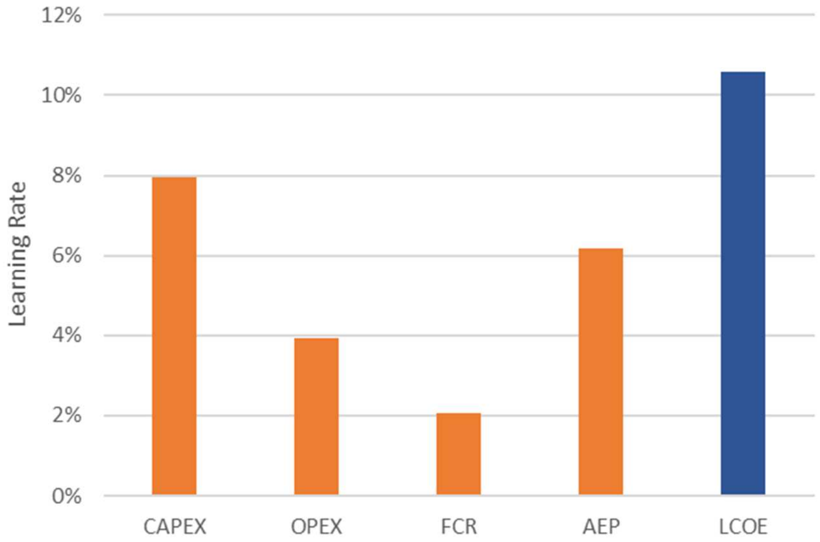


Figure 6.9: Learning Rates (LR) of the high-level components in the LCOE equation. Note resulting LR for the LCOE is propagated and not simply added.

Based on Table 6.4, a 10.6% LR implies a medium uncertainty of 18.5% in the cost reduction exponent (δb). Using Equation (25), the LR uncertainty is rescaled to 12.8% (low). Taking an 80% confidence interval as per Table 6.3 would result in an LCOE within \$0.60/kWh and \$0.83/kWh.

Despite the significant cost reduction that can be achieved through learning, the projection of future commercial costs for the RM5 technology is still far from the SET Plan €0.15/kWh target for 2030 since the starting cost for this emerging technology is well above this target. A closer look at the case study results unveils two main factors for the discouraging result leading to a very high projection of costs.

On the one hand, the AEP is subjected to significant uncertainty (35.7%) penalising the LCOE from which learning can start. The lowest bound in Step 2, \$0.50/kWh, remains far from the SET Plan target for wave technologies. On the other hand, the baseline costs are established for the 100-unit farm, limiting the ability to capitalise on cost reductions through component-based learning beyond a certain deployment level. This outcome reinforces the recommendation for technology developers to deploy R&D activities to collect evidence that can reduce the uncertainty regarding the availability factor, the capture efficiency and baseline costs since they will significantly lower the overall uncertainty in the LCOE and open the way to a starker cost reduction.

6.5 Conclusions

Direct quantification of the LCOE is unsuitable for prototype technology. This chapter described a unique strategy for estimating the future costs of emerging wave energy systems that avoids the human tendency to overestimate costs. It enhances the IEA-OES international evaluation framework [142], which identifies the LCOE as the highest-level affordability criterion but does not specify how to perform such an estimation.

Compared with current cost estimation approaches, it offers a tool for exploring uncertainties, focusing on the cost estimate accuracy and quantifying the potential learning since the initial development phases. Furthermore, this approach provides useful information for identifying remaining technological challenges, concentrating innovation efforts and collecting evidence through testing activities. This is significant since there are currently 87 active wave energy developers, with 60% still in the early stages [30].

A case study is used to highlight this innovative method. The primary information needed to apply this approach is available from the Reference Model Project [176]. Results indicate that the uncertainties are in the same range as potential future learning, which leads to a future cost that is comparable to the initial LCOE estimation. It is important to focus technology development efforts on bridging the cost and performance knowledge gaps.

The case study outcomes just represent one potential trajectory an emerging technology may go through in its future cost projection. The approach detailed before can be replicated with other wave energy typologies, such as Reference Models 3 and 6 [176], leading to different results. Figure 6.10 shows three possible situations that might be expected by mixing various amounts of uncertainty (U) and learning capacity (L).

(a) **Uncertainty overweighs potential learning (U > L).** This path results in a long-term cost forecast in Step 3 that is greater than the initial LCOE. The LCOE computed in Step 1 should be much lower than the energy price in the target market. Otherwise, major modifications in emerging technology are required. As long as technological advancement continues, efforts should be directed at gathering data that reduces the cost estimation uncertainty in Step 2. If successful, the LCOE reassessment at the next development stage should be in either scenario (b) or (c).

(b) **Uncertainties at a similar learning capacity range (U ≈ L)**. Similar future cost projections are produced by this scenario as by the original LCOE assessment in Step 1. There is still space to close the important cost and performance information gaps for developing technologies with a high level of uncertainty, like the RM5. Again, if efforts are successful, scenario (c) should be the result of the LCOE reassessment at the following development stage. However, to achieve the commercial objectives, either technologies with relatively low levels of uncertainty and learning capacity should show an LCOE in Step 1 below the energy price in the targeted market, or technological advances should be made.

(c) **Uncertainty is outweighed by learning capacity (U < L)**. A stronger capacity for learning creates a more favourable environment for new technologies. The cost prediction for the future will be less than the preliminary estimate from Step 1. If the long-term estimate from Step 3 is less than the energy price in the target market, the technology can move on to the following stage of development without significant adjustments. When LCOE is reassessed, care must be taken to ensure that the emerging technology is not trapped in scenarios (a) or (b) above.

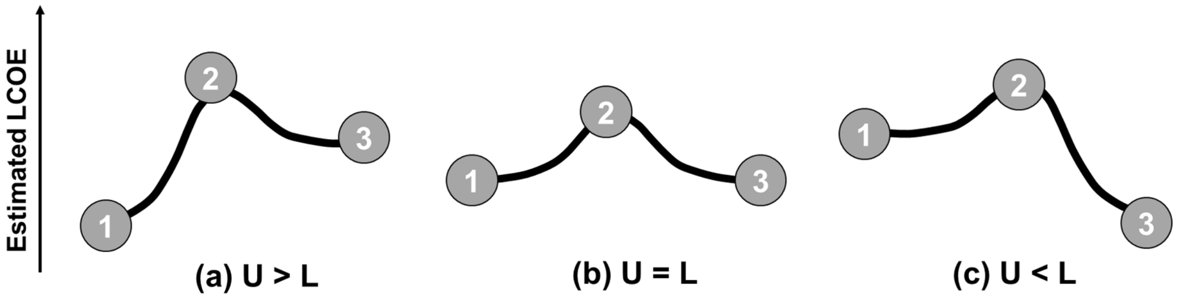


Figure 6.10: Emerging technology cost trajectories with three distinct levels of uncertainty (U) and learning capacity (L). The numbers ①②③ relate to methodological steps, depicted in Figure 6.3.

The economics of new wave energy systems might be increased by combining them with other marine space activities, such as wind energy farms, marine aquaculture or offshore oil & gas platforms. The use of shared infrastructure will significantly lower future cost estimates. If connected to the same onshore grid point, the cost centres might be the structural systems in the case of fixed devices integrated into breakwaters and existing platforms or the electrical components for any device. Although this strategy can reduce the LCOE, it is important to note that because the AEP is the major contributor, the overall level of cost estimation uncertainty will not be significantly modified.

The standardised breakdown of CAPEX, OPEX, FCR, and AEP was able to identify the most significant sources of uncertainty with the use of the error propagation approach. Enlarging the number of components in Equation (26) reduces the relative uncertainty, which implies that increasing the breakdown levels in CAPEX and OPEX is a viable approach for improving the quality of future LCOE estimates.

The error propagation method proved useful in identifying the most significant contributors to uncertainty in the standardised breakdown of CAPEX, OPEX, FCR and AEP. Adding several components as per Equation (26) decreases the relative uncertainty, suggesting that expanding the breakdown levels in the CAPEX and OPEX is a valuable strategy to improve the quality of future LCOE projections. However, the product of components defined by Equation (27), such as AEP, will always increase the relative uncertainty, which implies that the emerging technology should strive for greater accuracy of the performance estimations while keeping the number of energy transformation steps in the PTO design to a minimum.

The statistical fit of lognormal features with an 80% confidence interval, drawn from prior research in other engineering applications, produced quantitative values consistent with NREL's cost model assumptions for the CAPEX. The propagated uncertainty found with the suggested technique (11.4%) is close to the 10% contingency estimated by NREL's cost model for the 50-unit RM5 farm. It corresponds to the AACE's Class 2 estimate (i.e. detailed estimate, project definition between 30% and 75%). The suggested cost estimation method also highlights other sources of uncertainty in the OPEX and financial assumptions that can account for comparable contingencies (9% for OPEX and 12.1% for the FCR, respectively) but are considered by NREL. Moreover, AEP's overall level of uncertainty is comparable to that of a simplified estimate (Class 4).

Over-optimism can also be avoided by using component-based learning rates and baseline costs. The standardised breakdown was assigned LRs ranging from 2% (mature) to 20% (developing), yielding a combined LR of 10.6%. Although the quantification is largely qualitative, this indirect estimation assists in finding cost reduction constraints that might be missed if taken into account in the emerging WEC's LR as a whole.

The key advantage of this cost assessment approach is that it offers a clear and verifiable technique to judge whether emerging wave energy technologies could be affordable in the future. It concentrates on the early cost estimates' accuracy. In order to counteract any optimism bias for the first-of-a-kind commercial deployment, the method includes these unknowns as uncertainties rather than oversimplifying the LCOE estimation while there are still major information gaps. Estimating the costs of the first commercial farm is crucial since it affects the additional spending necessary for new technology to be cost-competitive in the market. Starting a cost reduction project from an overly optimistic assumption will result in very unrealistic LCOE values for a mature technology.

Considering a first commercial deployment is beneficial for tracking the evolution of expenses along the development cycle of emerging technologies. It cannot, however, be used to predict the learning investment or the timeframes required to reach future LCOE. As the wind industry has demonstrated, the wave energy sector must reach specific deployment levels before consistent cost reductions can occur. As a result, the estimates will be offset by a few years, and the learning investment necessary to converge to this cost will go up.

CHAPTER 7 OVERCOMING THE CHALLENGES

"Smooth seas do not make skilful sailors"

African Proverb

7.1 Overview

This chapter explores the solutions space and provides structured innovation approaches to overcome the performance barriers identified during the development of wave energy technologies.

Section 7.2 introduces the specific methods and tools used in this step of the methodology. A standard representation of the physical embodiment of wave energy subsystems and interfaces is presented based on the Design Structured Matrix (DSM) functional allocation of capabilities as a means to analyse the structural patterns. Structured innovation methods based on TRIZ are applied to point out potential innovation strategies.

Section 7.3 develops the specific innovation strategies. DSM is used to visualise and better manage system complexity and support the improvement of the wave energy system. On the other hand, TRIZ facilitates innovative concept generation. A ranking of inventive principles, suggested for solving contradictions, is used to point to the most promising innovation strategies.

Section 7.4 describes the practical implementation of this step. First, a comparison of two failed technologies with akin wave energy concepts currently under development is presented to extract useful learnings. Later, the analysis of the three most impactful contradictions and corresponding inventive principles are discussed as a way to identify promising concepts worth exploring.

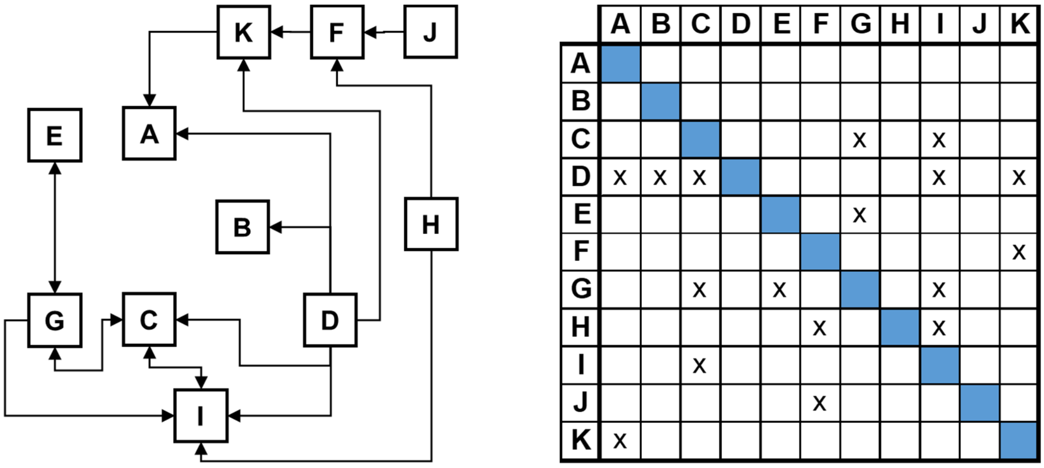
Finally, section 7.5 summarises the chapter and discusses some findings from this novel methodology that might be of interest to the wave energy sector.

7.2 Methods and Tools

7.2.1 Design Structured Matrix (DSM)

Design Structured Matrix (DSM) is a modelling tool used to represent the system design and structure. It was introduced by Steward in 1981 [88] and later extended by Eppinger et al. in 1994 [283]. Compared with other network modelling methods, it provides a condensed, scalable and intuitive description of system architecture. DSM has been applied to model static systems, such as engineering products and organisations, and dynamic systems, such as processes and activities [74].

DSM is a square matrix representation of the system graph. The system elements (graph nodes) correspond to the row and column headings in the matrix. In addition, the element interactions (graph arrows) correspond to the non-null cells inside the matrix. Diagonal elements have no significance and are often blacked out. Figure 7.1 shows a DSM example. The "x" mark represents individual connections among corresponding elements in the system graph.



	A	B	C	D	E	F	G	H	I	J	K
A	■										
B		■									
C			■				x		x		
D	x	x	x	■					x		x
E					■		x				
F						■					x
G			x		x		■		x		
H						x		■	x		
I			x						■		
J						x				■	
K	x										■

Figure 7.1: Example of system graph (left) and corresponding DSM (right).

DSM is related to other matrix methods such as the dependency map, precedence matrix, contribution matrix, adjacency matrix, reachability matrix, and N-square diagram [284].

DSM is a highly flexible system modelling tool. The simplest representation is called a binary DSM [74] since the off-diagonal marks designate the presence or absence of a connection as shown in Figure 7.1. However, the DSM representation can be extended to include further attributes, such as the number of interconnections, and their strength or importance. This extended form is called numerical DSM because it uses numbers, symbols or colours instead of binary marks.

System elements are interconnected through three basic configurations [284], as shown in Figure 7.2. In the parallel configuration, system elements do not interact with each other, are independent and therefore have no relation link. In the sequential configuration, there is a dependence or precedence relationship, i.e. one system element influences another element unidirectionally. A mark above the diagonal represents a forward link, whereas a mark below the diagonal means a backward dependency. Finally, system elements are interdependent in the coupled configuration as the influence is bidirectional.

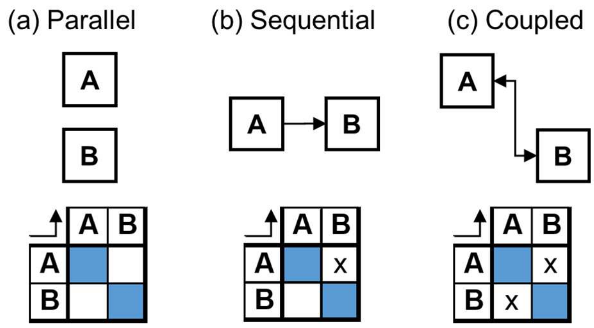


Figure 7.2: Types of interconnections and corresponding DSM representations.

While the convention of "row impacts column" prevails in some DSM applications, the opposite convention, the transposed matrix, can also be used. Both conventions convey identical information, are widely used and can be easily transformed for anyone familiar with the method.

DSM helps engineers better manage system complexity, offering a shared view of a system, enhancing the understanding of causality within the system, and channelling innovation toward useful improvements. The DSM approach to system design and architecture consists of five common steps [74]:

- Decompose the system into its subsystems.
- Document the relationships among the system elements.
- Analyse the structural patterns of elements and implications at the system level.
- Create a proper representation of the DSM.
- Improve the system considering the interpretation of the DSM model.

Clustering is the most common method of analysis when the DSM represents design components. The DSM model is manipulated to find subsets of elements (clusters) that are mutually exclusive or minimally interacting with each other.

7.2.2 Theory of Inventive Problem Solving (TRIZ)

The Theory of Inventive Problem Solving is a systematic approach to innovation, and TRIZ (Teoriya Resheniya Izobretatelskikh Zadatch) is the Russian acronym for this problem-resolution method. It was initially developed by Genrich Altshuller and his school following the statistical analysis of 400,000 patents [233]. This work has been continued, and, at present, TRIZ practitioners have examined circa two million patents worldwide constituting approximately 10% of all patents in the world [285].

TRIZ is built on the assumption that the same problems have been addressed across industries and science fields, and similar solutions have been used repeatedly [285]. Accordingly, creativity means finding that solution and adapting it to the current problem. TRIZ allows looking at problems and solutions more broadly, thus discarding the traditional trial-and-error method.

During the patent analysis, Altshuller identified the fundamental principles underlying technical developments and solutions. The main consideration is that engineering problems could be expressed in terms of a conflict between two design parameters, i.e. improving one parameter will mean worsening the other one. The analysis resulted in a list of only 39 parameters that describe all technical contradictions found in patents, 40 inventive principles consisting of a group of deducted conceptual solutions to technical contradictions, and a 39x39 contradiction matrix that facilitates handling and resolving the intrinsic system conflicts.

The TRIZ approach to problem-solving is represented in Figure 7.3. The current problem is transformed into an existing conceptual problem, and a generic solution that removes the conflicts is identified and then 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.

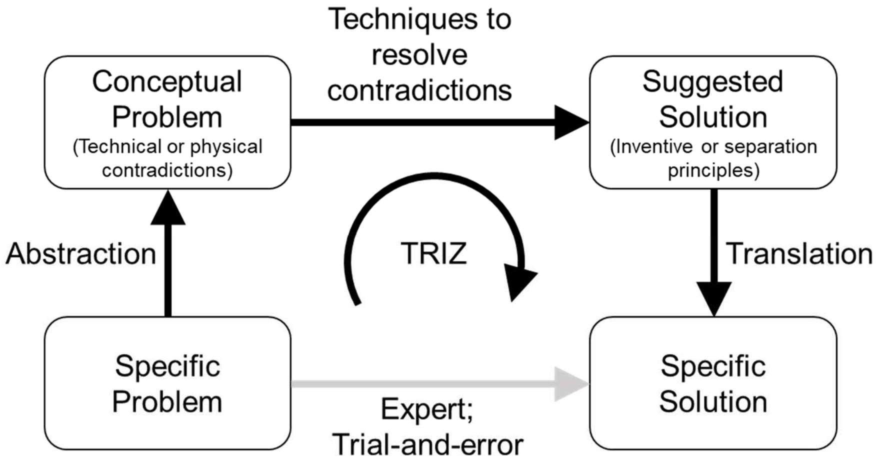


Figure 7.3: The TRIZ approach to problem-solving.

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.

TRIZ is an algorithmic approach based on three main steps.

Step 1: Find technical and physical contradictions

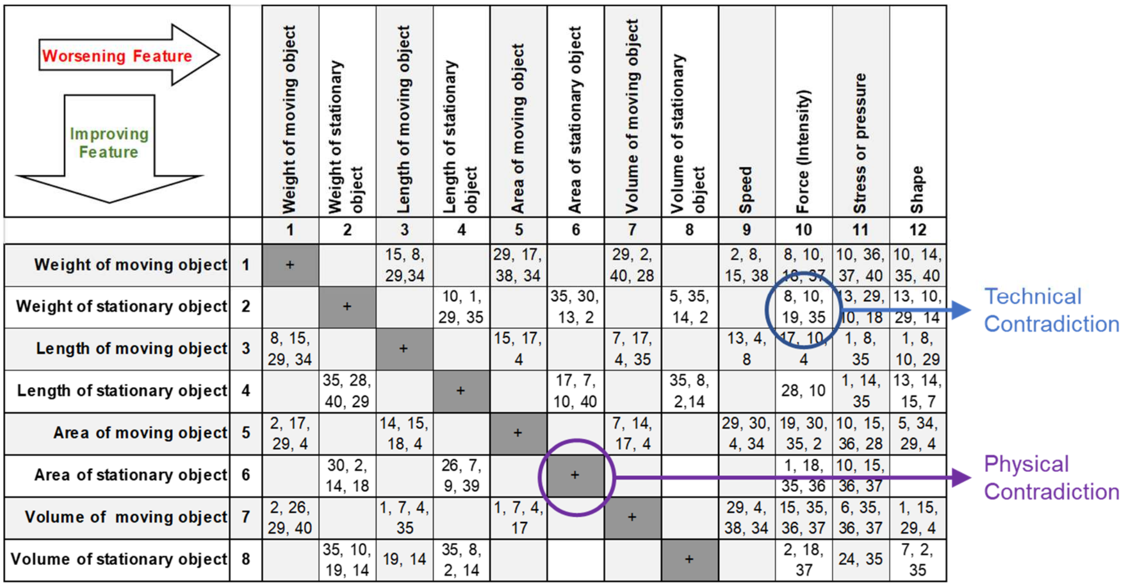
Technical contradictions arise when there is a conflict between two different technical parameters (i.e. when one feature improves, another worsens). Physical contradictions happen when the same technical parameters conflict (i.e. they require opposite solutions). The 39 technical parameters designate features or functions common to engineering systems (Table 7.1). See Appendix C for more detailed descriptions of this list.

Table 7.1: TRIZ 39 Technical Parameters

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

Step 2: Look for the corresponding inventive principles

The contradiction matrix is utilised to solve technical contradictions between two different technical parameters. This matrix identifies which of the 40 inventive principles are relevant to the problem (Figure 7.4). See Appendix D for the full version of the contradiction matrix.



Worsening Feature Improving Feature		Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object	Speed	Force (Intensity)	Stress or pressure	Shape
		1	2	3	4	5	6	7	8	9	10	11	12
Weight of moving object	1	+		15, 8, 29,34		29, 17, 38, 34		29, 2, 40, 28		2, 8, 15, 38	8, 10, 18, 37	10, 36, 37, 40	10, 14, 35, 40
Weight of stationary object	2		+		10, 1, 29, 35		35, 30, 13, 2		5, 35, 14, 2		8, 10, 19, 35	13, 29, 10, 18	13, 10, 29, 14
Length of moving object	3	8, 15, 29, 34		+		15, 17, 4		7, 17, 4, 35		13, 4, 8	17, 10, 4	1, 8, 35	1, 8, 10, 29
Length of stationary object	4		35, 28, 40, 29		+		17, 7, 10, 40		35, 8, 2,14		28, 10	1, 14, 35	13, 14, 15, 7
Area of moving object	5	2, 17, 29, 4		14, 15, 18, 4		+		7, 14, 17, 4		29, 30, 4, 34	19, 30, 35, 2	10, 15, 36, 28	5, 34, 29, 4
Area of stationary object	6		30, 2, 14, 18		26, 7, 9, 39		+				1, 18, 35, 36	10, 15, 36, 37	
Volume of moving object	7	2, 26, 29, 40		1, 7, 4, 35		1, 7, 4, 17		+		29, 4, 38, 34	15, 35, 36, 37	6, 35, 36, 37	1, 15, 29, 4
Volume of stationary object	8		35, 10, 19, 14	19, 14	35, 8, 2, 14				+		2, 18, 37	24, 35	7, 2, 35

Figure 7.4: Finding contradictions in the matrix.

However, the separation principles are used when the same technical parameters (diagonal terms) enter into conflict (Table 7.2). Separation eliminates the contradiction and enables it to meet each conflicting requirement. The numbers in the column are the inventive principles shown in Table 7.3.

When a physical contradiction cannot be resolved with the separation principles, the contradictory requirements can be fulfilled using a new effect (radically changing the system structure) or making the contradictory requirements irrelevant (bypassing).

Table 7.2: TRIZ Separation Principles and Inventive Principles

1	Separate in time	One solution at one time, the opposite solution at another	1, 7, 9, 10, 11, 15, 16, 18, 19, 21, 24,26, 27, 29, 34, 37
2	Separate in space	One solution at one place, the opposite solution at another	1, 2, 3, 4, 7, 13, 14, 17, 24, 26, 30, 40
3	Separate on condition	Opposite solutions in the same place and at the same time; One solution for one element, the opposite for another	28, 29, 31, 32,35, 36, 38, 39
4	Separate by system	System transition; Separate by scale (to sub-system or super-system); Switch to inverse or alternative system	Super-system: 5, 6, 12, 22, 33, 40 Sub-system: 1, 3, 24, 27 Inverse system: 13 Alternative system: 6, 8, 22, 27, 25, 40

Step 3: Select and apply one of the suggested principles

Both physical and technical contradictions can be solved with the 40 Inventive Principles (Table 7.3). See Appendix E for more detailed descriptions of this list.

Table 7.3: TRIZ 40 Inventive Principles

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

There are several ways of grouping inventive principles to work with a smaller set, significantly speeding up the process of finding solutions. Sergey A. Fayer [286] recommends grouping inventive principles into the following four sets:

- **Group 1: Changing substance quantity, quality, structure or shape**. Inventive Principles 1, 2, 3, 4, 7, 14, 17, 30, 31, 40
- **Group 2: Dealing with harmful factors**. Inventive Principles 9, 10, 11, 12, 13, 19, 21, 23, 24, 26, 33, 39
- **Group 3: Increasing effectiveness and ideality**. Inventive Principles 5, 6, 15, 16, 20, 25, 26, 34
- **Group 4: Using scientific effects, special fields and substances**. Inventive Principles 8, 18, 28, 29, 30, 31, 32, 35, 36, 37, 38, 40

Inventive Principles 22 and 27 are not included, and 26, 30, 31 and 40 are listed in two groups. Inventive Principle 22 can be included in Group 2 whereas Inventive Principle 27 may fit in Group 3.

7.3 Innovation Strategies

7.3.1 Background

Despite the international research community's considerable efforts over the last decades, wave energy technologies have failed to achieve the desired design convergence to support their future market growth [164]. Many technical challenges remain unresolved, leading to high costs of energy in comparison with other renewable energy sources. 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.

A systematic problem-solving approach must be embedded from the outset of technology development to meet the high sector expectations [287]. 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.

The previous chapters of this thesis focused on the wave energy problem formulation, assessment and selection with the assistance of sound Systems Engineering (SE) methods:

- Analytic Hierarchy Process (AHP), Quality Function Deployment (QDF) and Functional Analysis have been used to understand the wave energy context and formalise the system requirements.
- Logical Scoring of Preference (LSP), value functions and target allocation have been used to assess wave energy capabilities and guide design decisions.
- Propagation of uncertainties and technological learning facilitates projecting future costs of emerging wave energy technologies.

All these activities provide a means to create awareness of potential technology gaps, identify remaining technology challenges, and concentrate the innovation efforts on improving those areas with the greatest impact on technology performance.

However, searching for solutions is a constructive and creative step in SE. Its goal is to generate solution variants from the results obtained during the problem definition, and whose details are sufficient for the corresponding design stage [79]. The inherent problem difficulty (or size of the solution space) will depend on the ratio of possible variants and the number of acceptable solutions that might exist [285]. In this respect, engineering problems can be classified into different levels of invention [78]:

- **Level 1: The solution is ready**. A proven technology or existing design is used. The solution can be easily obtained using the trial-and-error method and is found within the knowledge base of one profession. As a rule of thumb, no more than ten trials are spent.

- **Level 2: Select a solution**. The solution involves choosing one technology or design out of several ones within the knowledge base of one industry. Up to 100 trials may be needed.
- **Level 3: Modify the solution**. In this case, a known technology or design must be changed. The solution lies within the knowledge base of one scientific field. Up to 1,000 trials may be required.
- **Level 4: Create a solution**. A new technology or design needs to be created to solve these problems. The solution is outside the boundary of the science where the problem originated. Up to 10,000 trials may be needed.
- **Level 5: Discover the solution**. Solving the most challenging types of problems entails the development of new design principles. The solution is outside the boundary of contemporary science and the number of trials could be endless (> 100,000).

Levels 1 & 2 are frequently found at the subsystem and component levels in wave energy. Sometimes, subsystem designs need to be modified since there is no history for the current application (Level 3). As a whole, wave energy systems need a new design (Level 4). Due to the large solutions space to explore, a systematic problem-solving approach is needed.

Initially, functions are allocated to the physical embodiment. Then the Design Structure Matrix (DSM) is used to visualise and better manage system complexity. Finally, the Theory of Inventive Problem Solving (TRIZ) facilitates innovative concept generation.

7.3.2 Design Structure of Wave Energy Systems

The Wave Energy System consist of one or more Wave Energy Converters (WECs) and the corresponding Balance of Plant (BoP). As introduced in Table 2.1, WECs can be further broken down into the following subsystems:

- Hydrodynamic System (HS) to capture energy from the wave.
- Power Take-Off (PTO) to transform it into a useful form of energy.
- Reaction Body (RB) to provide a reaction point for the PTO and/or HS.
- Instrumentation and Control (IC) to control operation.

CHAPTER 2 also presented the alternative PTO configurations. They can comprise up to three power conversion steps for hydraulic options: a primary conversion (1C), a secondary conversion (2C) and a third conversion (3C). On the other hand, direct drive PTO options have a single conversion step.

Storage and Conditioning (SC) can be placed at various points within the WEC or between the WEC and the BoP. Finally, BoP is divided in Station Keeping (SK) to maintain position with respect to the seabed and Transmission System (TS) to deliver energy to the grid.

The hierarchical representation of the wave energy system described above is shown in Figure 7.5.

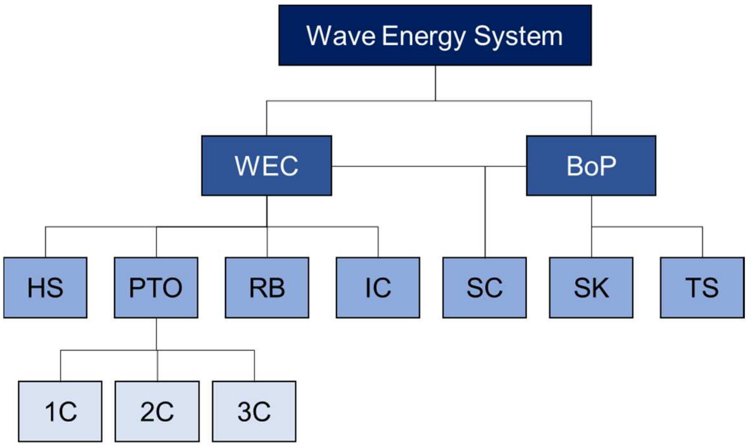


Figure 7.5: Hierarchical representation of the wave energy system

The larger variety across the range of system designs stems from the diversity of subsystems and the various ways to combine them. The wave energy system may comprise one or more units of each subsystem and use different technologies and/or designs for their physical embodiment. Furthermore, the subsystems can be combined among themselves and with the external systems in several arrangements, as shown in the block diagram of Figure 7.6.

The external systems are 1. Ocean waves (W); 2. Seabed (SB); 3. Grid connection (GC); and 4. Plant operator (O).

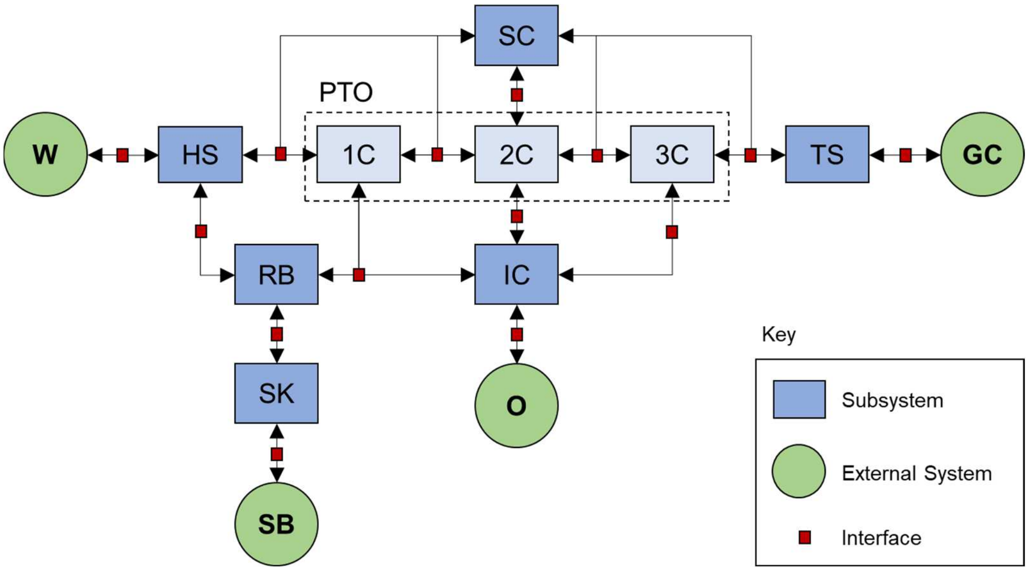


Figure 7.6: Block diagram of the wave energy system with interactions

Interfaces connect two elements of the system to perform the corresponding useful action. Designing the correct physical links and flows will produce the required system functionality. However, the absence of one vital flow may make the system unworkable. Flows can be structured in three main categories [288]:

- **Material flow** provides transportation of substance in different states or objects.
- **Energy flow** transmits loads, forces and power.
- **Information flow** transforms communication signals for control and regulation.

The block diagram shown in Figure 7.6 can be represented in the corresponding DSM model (Table 7.4). The diagonal terms contain the subsystems and external systems, whereas the off-diagonal terms display the connections through the various interfaces. All connections are bidirectional and thus the DSM matrix is axisymmetric. The diagonal terms for the external systems have a zero value to indicate they do not belong to the wave energy system. The two main clusters of the wave energy system are highlighted: WEC (larger square) and BoP (smaller square).

Table 7.4: DSM model for the block diagram from Figure 7.6.

	O	**W**	**HS**	**1C**	**2C**	**3C**	**RB**	**IC**	**SC**	**SK**	**TS**	**SB**	**GC**
O	0							1					
W		0	1										
HS		1	1	1			1		1				
1C			1	1	1		1	1	1				
2C				1	1	1		1	1				
3C					1	1		1	1		1		
RB			1	1			1	1		1			
IC	1			1	1	1	1	1					
SC			1	1	1	1			1		1		
SK							1			1		1	
TS						1			1		1		1
SB										1		0	
GC											1		0

For compactness purposes, a numerical DSM model will be used. The numeric values will indicate the number of subsystems and interfaces in the wave energy system variant under analysis. For instance, a wave energy system consisting of two WECs, each with two hydrodynamic systems (HS) and one direct drive generator (1C) will have a numeric value of 4 and 2 respectively in the diagonal and 4 in the off-diagonal cell.

The DSM model is built as a tool to support system improvement. It visualises the potential problems within the wave energy system. Complex architectures will have a high probability that major changes arise from problems discovered during the later integration phases. Moreover, interface design should not be taken lightly, since a low interface maturity can halve the TRL of the interconnected subsystems [226] and can increase the technology integration risk [289].

The Complexity Score (CS) can be used to measure the integration time and effort due to subsystem interdependencies and interactions [290]. The root square of the original definition by Keating will be adopted here to align with the geometric mean.

$$CS = \sqrt{{M_s}^2 + {I_s}^2} \qquad (29)$$

where M_s is the number of subsystems, and I_s is the number of interfaces. The complexity score for the DSM model with nine subsystems and 20 interfaces represented in Table 7.4 yields a value of 21.93. It is worth noting that the same installed farm capacity should be used to compare different wave energy system architectures.

7.3.3 Establishing Priorities of TRIZ Inventive Principles

As described in section 7.2.2, the contradiction matrix is a useful tool to identify the inventive principles that solve one technical contradiction (i.e. a pair of technical parameters in conflict). Similarly, separation principles can be used to suggest inventive principles for one physical contradiction.

In most engineering problems, it is common to identify several improving and worsening features [291]. Moreover, applying TRIZ to solve a single contradiction may lead to a local optimum, which TRIZ theory calls “local ideality” [285]. When multiple design parameters can simultaneously conflict, a different approach should be implemented to improve TRIZ's global innovation potential.

In 2004, Ivashkov and Souchkov [292] noticed that inventive principles could be ranked according to their number of appearances in the contradiction matrix. Those principles appearing most frequently will have a better chance of 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 [293] added an alternative ranking by counting the frequency of inventive principles 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 [294] and [295], have established the priority of TRIZ inventive principles 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 inventive principles from the contradiction matrix. Moreover, [291] presents an example of inventive principles ranking, involving two improving features and two worsening features, which have been assigned weights.

The methodology developed in this thesis applies QFD to create a traceable prioritisation of Stakeholder Requirements (SRs), Functional Requirements (FRs) and Design

Parameters (DPs). The DPs have been defined by mapping the Technical Requirements (TRs) to the 39 technical parameters in TRIZ. Thus, DPs weightings in section 4.4.3 can be used to rank the inventive principles having the most significant impact on the initial SRs. As DPs have relatively equal importance for the two application markets under consideration, the ranking of inventive principles does not suffer any alteration.

When the aim is to improve a positive feature (i.e. DP), the weightings for the inventive principles (IP), W_{k+}, are computed as follows:

$$W_{k+} = \sum_{j=1}^{10} w_j \sum_{i=1}^{10} k_{ij} w_i \qquad (30)$$

$$k_{ij} = 1 \; if \; IP_k \neq 0$$

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 7.5 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 7.5: 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 and 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:

$$W_{k-} = \sum_{i=1}^{10} w_i \sum_{j=1}^{10} k_{ij} w_j \qquad (31)$$

$$k_{ij} = 1 \; if \; IP_k \neq 0$$

Table 7.6 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 columns of the contradiction matrix and the corresponding importance (W_{k-}) are also included.

Table 7.6: Top-10 inventive principles for the utility market – minimising the impact of a worsening 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 and 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 inventive principles (nine out of ten) are suggested for 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 (see Table 7.5), whereas inventive principle no. 15 “Dynamism” is ranked first when aiming to minimise the impact of a worsening feature (see Table 7.6).

Table 7.7 combines the prioritisation of both objectives into a single ranking.

Table 7.7: 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 and 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”. To apply separation in scale and/or system, it is necessary to get till innovation principle no. 13 “Inversion”.

7.4 Practical Implementation

7.4.1 Learning from Failed Technologies

7.4.1.1 Pelamis vs Mocean

Pelamis P2 and Mocean Blue Horizon are two floating offshore wave energy technologies that employ the hinged contour working principle and are classified as attenuators according to their size and orientation. After Pelamis Wave Power went into administration in November 2014, some former employees founded Mocean in an effort to overcome the technical issues.

Pelamis P2 [296] was an articulated structure of five cylindrical steel sections linked by four hinged modules. The sections moved relative to each other by the action of waves, and the hinges converted this motion using an oleo-hydraulic system. Each PTO module comprised four hydraulic rams, a high-pressure accumulator and two hydraulic motors, which drove two induction generators to produce electricity. The modules fed the electricity onto a high voltage bus-line running along the device ending in the nose-mounted transformer. The machine had a rated power of 750 kW.

Figure 7.7: Pelamis P2 device, pictured at the European Marine Energy Centre, 2011.

The device output was delivered down to the seabed by an umbilical cable, which was joined to a static high-voltage cable to take the generated power to shore [297]. Several devices could be connected through a single static cable. P2 was held in position by a slack mooring system using a combination of steel wire, chain, dead weights and embedment anchors. The reference mooring system consisted of three mooring lines at the front linked to a tethered weight and one restraint line at the rear. This system enabled the machine to weathervane and maintain a heading perpendicular to the predominant wave direction.

In 2009, Pelamis started deploying a farm off the Aguçadoura coast (Portugal). The block diagram of the farm consisting of 4 units (3 MW) is presented in Figure 7.8.

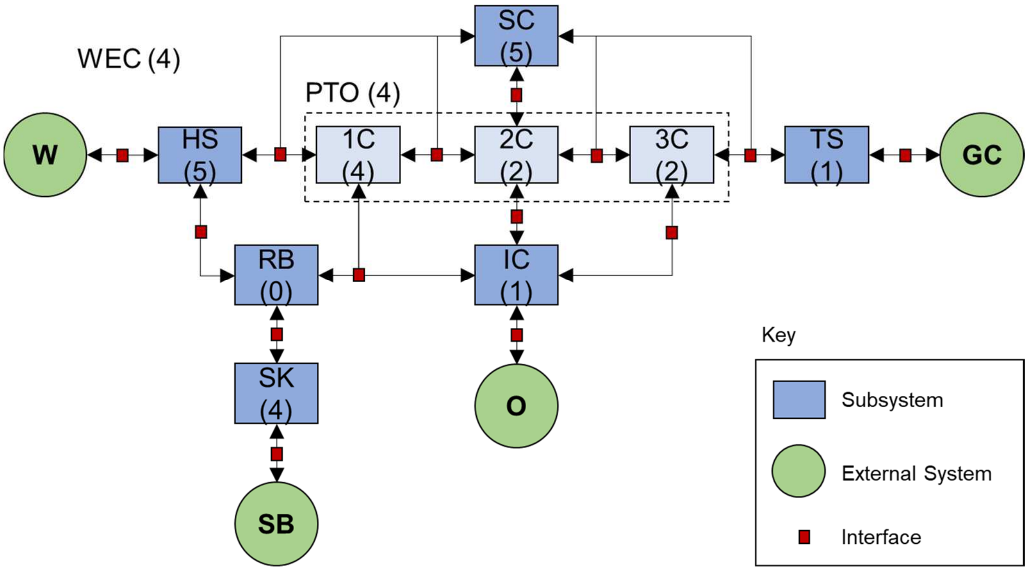


Figure 7.8: Block diagram for the 3 MW Pelamis P2 farm.

Numbers between brackets represent the units needed in the various subsystems. The farm consists of four WECs, each with five HS, four hinged PTO modules, five SC (four accumulators & one transformer), one IC, four SK lines (three at the front, one at the rear) and one TS. There is no RB since it is a self-reference device. Furthermore, each PTO is comprised of 1C (four hydraulic rams), 2C (two hydraulic motors) and 3C (two induction generators). The block diagram shown in Figure 7.8 is represented in the corresponding DSM model in Table 7.8.

Table 7.8: DSM model for the 3 MW Pelamis P2 farm

	O	**W**	**HS**	**1C**	**2C**	**3C**	**RB**	**IC**	**SC**	**SK**	**TS**	**SB**	**GC**
O	0							4					
W		0	20										
HS		20	20	64						20			
1C			64	64	64			64					
2C				64	32	32		32					
3C					32	32		32	32		32		
RB							0						
IC	4			64	32	32		4					
SC						32			20				
SK			20							16		16	
TS						32					4		4
SB										16		0	
GC											4		0

On the other hand, Mocean's Blue Horizon [38] is an asymmetric hinged raft designed to generate electricity at the utility-scale. The forward hull is longer than the aft hull, and both hulls end in sloped plates of different shapes to maximise energy capture. The rotation of the aft hull with respect to the forward hull drives an electrical generator eliminating the need for a gearbox. An umbilical cable connects the device with a subsea hub joined to an export cable. Blue Horizon's rated power can range from 250 kW to 1 MW. The mooring system is made of two identical mooring lines [298]. The two legs are attached to a bridle at the forward mooring point on the device. A swivel allows the device to self-orientate.

Figure 7.9: Mocean Blue X testing (left) and Blue Horizon artistic impression (right).

Blue Horizon has not been deployed to date. A farm of the same installed power will be considered to compare the two technologies. This leads to 12 units of a Blue Horizon 250 kW. A block diagram of such a farm is presented in Figure 7.10.

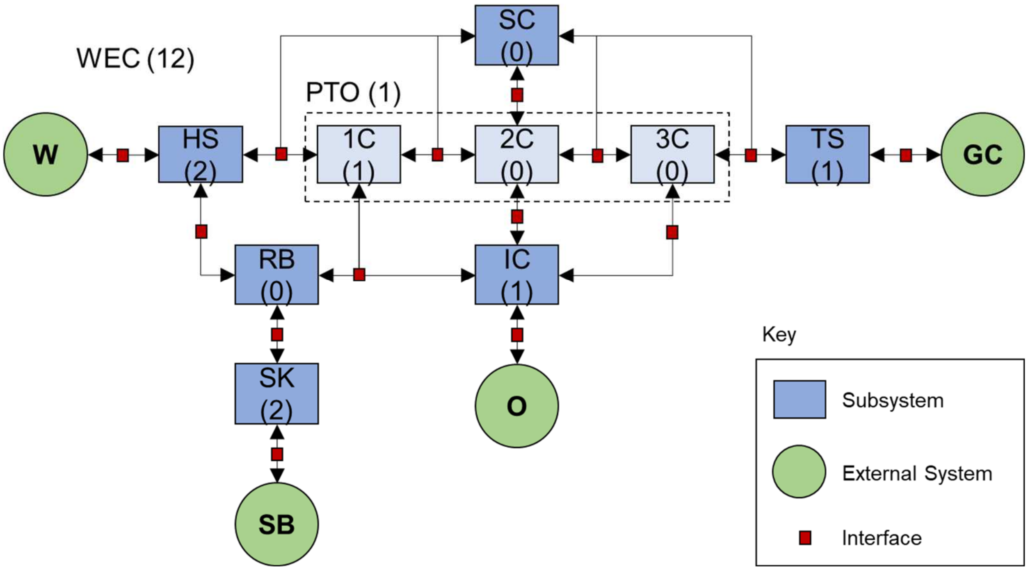


Figure 7.10: Block diagram for the 3 MW Blue Horizon 250 farm.

Again, numbers between brackets represent the units needed in the various subsystems. The farm consists of 12 WECs, each with two HS, one hinged PTO, one IC, two SK lines at the front and one TS. There is no SC and RB. Furthermore, each PTO is a direct drive meaning 2C and 3C are set to zero. The block diagram shown in Figure 7.10 is represented in the corresponding DSM model in Table 7.9.

Table 7.9: DSM model for the 3 MW Blue Horizon 250 farm

	O	W	HS	1C	2C	3C	RB	IC	SC	SK	TS	SB	GC
O	0							12					
W		0	24										
HS		24	24	24						24			
1C			24	12				12			12		
2C					0								
3C						0							
RB							0						
IC	12			12				12					
SC									0				
SK			24							24		24	
TS				12							12		12
SB										18		0	
GC											12		0

Using equation (29), the Complexity Score (CS) can be computed for both farms as a proxy of the integration time and effort due to subsystem interdependencies and interactions.

The farm based on four Pelamis P2 750 comprises 192 subsystems and 416 interfaces in total, resulting in a CS of 458. On the other hand, the farm based on 12 Mocean Blue Horizon 250 has 84 subsystems and 141 interfaces in total, resulting in a CS of 164. This reduces the complexity by a factor of 2.8. Moreover, increasing the unit power of the Blue Horizon machine will further reduce the complexity of the wave energy system. A Blue Horizon 750 (same capacity as Pelamis P2) would result in a CS of 56. This result strongly supports the objective of designing simple devices with large unit capacity.

Complex interfaces denote intricate interdependencies and interactions between the wave energy subsystems. If subsystems are developed independently, there is a high chance that major changes will have to be made due to interface issues discovered during integration. A modular wave energy concept benefits the technology qualification process since the subsystems and their interactions will have their novelties, uncertainties and risks identified, which significantly assists in defining the main engineering requirements.

7.4.1.2 WaveBob vs CorPower

Attenuators need PTOs to handle very low speed and high torque, making them either expensive or inefficient. Many buoyant devices with small dimensions relative to the incident wavelength (i.e. Point Absorbers) have been proposed. WaveBob is one discontinued development that will be compared with CorPower Ocean C4.

WaveBob [299] was a two-body axisymmetric point absorber which transformed the relative heaving motion between the floating torus and the reacting submerged mass into electricity using a hydraulic PTO and control system. The PTO consisted of three hydraulic cylinders, high-pressure accumulators, one hydraulic motor, an electrical generator and a step-up transformer. A simple four-leg slack catenary mooring system was used to hold the device in position [300]. The grid integration comprised an umbilical cable to connect the floating device to a bottom-mounted sub-sea hub and an export cable.

At full scale, the device could produce up to 1 MW of energy with an average output of over 500kW at sites in the North Atlantic and Pacific oceans. The device was demonstrated at a 1:4 scale in Galway Bay (Ireland).

Figure 7.11: WaveBob 1:4 device tests (left) and full-scaled design (right).

The full-scale version of the Wavebob was never deployed. For comparison, a 3 MW farm of six 500 kW units will be considered. The block diagram of such a farm is presented in Figure 7.12.

Numbers between brackets represent the units needed in the various subsystems. The farm consists of six WECs, each with two HS, one PTO, two SC (one accumulator & one transformer), one IC, four SK lines and one TS. There is no RB since it is a self-reference device. Furthermore, each PTO is comprised of 1C (three hydraulic rams), 2C (one hydraulic motor) and 3C (one electrical generator). The block diagram shown in Figure 7.12 is represented in the corresponding DSM model in Table 7.10.

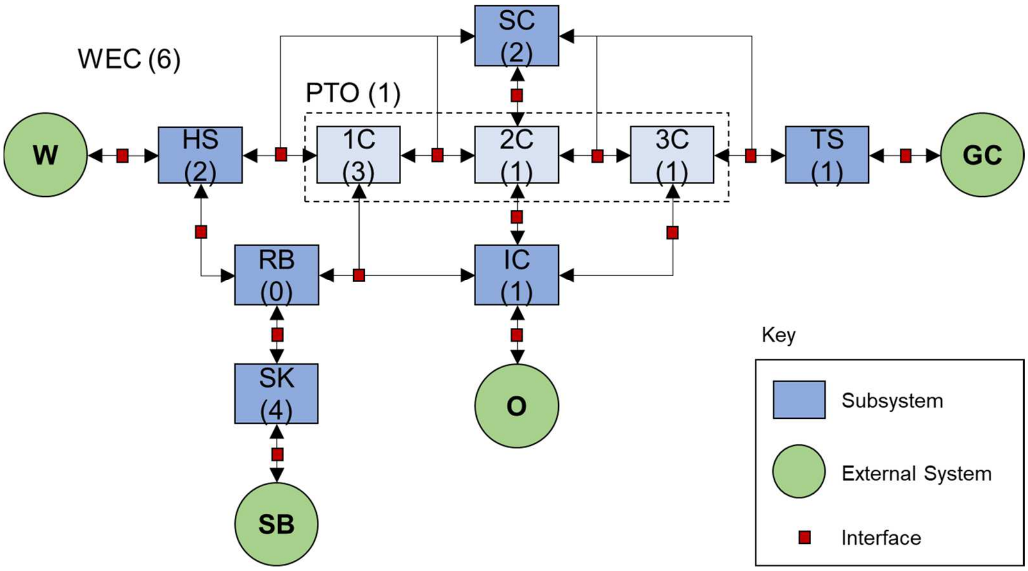


Figure 7.12: Block diagram for the 3 MW WaveBob farm.

Table 7.10: DSM model for the 3 MW WaveBob farm

	O	W	HS	1C	2C	3C	RB	IC	SC	SK	TS	SB	GC
O	0							6					
W		0	12										
HS		12	12	18						24			
1C			18	18	18			18					
2C				18	6	6		6					
3C					6	6		6	12		6		
RB							0						
IC	6			18	6	6		6					
SC						12			12				
SK			24							24		24	
TS						6					6		6
SB										24		0	
GC											6		0

On the other hand, CorPower Ocean C4 [37] is a heaving point absorber consisting of a light buoy attached to the seabed through a PTO module, tension leg mooring system and pile anchor. C4 uses stored pressure to generate energy from waves in two directions: the wave force pushes the buoy upwards while a pneumatic cylinder pulls the buoy downwards. This reciprocating buoy motion is converted into electrical power through a mechanical drive train with a cascade gearbox attached to a conventional generator. A phase control system is used to tune or de-tune the buoy response.

Figure 7.13: CorPower C4 hull (left) and schematic (right).

CorPower Ocean farms use a modular architecture to connect to the grid [301]. Up to 10 MW can be connected to a single floating collection hub, which then is joined to an export cable. A 3 MW farm consisting of ten C4 devices will be considered in this section. The block diagram of such a farm is presented in Figure 7.14.

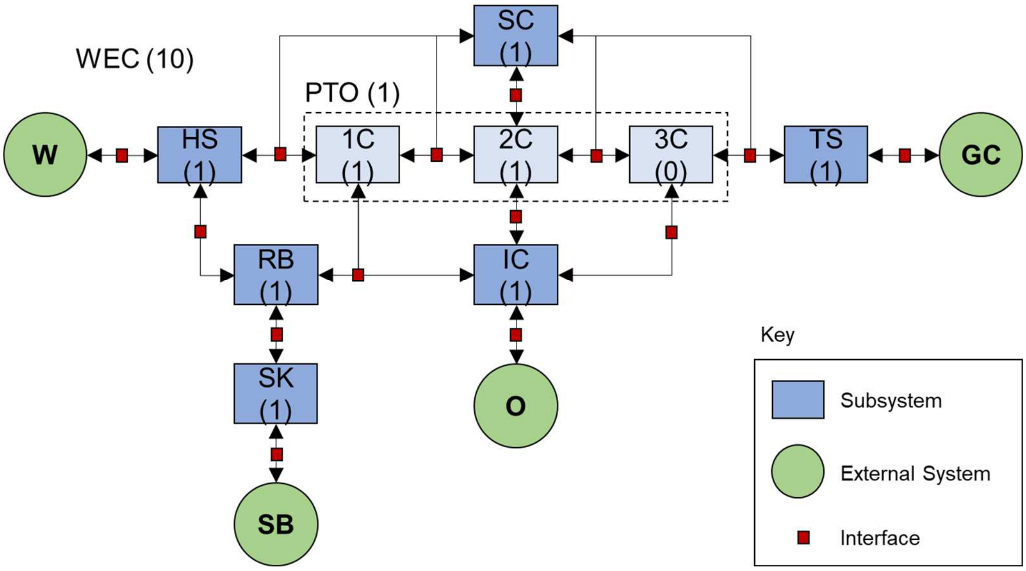


Figure 7.14: Block diagram for the 3 MW CorPower C4 farm.

Again, numbers between brackets represent the units needed in the various subsystems. The farm consists of ten WECs, each with one HS, one PTO, one SC (pre-tension cylinder), one IC, one RB (pile anchor), one SK line (tether) and one TS. Furthermore, each PTO comprises 1C (one cascade gearbox) and 2C (one electrical generator). 3C is zero since there is no need for a tertiary conversion.

The block diagram shown in Figure 7.14 is represented in the corresponding DSM model in Table 7.11.

Table 7.11: DSM model for the 3 MW CorPower C4 farm

	O	**W**	**HS**	**1C**	**2C**	**3C**	**RB**	**IC**	**SC**	**SK**	**TS**	**SB**	**GC**
O	0							10					
W		0	10										
HS		10	10	10			10			10			
1C			10	10	10			10					
2C				10	10			10	10		10		
3C						0							
RB			10				10						
IC	10			10	10			10					
SC					10				10				
SK			10							10		10	
TS					10						10		10
SB										10		0	
GC											10		0

Using equation (29), the CS can be computed for both farms. The farm based on six WaveBob comprises 90 subsystems and 162 interfaces in total, resulting in a CS of 185. On the other hand, the farm based on ten CorPower C4 has 80 subsystems and 120 interfaces in total, resulting in a CS of 144. This reduces the complexity by a factor of 1.3 with respect to WaveBob and 3.2 to Pelamis P2.

Table 7.12 presents the summary results of the design structure analysis and complexity of wave energy farms of the same installed power.

Table 7.12: Summary of Complexity Scores.

Technology	**WECs**	**M_s**	**I_s**	**CS**
Pelamis P2 750	4	192	416	458
Mocean Blue Horizon 250	12	84	141	164
Mocean Blue Horizon 750	4	28	48	56
WaveBob 500	6	90	162	185
CorPower C4 300	10	80	120	144

CorPower C4 seems to be an attractive concept according to its CS. However, we must remember that the capture width of a point absorber is not related to its size but is dependent on the wave period and oscillating mode [302]. Therefore, the device capacity cannot be freely scaled to produce more energy. The only way to increase the unit capacity is by combining more oscillating modes, such as heave and surge. On the contrary, the scalability of attenuators and terminators depends on the length and width respectively. In that respect, Mocean Blue Horizon is better positioned.

7.4.2 Promising Concepts Worth Exploring

The weightings of the inventive principles in Table 7.7 have been added in each DP cell of the contradiction matrix to detect the most impactful conflicts. This results in the following matrix.

Table 7.13: Impact of the DP conflicts (blue=high; red=low).

		Feature to preserve									
		DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10
		Area of moving object	Strength	Duration of action	Loss of energy	Loss of time	Quantity of substance	Adaptability	Device complexity	Difficulty of detecting	Productivity
Feature to improve	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%

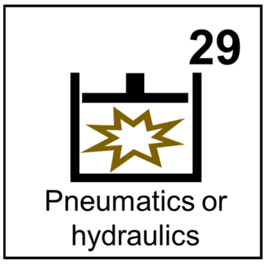
The most impactful contradictions, and corresponding inventive principles and potential ideas to overcome these recurrent challenges are discussed below.

7.4.2.1 Loss of energy (DP4) vs Productivity (DP10)

This conflict is related to the need to minimise conversion losses and reduce the maintenance frequency. The Inventive Principles suggested by TRIZ to remove this contradiction (see Appendix D) are as follows:

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

It can be appreciated that IPs 28, 29 and 35 belong to group 4, “Using scientific effects, special fields and substances”. A quick review of the list of TRIZ 40 Inventive Principles in Appendix E reveals that the inventive operators of pneumatic or hydraulic constructions provide more useful insights for wave energy application.



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.

Figure 7.15: Pneumatics or hydraulics and corresponding inventive operators.

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. 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 inventive principle are the classical OWC devices which replace the complex mechanical transmission by the airflow through an air turbine (see Figure 7.16-a). NoviOcean device [303] 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 7.16-b).

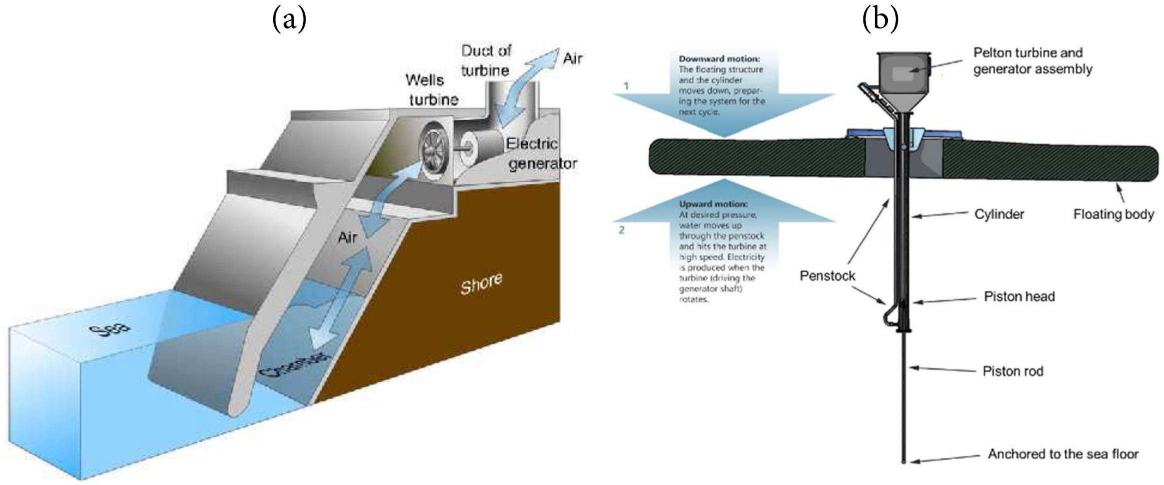


Figure 7.16: Use of pneumatics or hydraulics (a) Onshore OWC device [304]; (b) NoviOcean device [303].

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 [305]. 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.

7.4.2.2 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. As we have seen in section 7.4.1, 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.

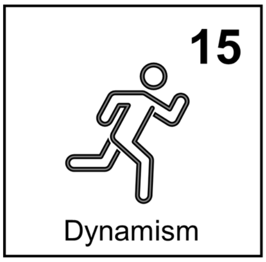
The Inventive Principles suggested by TRIZ to remove this contradiction (see Appendix D) are as follows:

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

It can be appreciated that the Inventive Principles belong to three different groups, whose only common feature is the trend 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 [232]. 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.

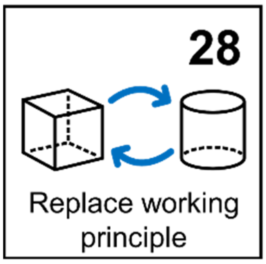
Dynamism is a significant driver for increasing ideality. Particularly, two suggested inventive operators are using adaptive and flexible elements and making the object movable and adaptive.



a) Make an object, external environment or process adjustable to enable optimal performance parameters at each stage of operation.
b) Divide an object into elements whose position changes relative to one another. Make the 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 structure.

Figure 7.17: Dynamism and corresponding inventive operators.

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 fluids.

Figure 7.18: Replace the working principle and corresponding inventive operators.

FlexWECs [306] 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 wave energy harvesting throughout the device structure continuously (see Figure 7.17-a). It is proposed the use of dielectric elastomer generators or any other type of solid-state conversion technologies [307]. 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, 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 [308].

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 [309]. 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 7.17-b). TENGs are low-cost, lightweight and can efficiently convert slow random waves into power.

Figure 7.19: Dynamism and replacing working principle (a) NREL's FlexWEC [306] ; (b) PNNL's FMC-TENG device [309].

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 to larger devices but provide much less revenue.

In 2018, WES commissioned a study into the potential of very large-scale (> 10MW) WECs [310]. 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.

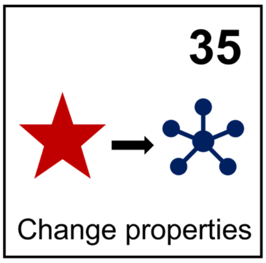
7.4.2.3 Strength (DP2) vs Productivity (DP10)

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 Inventive Principles suggested to remove this contradiction (see Appendix D) are the same as for section 7.4.2.1 but in a slightly different order:

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

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.

Inventive Principle 35 suggests changing the physical properties or operational conditions.



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 process chemistry.

Figure 7.20: Change properties and corresponding inventive operators.

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 [311]. 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 7.21-a).

The concept of large-scale geometric variability has also been considered in the Danish WEPTOS [312]. In this case, the floating structure can adjust the opening angle between the two legs (see Figure 7.21-b). Additionally, the device allows 360° weather-vanning through its single anchor leg mooring system to reduce 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 [37]. 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 7.21-c).

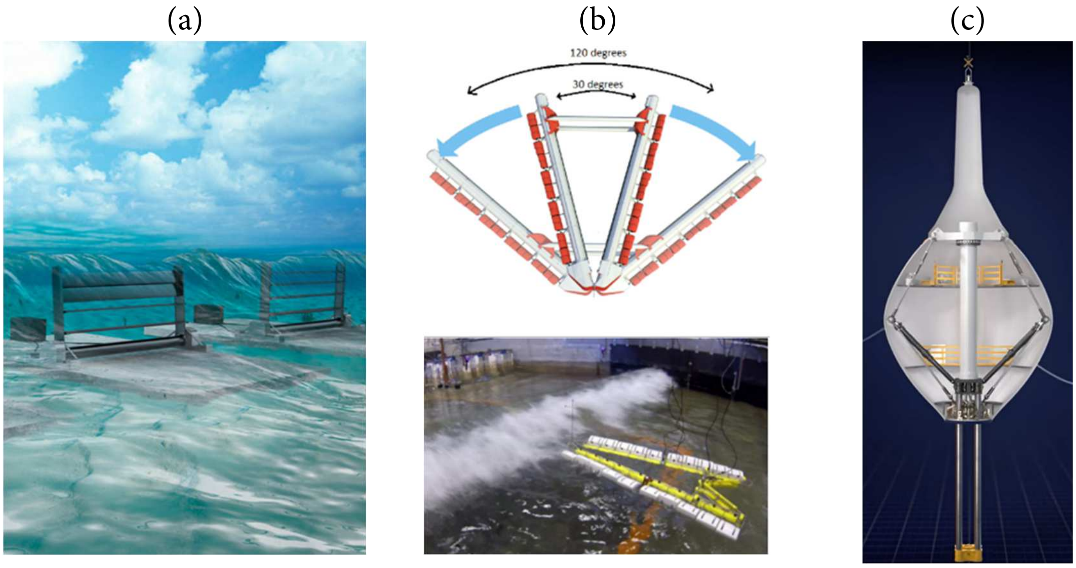
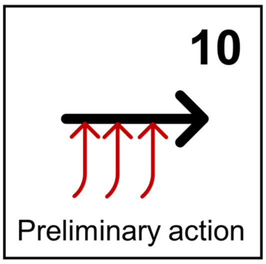


Figure 7.21: Change properties (a) NREL's Variable Geometry OSWC [311]; (b) WEPTOS [312]; (c) CorPower C4 [37].

The previous strategies can increase the wave energy system reliability. However, they do not improve the productivity of the installation and maintenance operations. Inventive Principle 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.

Figure 7.22: Preliminary action and corresponding inventive operators.

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 [313].

7.5 Conclusions

A systematic problem-solving approach must be embedded from the outset of technology development to create awareness of potential technology gaps, identify remaining technology challenges, and focus innovation on enhancing the areas that have the biggest influence on technology performance.

Incremental innovation alone is not enough to achieve the medium-term policy targets established for wave energy. Developing cost-effective wave energy systems is a challenging endeavour due to the size of the solution space, which calls for new technologies or designs. The allocation of functional requirements to the physical embodiment has a crucial role in determining the future costs of wave energy.

The Design Structured Matrix (DSM) representation is a tool to support improving the wave energy system, helping visualise the potential problems. Complex architectures can lead to significant changes in the latter development phases, longer integration time, and greater uncertainties and risks. The importance of device simplicity and large unit capacity has been showcased with the assistance of two failed technologies with akin wave energy concepts currently under development. The Complexity Score (CS) of the former Pelamis P2 is several times larger than more recent designs such as Mocean Blue Horizon or CorPower C4. It is important to note, however, that the CS for wave energy farms built with point absorbers cannot be improved beyond a certain limit since this class of device is not inherently scalable. This must be taken into consideration for large-scale grid integration of wave energy. In this respect, attenuators and terminators are more favourable as they scale with their length and width respectively.

The TRIZ structured innovation approach has permitted the identification of the most impactful contradictions and corresponding inventive principles. Design Parameters (DPs) weights resulting from the application of QFD in previous steps of the methodology have been used to rank the inventive principles 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 maintenance frequency or downtime.

Inventive principles 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.

CHAPTER 8 OVERALL CONCLUSIONS

> “A beautiful thing is never perfect”
>
> *Egyptian Proverb*

8.1 Overview

This chapter combines and summarises the findings from the preceding chapters with the aim of analysing, assessing and comparing wave energy technology solutions from the early stages of technology development.

Section 8.2 highlights the key findings and contributions made in this research. Moreover, the strengths and limitations of the novel methodology approaches are discussed for the sake of maximising their utility and value.

Section 8.3 outlines future research lines that will extend the impact and applicability of the proposed approaches.

8.2 Summary of Findings

Any innovation needs to be socially desirable, technically feasible and commercially viable to succeed in the market. While wave energy development is favoured by an ample social demand backing the energy transition, and prototypes deployed in the water have shown the feasibility of harnessing wave energy, unfortunately, none of the wave energy concepts has demonstrated long-term reliable performance to compete with commercial alternatives.

To achieve the wave energy system's cost and performance goals, the initial phases of technology development are critical. Conventional approaches, which primarily focus on assessing technology maturity, have proven insufficient to ensure wave energy satisfies its technical, economic and social objectives.

Precisely, the ultimate research goal of this thesis is to develop a systematic design approach to:

1. Build a common framework that ensures traceability and consistency of wave energy system requirements and metrics.
2. Create fair performance assessments of wave energy technologies to objectively guide design decisions throughout the development process.
3. Apply sound innovation strategies to suggest promising concepts that can improve the cost-effectiveness of wave energy technologies.

The research questions behind this overarching goal are:

- How can we best measure the success of wave energy technology?
- Will a technology concept be able to meet its techno-economic targets?
- What can be done to overcome the remaining technical challenges?

Table 8.1 summarises the main elements of the research and novel methodology. The following subsections elaborate on the specific contributions, strengths and limitations.

Table 8.1: Summary of the Novel Methodology.

	Wave Energy System (Farm – Devices – Subsystems)		
	Common Framework	**Fair Assessment**	**Innovation Strategies**
Research Question	How can we measure wave energy success?	Can the technology meet its techno-economic targets?	What can be done to overcome the challenges?
Systems Engineering Methods	• AHP • QFD • FAST • LSP	• Value functions • Allocation of targets • Uncertainty propagation • Technological learning	• DSM • TRIZ
Key Features	• Context: SD, SH. • Requirements: SR, FR, TR, DP. • Metrics: GM.	• Development Stages: PR, CA, TA. • Future costs: Prototype, FOAK, Mature techn.	• System Architecture: CS. • Contradictions: IP.
Main Outcome	Prioritisation of technical attributes	Technology selection and benchmarking	Identification of promising concepts

8.2.1 Common framework of wave energy system requirements and metrics

A common framework of system requirements and metrics is essential to measure the ability of a wave energy technology to meet stakeholders' expectations. The framework developed through this research, based on sound Systems Engineering principles, comprises the external context, system requirements and evaluation criteria. This step of the methodology prioritises the various wave energy attributes for the qualitative assessment of wave energy technologies. AHP and QFD are the Systems Engineering methods used to determine the weightings of these attributes.

The analysis of the external context provides an understanding of the factors influencing the development of wave energy technologies and the corresponding impact on system requirements. Identifying the market application, key drivers and stakeholder groups offer a solid basis for objectively evaluating wave energy technologies against systems requirements.

The practical implementation of the methodology explores two power markets for wave energy; the most attractive utility-scale generation market owing to its size and the niche applications to powering remote communities that could provide a stepping stone supporting the deployment of wave energy technologies.

An anonymous survey was designed to prioritise the external forces. A 90% degree of confidence and a 10% margin of error are guaranteed by the volume of answers gathered. When working with small populations and novel research topics without prior studies, these values are acceptable.

It was found that Economic and Political factors are the primary motivations for developing utility-scale generation projects, whereas the Social drivers stand out in a remote generation market. The requirements of the Owner and the Government for utility-scale and remote community projects, respectively, will have a significant impact on the development of wave energy technology.

The systematic analysis of system requirements and evaluation criteria also summarises the purposes that should drive searching for solutions. Developing a common framework based on the notion of design domains assists in the organisation of requirements and metrics information to facilitate system verification and validation. The Octopus diagram and FAST are the Systems Engineering methods used for the external and internal analysis.

In the systems requirements hierarchy, the top-level Stakeholder Requirements (SRs) capture all essential and prioritised considerations. The Functional Requirements (FRs) define what the system must accomplish to achieve the SRs at the next hierarchical level. Finally, Technical Requirements (TRs) and Design Parameters (DPs) outline the technology-related challenges that must be considered for the system to be properly implemented in physical parts and assemblies. Satisfaction of wave energy requirements is expressed at different hierarchical levels through Measures of Effectiveness (MOEs), Measures of Performance (MOPs) and Technical Performance Measures (TPMs).

Using the LSP method provides more granularity in the definition of the aggregation logic and seamlessly enables the combination of metrics. This Systems Engineering approach can combine different attributes and criteria expressed in multiple units, orders of magnitude and qualities, such as MOE, MOP and TPM.

The practical implementation of the methodology quantifies the relative importance of system requirements at different hierarchical levels. Moreover, aggregating system requirements into a final figure, or Global Merit (GM), enables a qualitative assessment of the overall suitability of the wave energy technology.

At the stakeholder domain, the highest-ranked SRs were found to be converting wave energy (SR1) and preventing business risks (SR5). The former scored first for the remote community market, whilst the latter did it for the utility-scale generation. However, when assessing the GM, low utility values of converting wave energy (SR1) penalised to the greatest extent both market applications. In the functional domain, capturing wave energy (FR1), Surviving the harsh environment (FR9), minimising downtime (FR5) and transforming energy (FR2) were the highest-ranked FRs. FR1 is first for the remote community and second for the utility-scale application. FR9 swaps the ranking for the two markets considered. Low utility values of FR9 and FR5 penalise the MOE utility and GM more significantly. Finally, when analysing the technical domain, the top-ranked Design Parameters are connected to converting wave energy (SR1), operating when needed (SR2) and preventing business risks (SR5), through the corresponding FRs and TRs. This result is in agreement with the techno-economic goals of wave energy systems.

Wave energy system requirements are equally important for the two application markets under consideration, with lower than 10% variability. Although the overarching context might play a relevant role in the initiation of projects, the technical requirements are not much influenced by the intended market application.

The common framework provides the following benefits and value:

- It avoids any inconsistency with the formulation of system requirements.
- It ensures wave energy requirements are fully traceable throughout the entire design process.
- It applies to different levels of technology maturity.
- It provides flexibility for adaptation to rapidly changing market conditions and stakeholder priorities.
- It can be expanded to focus the analysis on specific wave energy sub-systems, assemblies or components by repeating the domain mapping process and adding subsequent layers to the requirements hierarchy.
- It grasps the qualitative aspects related to the stakeholder expectations that higher-level metrics such as LCOE cannot provide.

Nevertheless, the results obtained present some limitations. The final prioritisation of wave energy system attributes might be sensitive to geographical and economic development considerations, particularly for remote coastal communities with a much flatter response distribution. Additionally, the ranking contains a certain degree of uncertainty due to the sample size and corresponding margin of error (i.e. 10%). Higher statistical significance may be obtained by replicating the study with a larger sample size (e.g. 220 participants for a 5% margin of error).

8.2.2 A fair assessment of wave energy technology performance throughout the development process

Evaluation of technology performance is inherently a continuous activity. Too little time invested in the early design phases can result in gaps in understanding of the system requirements, less potential for new concept development, and loss of time and resources developing a concept that is not capable of performing well enough to become a feasible solution.

Technologies with substantial development duration, such as wave energy, need guidance along the development process to manage risk and uncertainty adequately. To this purpose, the holistic assessment developed through this research comprises the evaluation at intermediate development stages and the projection of future costs when the technology has been sufficiently replicated. This step of the methodology facilitates wave energy technology selection and benchmarking at different maturity levels in a controlled manner.

The assessment of wave energy capabilities at intermediate development stages requires assigning value to evaluation metrics and allocating design targets. Value functions are used to convert design attributes into a quantitative measure of the decision-maker preference. Nonlinear value functions enable a more accurate representation of preferences by grasping the underlying fundamental relationships, risk-avoidance attitudes, constraints and/or optimal values. Generic curve families are implemented in this methodology, making it possible to generate linear, concave, convex and S-shaped functions. On the other hand, design targets are allocated from the achievable range from the technology spectrum known, respecting the theoretical or fundamental limits. The allocation of design targets to the lower-level assessment criteria avoids any unfeasible combination and enables tracking progress towards those targets.

Due to the small differences in the weights for the two application markets, the practical application of this method to six illustrative cases of hypothetical wave energy devices produced very similar GM. This outcome supports the preceding section's conclusion that the application market is less important than the overall performance of the technology. In general, GM and LCOE are correlated, meaning that the former falls as the latter rises.

The Performance Ratio (PR) facilitates benchmarking of wave energy systems. Technologies that meet all statutory requirements and operate within the allowed performance range can be compared in terms of Commercial Attractiveness (CA). Otherwise, the Technical Achievability (TA) should be analysed.

When a technology fulfils or surpasses the system requirements, CA allows for a more impartial assessment of wave energy technologies. It combines qualitative (i.e. GM) and quantitative (i.e. LCOE) aspects. For the same market application, this indicator disambiguates the selection of the best-suited wave energy alternative whenever the LCOE or the GM are identical. Furthermore, CA allows for objectively comparing wave energy technologies across different market applications.

Although CA is mainly a useful concept for comparing the highest-level metric affordability of wave energy systems, it can be equally applied to the partial evaluation of lower-level design attributes in wave energy technologies, such as MOEs, MOPs or TPMs. It only requires substituting the GM for the partial utility of the performance metric under consideration resulting from the QFD analysis.

TA is used for wave energy systems that fail to achieve one or more of the mandatory requirements, necessitating therefore additional technical advancements. It combines the PR and the Degree of Difficulty (DD), which indicates the learning effort required to achieve a PR = 1. The larger the gap from the expected targets, the greater the challenges ahead, which can compromise the technological feasibility for market entry. The “cone of uncertainty” delimits each development stage's upper and lower performance bounds.

The direct measurement of the LCOE is particularly inappropriate when developers are tasked with estimating the future cost of prototype technology. This technique provides a clear and verifiable mechanism for determining the future affordability of wave energy systems in development. Instead of oversimplifying the LCOE quantification while there are still many unknowns, the method incorporates these unknowns as uncertainties to offset the inherent optimism bias in early-stage estimations. The mathematical technique of uncertainty propagation combines the standard deviation of the individual estimations according to the accuracy ranges provided by engineering guidelines. When the technology has reached maturity and has been widely replicated, component-based learning rates are then used to assess it. A disaggregated approach to the learning curve method at the component level uses prior learning rates for similar technologies to generate a composite learning rate at the system level.

A case study of a 50-unit farm of floating oscillating wave surge converters (NREL's RM5) is used to demonstrate this new method. The statistical fit of lognormal features with an 80% confidence interval, drawn from prior research in other engineering applications, produced quantitative values that were consistent with NREL's CAPEX cost model assumptions. Furthermore, the proposed cost estimation approach identifies additional sources of uncertainty in the OPEX and financial assumptions, which can carry out similar contingencies but are not taken into account by NREL.

The results reveal that the uncertainties are in the same range as prospective technical learning, resulting in a future cost prediction close to the initial LCOE estimation. This suggests that emerging technologies should strive to collect evidence that increases estimation accuracy as soon as possible.

Awareness of the cost estimate uncertainty level and future learning capacity provides useful information for identifying outstanding technology challenges before moving on to the next development phase. AEP is the most significant contributor to global uncertainty. Its multiplicative nature strongly backs the suggestion to keep the number of PTO's energy transformation steps to a minimum. In addition, increasing the breakdown levels in the CAPEX and OPEX is a valuable strategy for improving the accuracy of future LCOE projections. Component-based learning rates and baseline costs are also important to minimise over-optimism. It also helps with identifying inherent cost reduction constraints that could be overlooked if the LR of the emerging technology were analysed as a whole.

To achieve a more attractive cost projection in the next iteration of the wave energy technology, it is worthwhile noting that the newly introduced innovations should provide greater advantages than the associated uncertainty rise resulting from a lower maturity level.

The fair assessment of wave energy technology performance throughout the development process provides the following benefits and value:

- It creates awareness of potential technology gaps and guides design decisions throughout the various development stages.
- It facilitates the selection of the most suitable option for a particular market application and benchmarks technologies across different markets.
- It provides a tool for exploring uncertainties and focusing attention on the accuracy of cost estimates as well as potential learnings from the early development stages.
- It provides valuable information for concentrating innovation efforts on areas with the greatest influence on technology performance.

Nevertheless, the results obtained present some limitations. Although some useful guidelines have been provided in previous chapters, the allocation of targets, degree of difficulty, uncertainty ranges, and learning rates are highly qualitative. Therefore, any assumptions must be based on evidence from literature or qualified experts.

The total level of uncertainty and the resulting LCOE will often be underestimated by the assumption of independence in the statistical treatment of cost centres. Alternatively, when the technology developer can create a completely parametric model for the emerging technology, Monte Carlo methods might be used to integrate the different uncertainty sources.

The consideration of a first-of-a-kind commercial deployment is important to track the evolution of costs along the development cycle of the emerging technology. However, it cannot be used to calculate the time required or necessary learning investment to attain the future LCOE. As the wind industry has demonstrated, the wave energy sector has to reach a specific deployment level before there is a consistent cost drop. This will push the estimates back a few years and raise the learning investment needed to get to this cost.

8.2.3 Innovation strategies to improve the cost-effectiveness of wave energy

Searching for solutions is a constructive and creative phase in Systems Engineering. Due to the large solutions space to explore, a systematic problem-solving approach is needed to overcome the performance barriers identified in the development of wave energy systems. The innovation strategies proposed in this research comprise the analysis of structural patterns in the wave energy system architecture and the identification of trade-offs and corresponding inventive principles. This step of the methodology results in the identification of promising concepts.

The Design Structured Matrix (DSM) is a flexible modelling tool providing a condensed, scalable and intuitive system architecture description. It visualises the potential problems within the wave energy system. Complex architectures will have a high probability that major changes arise from problems discovered during the later integration phases. Moreover, interface design should not be taken lightly since a low interface maturity can halve the TRL of the interconnected subsystems and can increase the technology integration risk. The Complexity Score (CS) measures the integration time and effort due to subsystem interdependencies and interactions.

The practical implementation of the methodology has showcased the importance of device simplicity and large unit capacity with the assistance of two failed technologies with akin wave energy concepts currently under development. The CS of the former Pelamis P2 is several times larger than more recent designs such as Mocean Blue Horizon or CorPower C4. It is important to note, however, that the CS for wave energy farms built with point absorbers cannot be improved beyond a certain limit since this device category is not inherently scalable. This must be taken into consideration for large-scale grid integration of wave energy. In this respect, attenuators and terminators are more favourable as they can scale with their length and width.

On the other hand, TRIZ facilitates innovative concept generation. 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. A ranking of inventive principles suggested for solving contradictions is used to point to the most promising innovation strategies.

The practical implementation of the methodology has permitted the identification of the most impactful contradictions and corresponding inventive principles. Design Parameters (DPs) weightings resulting from the application of QFD in previous steps of the methodology have been used to rank the innovation principles 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.

Inventive principles 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.

The integration of effective innovation strategies in the development of wave energy systems provides the following benefits and value:

- It helps to manage system complexity, enhance the understanding of causality within the system, and channel innovation toward useful improvements.
- It substitutes the conventional trial-and-error method based on expert judgement and an engineering compromise.
- It provides a predictable technique to deal with problems based on past knowledge and proven principles, bringing efficiency into the process.

Nevertheless, the results obtained present some limitations. Station Keeping (SK) and Transmission System (TS) solutions for farm deployments are not always defined with sufficient detail at the early stages of development, which restricts an adequate assessment of complexity and technology showstoppers. Besides, the subsystem breakdown can hide technical contradictions that may make unworkable a promising concept. Eventually, the findings of this research do not focus on a specific wave energy concept that can bring about the required step change in the sector, but the thesis as a whole offers a comprehensive and structured method for evaluating the potential of novel wave energy archetypes.

8.3 Recommendations for Future Research

This thesis has focused on developing a novel methodology for assessing wave energy options at the early stages of development. The wave energy farm was chosen as the baseline system for the overarching evaluation and electricity generation as the primary market. Further work will be needed to explore the application of the proposed approach to other possible settings.

Some of the areas that could lead to further research are as follows:

- **Expanding the methodology to the evaluation of subsystems**. To analyse the subsystem impact as a whole, it must be placed in the context of a device, and that device must then be placed in the context of an array. The PTO is an example of the need for this kind of assessment. In this respect, work has been initiated in the H2020-funded VALID project [314] for the stage-gate assessment of critical components in the PTO.
- **Explore social desirability**. The social desirability of wave energy is linked to potential environmental and social opportunities. Although these concerns were present in the definition of stakeholders' expectations, the impact exceeds a single-wave energy farm. They should be evaluated in the long run and with the cumulative effect. Work is underway at IEA-OES to extend the international evaluation and guidance framework for ocean energy technology [142] beyond affordability with the inclusion of environmental acceptability.
- **Adapt the methodology to the assessment of other emerging renewable energy technologies**. Tidal stream energy, floating offshore wind, airborne wind and floating photovoltaics are innovative technologies under development that share many similarities with wave energy. Particularly those versions deployed in an offshore environment will face similar challenges.

Lastly, the research has suggested several promising concepts worth exploring. However, the thesis scope has made it impossible to develop further and assess these concepts. A complete assessment and benchmarking of wave energy options using flexible bodies, direct drive and/or terminator configurations would be of great interest.

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APPENDICES

Appendix A: Survey of External Forces

1.- What are the key drivers of wave energy projects for each market application?

1.a.- Please rank the following factors in order of importance (**1-highest; 6-lowest**)

- **Political factors**: Supporting policies such as energy security, finance, sustainability and job creation.
- **Economic factors**: Access to finance, credit & insurance.
- **Social factors**: Growing energy demand and social acceptance.
- **Technological factors**: Technology maturity and infrastructure readiness.
- **Legal factors**: Simplified procedures such as consenting and environmental impact assessment.
- **Environmental factors**: Stricter environmental protection (e.g. pollution, natural disaster recovery, climate change).

Table cells have drop-down menus to provide your choices. You are kindly asked to select **a minimum of 4** drivers per market application.

Ranking	Sample response	Utility-scale	Remote communities
1	Economic	[Select]	[Select]
2	Political	[Select]	[Select]
3	Technological	[Select]	[Select]
4	Environmental	[Select]	[Select]
5	Social	[Select]	[Select]
6	Legal	[Select]	[Select]

1.b.- Please feel free to use the box below to provide further comments on driver prioritisation. Do you miss any key drivers in the above list?

2.- Which of the above drivers concerns each wave energy stakeholder group more?

2.a.- Please rank the following stakeholder groups in order of importance (**1-highest; 8-lowest**)

- **Owner**: Initiates the project; designs the farm; provides equity; sets return on investment targets; manages project risks; sells electricity to consumers.
- **Lenders**: Provides debt; sets interest rate; assesses financial risk.
- **EPCI contractor**: Manages farm construction and installation; provides insurance during construction; selects suppliers; manages end-of-life recycling.
- **O&M provider**: Provides spare parts and services; performs (un)scheduled maintenance; provides insurance during operation; selects service suppliers.
- **Government**: Develops and implements sectoral policies; reviews compliance; provides investment and generation incentives.
- **Regulators**: Establishes permitting requirements; reviews project use of ocean space; provides concession.
- **Pressure groups**: Lobbies for or against the project; improves the well-being of the community.
- **Consumers**: Sets power quality requirements; purchases generated electricity.

Table cells have drop-down menus to provide your choices. You are kindly asked to select **a minimum of 5** stakeholder groups per driver.

Ranking	Political	Economic	Social	Technolog.	Legal	Environm.
1	[Select]	[Select]	[Select]	[Select]	[Select]	[Select]
2	[Select]	[Select]	[Select]	[Select]	[Select]	[Select]
3	[Select]	[Select]	[Select]	[Select]	[Select]	[Select]
4	[Select]	[Select]	[Select]	[Select]	[Select]	[Select]
5	[Select]	[Select]	[Select]	[Select]	[Select]	[Select]
6	[Select]	[Select]	[Select]	[Select]	[Select]	[Select]
7	[Select]	[Select]	[Select]	[Select]	[Select]	[Select]
8	[Select]	[Select]	[Select]	[Select]	[Select]	[Select]

2.b.- Please feel free to use the box below to provide further comments on stakeholder prioritisation. Do you miss any key stakeholder groups in the above list?

Appendix B: Prioritisation Matrices

Table A.1: System Drivers for Utility-scale Generation.

System Drivers (SDs)	SD1	SD2	SD3	SD4	SD5	SD6		
	Political Factors	**Economic Factors**	**Social Factors**	**Technological Factors**	**Legal Factors**	**Environmental Factors**	**Total**	**Weight**
SD1 Political factors	0.28	0.34	0.27	0.22	0.29	0.29	1.68	**28%**
SD2 Economic factors	0.28	0.34	0.30	0.43	0.33	0.36	2.04	**34%**
SD3 Social factors	0.04	0.04	0.03	0.03	0.02	0.02	0.18	**3%**
SD4 Technological factors	0.28	0.17	0.23	0.22	0.24	0.22	1.37	**23%**
SD5 Legal factors	0.04	0.04	0.07	0.04	0.04	0.04	0.26	**4%**
SD6 Environmental factors	0.07	0.07	0.10	0.07	0.08	0.07	0.46	**8%**

Table A.2: System Drivers for Remote Community Generation.

System Drivers (SDs)	SD1	SD2	SD3	SD4	SD5	SD6		
	Political Factors	**Economic Factors**	**Social Factors**	**Technological Factors**	**Legal Factors**	**Environmental Factors**	**Total**	**Weight**
SD1 Political factors	0.26	0.21	0.49	0.13	0.20	0.20	1.48	**25%**
SD2 Economic factors	0.26	0.21	0.12	0.27	0.23	0.24	1.33	**22%**
SD3 Social factors	0.13	0.41	0.24	0.40	0.30	0.34	1.82	**30%**
SD4 Technological factors	0.26	0.10	0.08	0.13	0.17	0.15	0.89	**15%**
SD5 Legal factors	0.04	0.03	0.03	0.03	0.03	0.02	0.18	**3%**
SD6 Environmental factors	0.06	0.04	0.03	0.04	0.07	0.05	0.30	**5%**

Table A.3: System Drivers to Stakeholders (SHs) for Utility-scale Generation.

		SH1	**SH2**	**SH3**	**SH4**	**SH5**	**SH6**	**SH7**	**SH8**
System Drivers (SDs)	**Prioritisation**	**Owner**	**Lenders**	**EPCI Contractor**	**O&M Provider**	**Government**	**Regulators**	**Pressure groups**	**Consumers**
SD1 Political factors	28.0%	0.10	0.10	0.03	0.00	0.29	0.23	0.16	0.10
SD2 Economic factors	34.1%	0.24	0.19	0.14	0.14	0.14	0.00	0.08	0.08
SD3 Social factors	3.0%	0.09	0.09	0.09	0.00	0.14	0.14	0.20	0.26
SD4 Technological factors	22.8%	0.27	0.21	0.15	0.15	0.09	0.09	0.03	0.00
SD5 Legal factors	4.4%	0.23	0.13	0.08	0.03	0.18	0.23	0.13	0.00
SD6 Environmental factors	7.7%	0.08	0.00	0.08	0.08	0.13	0.23	0.23	0.18
Total	**100%**	**19.1%**	**14.8%**	**10.1%**	**8.8%**	**17.0%**	**11.6%**	**10.9%**	**7.6%**

Table A.4: System Drivers to Stakeholders (SHs) for Remote Community Generation.

		SH1	**SH2**	**SH3**	**SH4**	**SH5**	**SH6**	**SH7**	**SH8**
System Drivers (SDs)	**Prioritisation**	**Owner**	**Lenders**	**EPCI Contractor**	**O&M Provider**	**Government**	**Regulators**	**Pressure groups**	**Consumers**
SD1 Political factors	24.6%	0.10	0.10	0.03	0.00	0.29	0.23	0.16	0.10
SD2 Economic factors	22.1%	0.24	0.19	0.14	0.14	0.14	0.00	0.08	0.08
SD3 Social factors	30.4%	0.09	0.09	0.09	0.00	0.14	0.14	0.20	0.26
SD4 Technological factors	14.8%	0.27	0.21	0.15	0.15	0.09	0.09	0.03	0.00
SD5 Legal factors	3.1%	0.23	0.13	0.08	0.03	0.18	0.23	0.13	0.00
SD6 Environmental factors	5.0%	0.08	0.00	0.08	0.08	0.13	0.23	0.23	0.18
Total	**100%**	**15.5%**	**12.7%**	**9.2%**	**5.7%**	**17.0%**	**13.1%**	**13.8%**	**12.9%**

Table A.5: Stakeholders to Stakeholder Requirements (SRs) for Utility-scale Generation.

Stakeholders (SHs)		**Prioritisation**	**SR1** **Convert wave energy into power**	**SR2** **Operate when needed**	**SR3** **Reduce upfront costs**	**SR4** **Reduce annual costs**	**SR5** **Prevent business risks**
SH1	Owner	19.1%	0.36	0.12	0.20	0.04	0.28
SH2	Lenders	14.8%	0.04	0.19	0.26	0.19	0.33
SH3	EPCI Contractor	10.1%	0.00	0.00	0.64	0.00	0.36
SH4	O&M Provider	8.8%	0.12	0.27	0.00	0.35	0.27
SH5	Government	17.0%	0.32	0.05	0.23	0.41	0.00
SH6	Regulators	11.6%	0.24	0.33	0.00	0.00	0.43
SH7	Pressure groups	10.9%	0.28	0.36	0.04	0.20	0.12
SH8	Consumers	7.6%	0.38	0.29	0.00	0.29	0.04
	Total	**100%**	**22.5%**	**18.2%**	**18.5%**	**17.9%**	**22.9%**

Table A.6: Stakeholders to Stakeholder Requirements (SRs) for Remote Community Generation.

Stakeholders (SHs)		**Prioritisation**	**SR1** **Convert wave energy into power**	**SR2** **Operate when needed**	**SR3** **Reduce upfront costs**	**SR4** **Reduce annual costs**	**SR5** **Prevent business risks**
SH1	Owner	15.5%	0.36	0.12	0.20	0.04	0.28
SH2	Lenders	12.7%	0.04	0.19	0.26	0.19	0.33
SH3	EPCI Contractor	9.2%	0.00	0.00	0.64	0.00	0.36
SH4	O&M Provider	5.7%	0.12	0.27	0.00	0.35	0.27
SH5	Government	17.0%	0.32	0.05	0.23	0.41	0.00
SH6	Regulators	13.1%	0.24	0.33	0.00	0.00	0.43
SH7	Pressure groups	13.8%	0.28	0.36	0.04	0.20	0.12
SH8	Consumers	12.9%	0.38	0.29	0.00	0.29	0.04
	Total	**100%**	**24.0%**	**19.6%**	**16.8%**	**18.4%**	**21.2%**

Table A.7: Stakeholder Requirements to Functional Requirements (FRs) for Utility-scale Generation.

			FR1	**FR2**	**FR3**	**FR4**	**FR5**	**FR6**	**FR7**	**FR8**	**FR9**	**FR10**
Stakeholder Requirements (SRs)		**Prioritisation**	**Capture energy from waves**	**Transform into energy**	**Deliver energy to point of consumption**	**Maximise total uptime**	**Minimise total downtime**	**Manufacture by industrial processes**	**Install by service vessels**	**Maintain by service vessels**	**Survive the harsh environmental**	**Avoid risks to receptors**
SR1	Convert energy into power	22.5%	0.30	0.33	0.23	0.10	0.03	0.00	0.00	0.00	0.00	0.00
SR2	Operate when needed	18.2%	0.20	0.09	0.08	0.25	0.20	0.00	0.00	0.13	0.03	0.03
SR3	Reduce upfront costs	18.5%	0.00	0.00	0.04	0.13	0.00	0.35	0.28	0.04	0.12	0.04
SR4	Reduce annual costs	17.9%	0.00	0.00	0.00	0.00	0.24	0.09	0.03	0.28	0.21	0.15
SR5	Prevent business risks	22.9%	0.12	0.04	0.04	0.00	0.12	0.04	0.04	0.04	0.32	0.25
	Total	**100%**	**13.1%**	**10.1%**	**8.5%**	**9.3%**	**11.3%**	**9.0%**	**6.5%**	**8.8%**	**13.9%**	**9.7%**

Table A.8: Stakeholder Requirements to Functional Requirements (FR) for Remote Community Generation.

			FR1	**FR2**	**FR3**	**FR4**	**FR5**	**FR6**	**FR7**	**FR8**	**FR9**	**FR10**
Stakeholder Requirements (SRs)		**Prioritisation**	**Capture energy from waves**	**Transform into energy**	**Deliver energy to point of consumption**	**Maximise total uptime**	**Minimise total downtime**	**Manufacture by industrial processes**	**Install by service vessels**	**Maintain by service vessels**	**Survive the harsh environmental**	**Avoid risks to receptors**
SR1	Convert energy into power	24.0%	0.30	0.33	0.23	0.10	0.03	0.00	0.00	0.00	0.00	0.00
SR2	Operate when needed	19.6%	0.20	0.09	0.08	0.25	0.20	0.00	0.00	0.13	0.03	0.03
SR3	Reduce upfront costs	16.8%	0.00	0.00	0.04	0.13	0.00	0.35	0.28	0.04	0.12	0.04
SR4	Reduce annual costs	18.4%	0.00	0.00	0.00	0.00	0.24	0.09	0.03	0.28	0.21	0.15
SR5	Prevent business risks	21.2%	0.12	0.04	0.04	0.00	0.12	0.04	0.04	0.04	0.32	0.25
	Total	**100%**	**13.6%**	**10.6%**	**8.8%**	**9.5%**	**11.5%**	**8.4%**	**5.9%**	**9.0%**	**13.3%**	**9.3%**

Table A.9: Functional Requirements to Design Parameters (DPs) for Utility-scale Generation.

		DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10
FRs	**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	13.1%	0.26	0.26	0.00	0.09	0.00	0.09	0.26	0.00	0.03	0.00
FR2	10.1%	0.00	0.11	0.00	0.32	0.00	0.04	0.11	0.32	0.11	0.00
FR3	8.5%	0.00	0.05	0.00	0.41	0.00	0.14	0.00	0.41	0.00	0.00
FR4	9.3%	0.00	0.31	0.31	0.00	0.03	0.00	0.31	0.03	0.00	0.00
FR5	11.3%	0.00	0.00	0.05	0.14	0.41	0.05	0.05	0.05	0.14	0.14
FR6	9.0%	0.10	0.10	0.10	0.00	0.00	0.30	0.00	0.10	0.00	0.30
FR7	6.5%	0.13	0.00	0.00	0.00	0.04	0.39	0.00	0.04	0.00	0.39
FR8	8.8%	0.09	0.00	0.09	0.00	0.09	0.27	0.00	0.09	0.09	0.27
FR9	13.9%	0.09	0.28	0.03	0.00	0.00	0.00	0.28	0.03	0.28	0.00
FR10	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%**

Table A.10: Functional Requirements to Design Parameters (DPs) for Remote Community Generation.

		DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10
FRs	**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	13.6%	0.26	0.26	0.00	0.09	0.00	0.09	0.26	0.00	0.03	0.00
FR2	10.6%	0.00	0.11	0.00	0.32	0.00	0.04	0.11	0.32	0.11	0.00
FR3	8.8%	0.00	0.05	0.00	0.41	0.00	0.14	0.00	0.41	0.00	0.00
FR4	9.5%	0.00	0.31	0.31	0.00	0.03	0.00	0.31	0.03	0.00	0.00
FR5	11.5%	0.00	0.00	0.05	0.14	0.41	0.05	0.05	0.05	0.14	0.14
FR6	8.4%	0.10	0.10	0.10	0.00	0.00	0.30	0.00	0.10	0.00	0.30
FR7	5.9%	0.13	0.00	0.00	0.00	0.04	0.39	0.00	0.04	0.00	0.39
FR8	9.0%	0.09	0.00	0.09	0.00	0.09	0.27	0.00	0.09	0.09	0.27
FR9	13.3%	0.09	0.28	0.03	0.00	0.00	0.00	0.28	0.03	0.28	0.00
FR10	9.3%	0.53	0.00	0.00	0.18	0.06	0.00	0.00	0.00	0.18	0.06
Total	**100%**	**12.2%**	**12.7%**	**5.6%**	**11.4%**	**6.7%**	**10.6%**	**12.0%**	**10.2%**	**9.3%**	**9.4%**

Appendix C: List of TRIZ 39 Technical Parameters

Free access at https://onlinelibrary.wiley.com/doi/10.1002/9780470684320.app1 [232].

Table A.11: List of TRIZ 39 Technical Parameters.

No.	Title	Explanation
1	Weight of moving object	The mass of the object, in a gravitational field. The force that the body exerts on its support or suspension
2	Weight of stationary object	The mass of the object, in a gravitational field. The force that the body exerts on its support or suspension, or on the surface on which it rests.
3	Length of moving object	Any one linear dimension, not necessarily the longest, is considered a length.
4	Length of stationary object	Same.
5	Area of moving object	A geometrical characteristic described by the part of a plane enclosed by a line. The part of a surface occupied by the object OR the square measure of the surface, either internal or external, of an object.
6	Area of stationary object	Same.
7	Volume of moving object	The cubic measure of space occupied by the object. Length x width x height for a rectangular object, height x area for a cylinder, etc.
8	Volume of stationary object	Same.
9	Speed	The velocity of an object; the rate of a process or action in time.
10	Force	Force measures the interaction between systems. In Newtonian physics, force = mass x acceleration. In TRIZ, force is any interaction that is intended to change an object's condition.
11	Stress or pressure	Force per unit area. Also, tension.
12	Shape	The external contours, appearance of a system.
13	Stability of the object's composition	The wholeness or integrity of the system; the relationship of the system's constituent elements. Wear, chemical decomposition, and disassembly are all decreases in stability. Increasing entropy is decreasing stability.
14	Strength	The extent to which the object is able to resist changing in response to force. Resistance to breaking.
15	Duration of action by a moving object	The time that the object can perform the action. Service life. Mean time between failure is a measure of the duration of action. Also, durability.

No.	Title	Explanation
16	Duration of action by a stationary object	Same.
17	Temperature	The thermal condition of the object or system. Loosely includes other thermal parameters, such as heat capacity, that affect the rate of change of temperature.
18	Illumination intensity	Light flux per unit area, also any other illumination characteristics of the system such as brightness, light quality, etc.
19	Use of energy by moving object	The measure of the object's capacity for doing work. In classical mechanics, Energy is the product of force x distance. This includes the use of energy provided by the super - system (such as electrical energy or heat.) Energy required to do a particular job.
20	Use of energy by stationary object	Same.
21	Power	The time rate at which work is performed. The rate of use of energy.
22	Loss of energy	Use of energy that does not contribute to the job being done. See 19. Reducing the loss of energy sometimes requires different techniques from improving the use of energy, which is why this is a separate category.
23	Loss of substance	Partial or complete, permanent or temporary, loss of some of a system's materials, substances, parts or subsystems.
24	Loss of information	Partial or complete, permanent or temporary, loss of data or access to data in or by a system. Frequently includes sensory data such as aroma, texture, etc.
25	Loss of time	Time is the duration of an activity. Improving the loss of time means reducing the time taken for the activity. 'Cycle time reduction' is a common term.
26	Quantity of substance/the matter	The number or amount of a system's materials, substances, parts or subsystems which might be changed fully or partially, permanently or temporarily.
27	Reliability	A system's ability to perform its intended functions in predictable ways and conditions.
28	Measurement accuracy	The closeness of the measured value to the actual value of a property of a system. Reducing the error in a measurement increases the accuracy of the measurement.
29	Manufacturing precision	The extent to which the actual characteristics of the system or object match the specified or required characteristics.
30	External harm affects the object	Susceptibility of a system to externally generated (harmful) effects.
31	Object-generated harmful factors	A harmful effect is one that reduces the efficiency or quality of the functioning of the object or system. These

No.	Title	Explanation
		harmful effects are generated by the object or system, as part of its operation.
32	Ease of manufacture	The degree of facility, comfort or effortlessness in manufacturing or fabricating the object/system.
33	Ease of operation	Simplicity: The process is not easy if it requires a large number of people, large number of steps in the operation, needs special tools, etc. ‘Hard’ processes have low yield and ‘easy’ process have high yield; they are easy to do right.
34	Ease of repair	Quality characteristics such as convenience, comfort, simplicity, and time to repair faults, failures or defects in a system.
35	Adaptability or versatility	The extent to which a system/object positively responds to external changes. Also, a system that can be used in multiple ways for under a variety of circumstances.
36	Device complexity	The number and diversity of elements and element interrelationships within a system. The user may be an element of the system that increases the complexity. The difficulty of mastering the system is a measure of its complexity.
37	Difficulty of detecting and measuring	Measuring or monitoring systems that are complex, costly, require much time and labour to set up and use, or that have complex relationships between components or components that interfere with each other all demonstrate ‘difficulty of detecting and measuring’. Increasing cost of measuring to a satisfactory error is also a sign of increased difficulty of measuring.
38	Extent of automation	The extent to which a system or object performs its functions without human interface. The lowest level of automation is the use of a manually operated tool. For intermediate levels, humans program the tool, observe its operation, and interrupt or re-program as needed. For the highest level, the machine senses the operation needed, programs itself and monitors its own operations.
39	Productivity	The number of functions or operations performed by a system per unit time. The time for a unit function or operation. The output per unit time, or the cost per unit output.

Appendix D: Contradiction Matrix

Free access at https://www.triz.co.uk/learning-centre-innovation-materials [232].

Table A.12: Contradiction Matrix.

Worsening Feature Improving Feature		Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object	Speed	Force (Intensity)	Stress or pressure	Shape	Stability of the object's composition	Strength	Duration of action of moving object	Duration of action of stationary object	Temperature	Illumination intensity	Use of energy by moving object	Use of energy by stationary object	Power	Loss of Energy	Loss of Substance	Loss of Information	Loss of Time	Quantity of substance	Reliability	Measurement accuracy	Manufacturing precision	Object-affected harmful factors	Object-generated harmful factors	Ease of manufacture	Ease of operation	Ease of repair	Adaptability or versatility	Device complexity	Difficulty of detecting and measuring	Extent of automation	Productivity
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Weight of moving object	1	+		15, 8, 29,34		29, 17, 38, 34		29, 2, 40, 28		2, 8, 15, 38	8, 10, 18, 37	10, 36, 37, 40	10, 14, 35, 40	1, 35, 19, 39	28, 27, 18, 40	5, 34, 31, 35		6, 29, 4, 38	19, 1, 32	35, 12, 34, 31		12, 36, 18, 31	6, 2, 34, 19	5, 35, 3, 31	10, 24, 35	10, 35, 20, 28	3, 26, 18, 31	1, 3, 11, 27	28, 27, 35, 26	28, 35, 26, 18	22, 21, 18, 27	22, 35, 31, 39	27, 28, 1, 36	35, 3, 2, 24	2, 27, 28, 11	29, 5, 15, 8	26, 30, 36, 34	28, 29, 26, 32	26, 35 18, 19	35, 3, 24, 37
Weight of stationary object	2		+		10, 1, 29, 35		35, 30, 13, 2		5, 35, 14, 2		8, 10, 19, 35	13, 29, 10, 18	13, 10, 29, 14	26, 39, 1, 40	28, 2, 10, 27		2, 27, 19, 6	28, 19, 32, 22	19, 32, 35		18, 19, 28, 1	15, 19, 18, 22	18, 19, 28, 15	5, 8, 13, 30	10, 15, 35	10, 20, 35, 26	19, 6, 18, 26	10, 28, 8, 3	18, 26, 28	10, 1, 35, 17	2, 19, 22, 37	35, 22, 1, 39	28, 1, 9	6, 13, 1, 32	2, 27, 28, 11	19, 15, 29	1, 10, 26, 39	25, 28, 17, 15	2, 26, 35	1, 28, 15, 35
Length of moving object	3	8, 15, 29, 34		+		15, 17, 4		7, 17, 4, 35		13, 4, 8	17, 10, 4	1, 8, 35	1, 8, 10, 29	1, 8, 15, 34	8, 35, 29, 34	19		10, 15, 19	32	8, 35, 24		1, 35	7, 2, 35, 39	4, 29, 23, 10	1, 24	15, 2, 29	29, 35	10, 14, 29, 40	28, 32, 4	10, 28, 29, 37	1, 15, 17, 24	17, 15	1, 29, 17	15, 29, 35, 4	1, 28, 10	14, 15, 1, 16	1, 19, 26, 24	35, 1, 26, 24	17, 24, 26, 16	14, 4, 28, 29
Length of stationary object	4		35, 28, 40, 29		+		17, 7, 10, 40		35, 8, 2,14		28, 10	1, 14, 35	13, 14, 15, 7	39, 37, 35	15, 14, 28, 26		1, 10, 35	3, 35, 38, 18	3, 25			12, 8	6, 28	10, 28, 24, 35	24, 26,	30, 29, 14		15, 29, 28	32, 28, 3	2, 32, 10	1, 18		15, 17, 27	2, 25	3	1, 35	1, 26	26		30, 14, 7, 26
Area of moving object	5	2, 17, 29, 4		14, 15, 18, 4		+		7, 14, 17, 4		29, 30, 4, 34	19, 30, 35, 2	10, 15, 36, 28	5, 34, 29, 4	11, 2, 13, 39	3, 15, 40, 14	6, 3		2, 15, 16	15, 32, 19, 13	19, 32		19, 10, 32, 18	15, 17, 30, 26	10, 35, 2, 39	30, 26	26, 4	29, 30, 6, 13	29, 9	26, 28, 32, 3	2, 32	22, 33, 28, 1	17, 2, 18, 39	13, 1, 26, 24	15, 17, 13, 16	15, 13, 10, 1	15, 30	14, 1, 13	2, 36, 26, 18	14, 30, 28, 23	10, 26, 34, 2
Area of stationary object	6		30, 2, 14, 18		26, 7, 9, 39		+				1, 18, 35, 36	10, 15, 36, 37		2, 38	40		2, 10, 19, 30	35, 39, 38				17, 32	17, 7, 30	10, 14, 18, 39	30, 16	10, 35, 4, 18	2, 18, 40, 4	32, 35, 40, 4	26, 28, 32, 3	2, 29, 18, 36	27, 2, 39, 35	22, 1, 40	40, 16	16, 4	16	15, 16	1, 18, 36	2, 35, 30, 18	23	10, 15, 17, 7
Volume of moving object	7	2, 26, 29, 40		1, 7, 4, 35		1, 7, 4, 17		+		29, 4, 38, 34	15, 35, 36, 37	6, 35, 36, 37	1, 15, 29, 4	28, 10, 1, 39	9, 14, 15, 7	6, 35, 4		34, 39, 10, 18	2, 13, 10	35		35, 6, 13, 18	7, 15, 13, 16	36, 39, 34, 10	2, 22	2, 6, 34, 10	29, 30, 7	14, 1, 40, 11	25, 26, 28	25, 28, 2, 16	22, 21, 27, 35	17, 2, 40, 1	29, 1, 40	15, 13, 30, 12	10	15, 29	26, 1	29, 26, 4	35, 34, 16, 24	10, 6, 2, 34
Volume of stationary object	8		35, 10, 19, 14	19, 14	35, 8, 2, 14				+		2, 18, 37	24, 35	7, 2, 35	34, 28, 35, 40	9, 14, 17, 15		35, 34, 38	35, 6, 4				30, 6		10, 39, 35, 34		35, 16, 32 18	35, 3	2, 35, 16		35, 10, 25	34, 39, 19, 27	30, 18, 35, 4	35		1		1, 31	2, 17, 26		35, 37, 10, 2
Speed	9	2, 28, 13, 38		13, 14, 8		29, 30, 34		7, 29, 34		+	13, 28, 15, 19	6, 18, 38, 40	35, 15, 18, 34	28, 33, 1, 18	8, 3, 26, 14	3, 19, 35, 5		28, 30, 36, 2	10, 13, 19	8, 15, 35, 38		19, 35, 38, 2	14, 20, 19, 35	10, 13, 28, 38	13, 26		10, 19, 29, 38	11, 35, 27, 28	28, 32, 1, 24	10, 28, 32, 25	1, 28, 35, 23	2, 24, 35, 21	35, 13, 8, 1	32, 28, 13, 12	34, 2, 28, 27	15, 10, 26	10, 28, 4, 34	3, 34, 27, 16	10, 18	
Force (Intensity)	10	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	28, 10	19, 10, 15	1, 18, 36, 37	15, 9, 12, 37	2, 36, 18, 37	13, 28, 15, 12	+	18, 21, 11	10, 35, 40, 34	35, 10, 21	35, 10, 14, 27	19, 2		35, 10, 21		19, 17, 10	1, 16, 36, 37	19, 35, 18, 37	14, 15	8, 35, 40, 5		10, 37, 36	14, 29, 18, 36	3, 35, 13, 21	35, 10, 23, 24	28, 29, 37, 36	1, 35, 40, 18	13, 3, 36, 24	15, 37, 18, 1	1, 28, 3, 25	15, 1, 11	15, 17, 18, 20	26, 35, 10, 18	36, 37, 10, 19	2, 35	3, 28, 35, 37
Stress or pressure	11	10, 36, 37, 40	13, 29, 10, 18	35, 10, 36	35, 1, 14, 16	10, 15, 36, 28	10, 15, 36, 37	6, 35, 10	35, 24	6, 35, 36	36, 35, 21	+	35, 4, 15, 10	35, 33, 2, 40	9, 18, 3, 40	19, 3, 27		35, 39, 19, 2		14, 24, 10, 37		10, 35, 14	2, 36, 25	10, 36, 3, 37		37, 36, 4	10, 14, 36	10, 13, 19, 35	6, 28, 25	3, 35	22, 2, 37	2, 33, 27, 18	1, 35, 16	11	2	35	19, 1, 35	2, 36, 37	35, 24	10, 14, 35, 37
Shape	12	8, 10, 29, 40	15, 10, 26, 3	29, 34, 5, 4	13, 14, 10, 7	5, 34, 4, 10		14, 4, 15, 22	7, 2, 35	35, 15, 34, 18	35, 10, 37, 40	34, 15, 10, 14	+	33, 1, 18, 4	30, 14, 10, 40	14, 26, 9, 25		22, 14, 19, 32	13, 15, 32	2, 6, 34, 14		4, 6, 2	14	35, 29, 3, 5		14, 10, 34, 17	36, 22	10, 40, 16	28, 32, 1	32, 30, 40	22, 1, 2, 35	35, 1	1, 32, 17, 28	32, 15, 26	2, 13, 1	1, 15, 29	16, 29, 1, 28	15, 13, 39	15, 1, 32	17, 26, 34, 10
Stability of the object's composition	13	21, 35, 2, 39	26, 39, 1, 40	13, 15, 1, 28	37	2, 11, 13	39	28, 10, 19, 39	34, 28, 35, 40	33, 15, 28, 18	10, 35, 21, 16	2, 35, 40	22, 1, 18, 4	+	17, 9, 15	13, 27, 10, 35	39, 3, 35, 23	35, 1, 32	32, 3, 27, 16	13, 19	27, 4, 29, 18	32, 35, 27, 31	14, 2, 39, 6	2, 14, 30, 40		35, 27	15, 32, 35		13	18	35, 24, 30, 18	35, 40, 27, 39	35, 19	32, 35, 30	2, 35, 10, 16	35, 30, 34, 2	2, 35, 22, 26	35, 22, 39, 23	1, 8, 35	23, 35, 40, 3
Strength	14	1, 8, 40, 15	40, 26, 27, 1	1, 15, 8, 35	15, 14, 28, 26	3, 34, 40, 29	9, 40, 28	10, 15, 14, 7	9, 14, 17, 15	8, 13, 26, 14	10, 18, 3, 14	10, 3, 18, 40	10, 30, 35, 40	13, 17, 35	+	27, 3, 26		30, 10, 40	35, 19	19, 35, 10	35	10, 26, 35, 28	35	35, 28, 31, 40		29, 3, 28, 10	29, 10, 27	11, 3	3, 27, 16	3, 27	18, 35, 37, 1	15, 35, 22, 2	11, 3, 10, 32	32, 40, 25, 2	27, 11, 3	15, 3, 32	2, 13, 25, 28	27, 3, 15, 40	15	29, 35, 10, 14
Duration of action of moving object	15	19, 5, 34, 31		2, 19, 9		3, 17, 19		10, 2, 19, 30		3, 35, 5	19, 2, 16	19, 3, 27	14, 26, 28, 25	13, 3, 35	27, 3, 10	+		19, 35, 39	2, 19, 4, 35	28, 6, 35, 18		19, 10, 35, 38		28, 27, 3, 18	10	20, 10, 28, 18	3, 35, 10, 40	11, 2, 13	3	3, 27, 16, 40	22, 15, 33, 28	21, 39, 16, 22	27, 1, 4	12, 27	29, 10, 27	1, 35, 13	10, 4, 29, 15	19, 29, 39, 35	6, 10	35, 17, 14, 19
Duration of action by stationary object	16		6, 27, 19, 16		1, 40, 35				35, 34, 38					39, 3, 35, 23			+	19, 18, 36, 40				16		27, 16, 18, 38	10	28, 20, 10, 16	3, 35, 31	34, 27, 6, 40	10, 26, 24		17, 1, 40, 33	22	35, 10	1	1	2		25, 34, 6, 35	1	20, 10, 16, 38
Temperature	17	36,22, 6, 38	22, 35, 32	15, 19, 9	15, 19, 9	3, 35, 39, 18	35, 38	34, 39, 40, 18	35, 6, 4	2, 28, 36, 30	35, 10, 3, 21	35, 39, 19, 2	14, 22, 19, 32	1, 35, 32	10, 30, 22, 40	19, 13, 39	19, 18, 36, 40	+	32, 30, 21, 16	19, 15, 3, 17		2, 14, 17, 25	21, 17, 35, 38	21, 36, 29, 31		35, 28, 21, 18	3, 17, 30, 39	19, 35, 3, 10	32, 19, 24	24	22, 33, 35, 2	22, 35, 2, 24	26, 27	26, 27	4, 10, 16	2, 18, 27	2, 17, 16	3, 27, 35, 31	26, 2, 19, 16	15, 28, 35
Illumination intensity	18	19, 1, 32	2, 35, 32	19, 32, 16		19, 32, 26		2, 13, 10		10, 13, 19	26, 19, 6		32, 30	32, 3, 27	35, 19	2, 19, 6		32, 35, 19	+	32, 1, 19	32, 35, 1, 15	32	13, 16, 1, 6	13, 1	1, 6	19, 1, 26, 17	1, 19		11, 15, 32	3, 32	15, 19	35, 19, 32, 39	19, 35, 28, 26	28, 26, 19	15, 17, 13, 16	15, 1, 19	6, 32, 13	32, 15	2, 26, 10	2, 25, 16
Use of energy by moving object	19	12,18, 28,31		12, 28		15, 19, 25		35, 13, 18		8, 35, 35	16, 26, 21, 2	23, 14, 25	12, 2, 29	19, 13, 17, 24	5, 19, 9, 35	28, 35, 6, 18	-	19, 24, 3, 14	2, 15, 19	+	-	6, 19, 37, 18	12, 22, 15, 24	35, 24, 18, 5		35, 38, 19, 18	34, 23, 16, 18	19, 21, 11, 27	3, 1, 32		1, 35, 6, 27	2, 35, 6	28, 26, 30	19, 35	1, 15, 17, 28	15, 17, 13, 16	2, 29, 27, 28	35, 38	32, 2	12, 28, 35
Use of energy by stationary object	20		19, 9, 6, 27								36, 37			27, 4, 29, 18	35				19, 2, 35, 32	-	+			28, 27, 18, 31			3, 35, 31	10, 36, 23			10, 2, 22, 37	19, 22, 18	1, 4					19, 35, 16, 25		1, 6
Power	21	8, 36, 38, 31	19, 26, 17, 27	1, 10, 35, 37		19, 38	17, 32, 13, 38	35, 6, 38	30, 6, 25	15, 35, 2	26, 2, 36, 35	22, 10, 35	29, 14, 2, 40	35, 32, 15, 31	26, 10, 28	19, 35, 10, 38	16	2, 14, 17, 25	16, 6, 19	16, 6, 19, 37		+	10, 35, 38	28, 27, 18, 38	10, 19	35, 20, 10, 6	4, 34, 19	19, 24, 26, 31	32, 15, 2	32, 2	19, 22, 31, 2	2, 35, 18	26, 10, 34	26, 35, 10	35, 2, 10, 34	19, 17, 34	20, 19, 30, 34	19, 35, 16	28, 2, 17	28, 35, 34
Loss of Energy	22	15, 6, 19, 28	19, 6, 18, 9	7, 2, 6, 13	6, 38, 7	15, 26, 17, 30	17, 7, 30, 18	7, 18, 23	7	16, 35, 38	36, 38			14, 2, 39, 6	26			19, 38, 7	1, 13, 32, 15			3, 38	+	35, 27, 2, 37	19, 10	10, 18, 32, 7	7, 18, 25	11, 10, 35	32		21, 22, 35, 2	21, 35, 2, 22		35, 32, 1	2, 19		7, 23	35, 3, 15, 23	2	28, 10, 29, 35
Loss of substance	23	35, 6, 23, 40	35, 6, 22, 32	14, 29, 10, 39	10, 28,24	35, 2, 10, 31	10, 18, 39, 31	1, 29, 30, 36	3, 39, 18, 31	10, 13, 28, 38	14, 15, 18, 40	3, 36, 37, 10	29, 35, 3, 5	2, 14, 30, 40	35, 28, 31, 40	28, 27, 3, 18	27, 16, 18, 38	21, 36, 39, 31	1, 6, 13	35, 18, 24, 5	28, 27, 12, 31	28, 27, 18, 38	35, 27, 2, 31	+		15, 18, 35, 10	6, 3, 10, 24	10, 29, 39, 35	16, 34, 31, 28	35, 10, 24, 31	33, 22, 30, 40	10, 1, 34, 29	15, 34, 33	32, 28, 2, 24	2, 35, 34, 27	15, 10, 2	35, 10, 28, 24	35, 18, 10, 13	35, 10, 18	28, 35, 10, 23
Loss of Information	24	10, 24, 35	10, 35, 5	1, 26	26	30, 26	30, 16		2, 22	26, 32						10	10		19			10, 19	19, 10		+	24, 26, 28, 32	24, 28, 35	10, 28, 23			22, 10, 1	10, 21, 22	32	27, 22				35, 33	35	13, 23, 15
Loss of Time	25	10, 20, 37, 35	10, 20, 26, 5	15, 2, 29	30, 24, 14, 5	26, 4, 5, 16	10, 35, 17, 4	2, 5, 34, 10	35, 16, 32, 18		10, 37, 36,5	37, 36,4	4, 10, 34, 17	35, 3, 22, 5	29, 3, 28, 18	20, 10, 28, 18	28, 20, 10, 16	35, 29, 21, 18	1, 19, 26, 17	35, 38, 19, 18	1	35, 20, 10, 6	10, 5, 18, 32	35, 18, 10, 39	24, 26, 28, 32	+	35, 38, 18, 16	10, 30, 4	24, 34, 28, 32	24, 26, 28, 18	35, 18, 34	35, 22, 18, 39	35, 28, 34, 4	4, 28, 10, 34	32, 1, 10	35, 28	6, 29	18, 28, 32, 10	24, 28, 35, 30	
Quantity of substance/the matter	26	35, 6, 18, 31	27, 26, 18, 35	29, 14, 35, 18		15, 14, 29	2, 18, 40, 4	15, 20, 29		35, 29, 34, 28	35, 14, 3	10, 36, 14, 3	35, 14	15, 2, 17, 40	14, 35, 34, 10	3, 35, 10, 40	3, 35, 31	3, 17, 39		34, 29, 16, 18	3, 35, 31	35	7, 18, 25	6, 3, 10, 24	24, 28, 35	35, 38, 18, 16	+	18, 3, 28, 40	13, 2, 28	33, 30	35, 33, 29, 31	3, 35, 40, 39	29, 1, 35, 27	35, 29, 25, 10	2, 32, 10, 25	15, 3, 29	3, 13, 27, 10	3, 27, 29, 18	8, 35	13, 29, 3, 27
Reliability	27	3, 8, 10, 40	3, 10, 8, 28	15, 9, 14, 4	15, 29, 28, 11	17, 10, 14, 16	32, 35, 40, 4	3, 10, 14, 24	2, 35, 24	21, 35, 11, 28	8, 28, 10, 3	10, 24, 35, 19	35, 1, 16, 11		11, 28	2, 35, 3, 25	34, 27, 6, 40	3, 35, 10	11, 32, 13	21, 11, 27, 19	36, 23	21, 11, 26, 31	10, 11, 35	10, 35, 29, 39	10, 28	10, 30, 4	21, 28, 40, 3	+	32, 3, 11, 23	11, 32, 1	27, 35, 2, 40	35, 2, 40, 26		27, 17, 40	1, 11	13, 35, 8, 24	13, 35, 1	27, 40, 28	11, 13, 27	1, 35, 29, 38
Measurement accuracy	28	32, 35, 26, 28	28, 35, 25, 26	28, 26, 5, 16	32, 28, 3, 16	26, 28, 32, 3	26, 28, 32, 3	32, 13, 6		28, 13, 32, 24	32, 2	6, 28, 32	6, 28, 32	32, 35, 13	28, 6, 32	28, 6, 32	10, 26, 24	6, 19, 28, 24	6, 1, 32	3, 6, 32		3, 6, 32	26, 32, 27	10, 16, 31, 28		24, 34, 28, 32	2, 6, 32	5, 11, 1, 23	+		28, 24, 22, 26	3, 33, 39, 10	6, 35, 25, 18	1, 13, 17, 34	1, 32, 13, 11	13, 35, 2	27, 35, 10, 34	26, 24, 32, 28	28, 2, 10, 34	10, 34, 28, 32
Manufacturing precision	29	28, 32, 13, 18	28, 35, 27, 9	10, 28, 29, 37	2, 32, 10	28, 33, 29, 32	2, 29, 18, 36	32, 23, 2	25, 10, 35	10, 28, 32	28, 19, 34, 36	3, 35	32, 30, 40	30, 18	3, 27	3, 27, 40		19, 26	3, 32	32, 2		32, 2	13, 32, 2	35, 31, 10, 24		32, 26, 28, 18	32, 30	11, 32, 1		+	26, 28, 10, 36	4, 17, 34, 26		1, 32, 35, 23	25, 10		26, 2, 18		26, 28, 18, 23	10, 18, 32, 39
Object-affected harmful factors	30	22, 21, 27, 39	2, 22, 13, 24	17, 1, 39, 4	1, 18	22, 1, 33, 28	27, 2, 39, 35	22, 23, 37, 35	34, 39, 19, 27	21, 22, 35, 28	13, 35, 39, 18	22, 2, 37	22, 1, 3, 35	35, 24, 30, 18	18, 35, 37, 1	22, 15, 33, 28	17, 1, 40, 33	22, 33, 35, 2	1, 19, 32, 13	1, 24, 6, 27	10, 2, 22, 37	19, 22, 31, 2	21, 22, 35, 2	33, 22, 19, 40	22, 10, 2	35, 18, 34	35, 33, 29, 31	27, 24, 2, 40	28, 33, 23, 26	26, 28, 10, 18	+		24, 35, 2	2, 25, 28, 39	35, 10, 2	35, 11, 22, 31	22, 19, 29, 40	22, 19, 29, 40	33, 3, 34	22, 35, 13, 24
Object-generated harmful factors	31	19, 22, 15, 39	35, 22, 1, 39	17, 15, 16, 22		17, 2, 18, 39	22, 1, 40	17, 2, 40	30, 18, 35, 4	35, 28, 3, 23	35, 28, 1, 40	2, 33, 27, 18	35, 1	35, 40, 27, 39	15, 35, 22, 2	15, 22, 33, 31	21, 39, 16, 22	22, 35, 2, 24	19, 24, 39, 32	2, 35, 6	19, 22, 18	2, 35, 18	21, 35, 2, 22	10, 1, 34	10, 21, 29	1, 22	3, 24, 39, 1	24, 2, 40, 39	3, 33, 26	4, 17, 34, 26		+					19, 1, 31	2, 21, 27, 1	2	22, 35, 18, 39
Ease of manufacture	32	28, 29, 15, 16	1, 27, 36, 13	1, 29, 13, 17	15, 17, 27	13, 1, 26, 12	16, 40	13, 29, 1, 40	35	35, 13, 8, 1	35, 12	35, 19, 1, 37	1, 28, 13, 27	11, 13, 1	1, 3, 10, 32	27, 1, 4	35, 16	27, 26, 18	28, 24, 27, 1	28, 26, 27, 1	1, 4	27, 1, 12, 24	19, 35	15, 34, 33	32, 24, 18, 16	35, 28, 34, 4	35, 23, 1, 24		1, 35, 12, 18		24, 2		+	2, 5, 13, 16	35, 1, 11, 9	2, 13, 15	27, 26, 1	6, 28, 11, 1	8, 28, 1	35, 1, 10, 28
Ease of operation	33	25, 2, 13, 15	6, 13, 1, 25	1, 17, 13, 12		1, 17, 13, 16	18, 16, 15, 39	1, 16, 35, 15	4, 18, 39, 31	18, 13, 34	28, 13 35	2, 32, 12	15, 34, 29, 28	32, 35, 30	32, 40, 3, 28	29, 3, 8, 25	1, 16, 25	26, 27, 13	13, 17, 1, 24	1, 13, 24		35, 34, 2, 10	2, 19, 13	28, 32, 2, 24	4, 10, 27, 22	4, 28, 10, 34	12, 35	17, 27, 8, 40	25, 13, 2, 34	1, 32, 35, 23	2, 25, 28, 39		2, 5, 12	+	12, 26, 1, 32	15, 34, 1, 16	32, 26, 12, 17		1, 34, 12, 3	15, 1, 28
Ease of repair	34	2, 27 35, 11	2, 27, 35, 11	1, 28, 10, 25	3, 18, 31	15, 13, 32	16, 25	25, 2, 35, 11	1	34, 9	1, 11, 10	13	1, 13, 2, 4	2, 35	11, 1, 2, 9	11, 29, 28, 27	1	4, 10	15, 1, 13	15, 1, 28, 16		15, 10, 32, 2	15, 1, 32, 19	2, 35, 34, 27		32, 1, 10, 25	2, 28, 10, 25	11, 10, 1, 16	10, 2, 13	25, 10	35, 10, 2, 16		1, 35, 11, 10	1, 12, 26, 15	+	7, 1, 4, 16	35, 1, 13, 11		34, 35, 7, 13	1, 32, 10
Adaptability or versatility	35	1, 6, 15, 8	19, 15, 29, 16	35, 1, 29, 2	1, 35, 16	35, 30, 29, 7	15, 16	15, 35, 29		35, 10, 14	15, 17, 20	35, 16	15, 37, 1, 8	35, 30, 14	35, 3, 32, 6	13, 1, 35	2, 16	27, 2, 3, 35	6, 22, 26, 1	19, 35, 29, 13		19, 1, 29	18, 15, 1	15, 10, 2, 13		35, 28	3, 35, 15	35, 13, 8, 24	35, 5, 1, 10		35, 11, 32, 31		1, 13, 31	15, 34, 1, 16	1, 16, 7, 4	+	15, 29, 37, 28	1	27, 34, 35	35, 28, 6, 37
Device complexity	36	26, 30, 34, 36	2, 26, 35, 39	1, 19, 26, 24	26	14, 1, 13, 16	6, 36	34, 26, 6	1, 16	34, 10, 28	26, 16	19, 1, 35	29, 13, 28, 15	2, 22, 17, 19	2, 13, 28	10, 4, 28, 15		2, 17, 13	24, 17, 13	27, 2, 29, 28		20, 19, 30, 34	10, 35, 13, 2	35, 10, 28, 29		6, 29	13, 3, 27, 10	13, 35, 1	2, 26, 10, 34	26, 24, 32	22, 19, 29, 40	19, 1	27, 26, 1, 13	27, 9, 26, 24	1, 13	29, 15, 28, 37	+	15, 10, 37, 28	15, 1, 24	12, 17, 28
Difficulty of detecting and measuring	37	27, 26, 28, 13	6, 13, 28, 1	16, 17, 26, 24	26	2, 13, 18, 17	2, 39, 30, 16	29, 1, 4, 16	2, 18, 26, 31	3, 4, 16, 35	30, 28, 40, 19	35, 36, 37, 32	27, 13, 1, 39	11, 22, 39, 30	27, 3, 15, 28	19, 29, 39, 25	25, 34, 6, 35	3, 27, 35, 16	2, 24, 26	35, 38	19, 35, 16	18, 1, 16, 10	35, 3, 15, 19	1, 18, 10, 24	35, 33, 27, 22	18, 28, 32, 9	3, 27, 29, 18	27, 40, 28, 8	26, 24, 32, 28		22, 19, 29, 28	2, 21	5, 28, 11, 29	2, 5	12, 26	1, 15	15, 10, 37, 28	+	34, 21	35, 18
Extent of automation	38	28, 26, 18, 35	28, 26, 35, 10	14, 13, 17, 28	23	17, 14, 13		35, 13, 16		28, 10	2, 35	13, 35	15, 32, 1, 13	18, 1	25, 13	6, 9		26, 2, 19	8, 32, 19	2, 32, 13		28, 2, 27	23, 28	35, 10, 18, 5	35, 33	24, 28, 35, 30	35, 13	11, 27, 32	28, 26, 10, 34	28, 26, 18, 23	2, 33	2	1, 26, 13	1, 12, 34, 3	1, 35, 13	27, 4, 1, 35	15, 24, 10	34, 27, 25	+	5, 12, 35, 26
Productivity	39	35, 26, 24, 37	28, 27, 15, 3	18, 4, 28, 38	30, 7, 14, 26	10, 26, 34, 31	10, 35, 17, 7	2, 6, 34, 10	35, 37, 10, 2		28, 15, 10, 36	10, 37, 14	14, 10, 34, 40	35, 3, 22, 39	29, 28, 10, 18	35, 10, 2, 18	20, 10, 16, 38	35, 21, 28, 10	26, 17, 19, 1	35, 10, 38, 19	1	35, 20, 10	28, 10, 29, 35	28, 10, 35, 23	13, 15, 23		35, 38	1, 35, 10, 38	1, 10, 34, 28	18, 10, 32, 1	22, 35, 13, 24	35, 22, 18, 39	35, 28, 2, 24	1, 28, 7, 10	1, 32, 10, 25	1, 35, 28, 37	12, 17, 28, 24	35, 18, 27, 2	5, 12, 35, 26	+

Appendix E: List of TRIZ 40 Inventive Principles

List of 40 inventive principles and 160 elementary operators based on the extensive experience of TRIZ application in industrial companies [315].

Table A.13: List of TRIZ 40 Inventive Principles.

No.	Inventive Principle	Inventive Operator
1	Segmentation	a) Divide the object into independent objects or parts. b) Design the object to be sectional or dismountable. c) Increase the object's degree of fragmentation or segmentation: reduce size up to granules and powder, micro- and nano-level, molecules and atoms. d) Divide the function of the object or system into independent sub-functions. e) Divide the process steps into sub-steps, make two or more process steps instead of one.
2	Leaving out / Trimming	a) Take out or remove the disturbing parts or substances from the system. b) Check which system components, parts or substances can be omitted. c) Take out or remove the disturbing functions from the system. Check which functions can be omitted. d) Take out or remove one of the process steps. e) Extract or single out the only one necessary part, substance, property or function from the system.
3	Local quality	a) Change the uniform structure or properties of an object to a non-uniform. b) Change the uniform structure or properties of surrounding medium (external environment) to non-uniform. c) The various parts of the object should fulfil different functions. d) Each part of the object should function under conditions which are most suitable for its operation. e) Different parts of the object can have opposite properties (e.g. one part hot, another part cold).
4	Asymmetry	a) Replace the symmetrical shape or property of an object with one that is asymmetrical. b) If the object is already asymmetrical, increase its degree of asymmetry. c) Convert the asymmetrical shape or property of an object back to symmetrical one.
5	Combining	a) Combine identical objects in space to perform parallel operations. b) Combine functions or process steps in time to perform parallel or contiguous operations. c) Combine similar objects with different characteristics, properties or parameters. d) Combine different objects complementing each other and enhancing positive properties. e) Combine objects with competing, alternative or opposing properties (e.g. caustic and acid).
6	Universality	a) Make a part or object universal, performing multiple functions, and thus eliminate unnecessary objects. b) Make a process universal, for example suitable for different substances, conditions, operations, etc.
7	Nesting / Integration	a) Place an object inside another one, which, in turn, is placed inside a third object and so on (Nested Doll principle). b) An object is passed through the cavities in another object.

No.	Inventive Principle	Inventive Operator
		c) Telescopic objects or systems.
8	Anti-weight	a) Compensate the object's weight by counterweight. b) Compensate the object's weight by merging it with another object that provides a lifting force /buoyancy (e.g. floating object or hot-air balloon). c) Compensate the object's weight by interaction with another medium (e.g. by means of aerodynamic or hydrodynamic forces). d) Use gravitational force or centrifugal force.
9	Prior counteraction of harm	a) If it is necessary to perform an action with both harmful and useful effects, b) counteraction measures against harm must be taken in advance. c) If the object will be under working stress, create beforehand stress in direction which is opposite the undesirable working stress. Thus, the working stress can be compensated. d) If the object will be exposed to high temperatures, cool it beforehand to avoid overheating. e) Use rigid constructions, highly stable structures (e.g. honeycomb) to withstand extreme operating conditions like high temperature, high pressure, high volume.
10	Prior useful action	f) Perform the required action or useful function in advance, either fully or partially. g) Pre-arrange the objects so they can come into action at the most convenient position and without losing time. h) Perform part of the process step or operation beforehand.
11	Preventive measure / Cushion in advance	a) Compensate the low reliability of an object by preparing emergency countermeasures in advance. b) Increase process reliability by preparing emergency countermeasures in advance.
12	Equipotentiality	a) Change the working conditions so that an object doesn't have to be raised or lowered. b) Avoid changes of potential energy in the system. c) Avoid strong fluctuations of process parameter, peaks and valleys in energy d) consumption, thermal shocks, etc.
13	Inversion	a) Instead of currently used action, carry out the inversed action with opposite direction or properties (e.g. heating instead of cooling, downwards instead upwards, etc). b) Make moving parts of the object fixed, and the fixed parts movable. c) Turn the object or process upside down. d) Perform the process or its phases in the reversed order. Change sequence of operations. e) Change properties or action mode of the external environment to the opposite (e.g. moving to fixed, high pressure to vacuum, etc).
14	Sphericity and rotation	a) Replace rectilinear parts or forms with curved, ball-shaped forms or structures. b) Use balls, rollers, spheres, domes or spirals. Apply cylindrical, conical or multi-conical configurations. c) Provide rotary motion of parts, substances or force fields. Replace a linear motion of objects or substances with rotation. d) Use vortex flows and swirling motion for cyclonic separation, cooling or heating. e) Use centrifugal and Coriolis forces.

No.	Inventive Principle	Inventive Operator
15	Dynamism	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.
16	Partial or excessive action	a) If it is difficult to obtain exactly 100% of a desired effect, then obtain slightly more or slightly less. The problem may be considerably easier to solve. b) If it is difficult to obtain the optimal or exact amount of substance, apply an excessive amount. Remove surplus substance by using additional force or energy field. c) If it is difficult to obtain the optimal or exact action (force or energy field), apply an excessive action. Compensate surplus action by using protective shield.
17	Shift to another dimension	a) Change the straight line to a 2D or 3D curve, or plane form or movement to the three-dimensional. b) Reduce object size or dimensions to mini-, micro- or nano-level. c) Use a multi-layered or multi-storey structure of objects or processes. d) Tilt the object, lay it on its side, use reversed side or internal surfaces (hollows). e) Increase contact area between objects or substances from the contact along a line or on a surface to interaction in 3D-space.
18	Mechanical vibration	a) Cause an object to oscillate or vibrate. b) If oscillation already exists, change, or increase its frequency (even up to the ultrasonic). c) Use the resonant frequency of an object and self-oscillations. d) Use piezo-electric vibrators instead of mechanical ones. e) Combine ultrasonic oscillations with other fields: ultrasonic and electromagnetic vibrations; ultrasonic with heat source; ultrasonic with capillary effect.
19	Periodic action	a) Replace a continuous action with a periodic or pulsed one. b) If an action is already periodic, change its frequency, amplitude, and mean value. c) Use pauses between impulses to perform additional actions. The frequencies of all periodic actions should be matched or intentionally mismatched. d) Avoid or use resonance. The frequencies of the periodic action should be matched or intentionally mismatched to the natural frequency of one of the objects. e) Apply mutually exclusive periodic actions alternately. Separate contradictory properties in time.
20	Continuity of useful action	a) Carry on a process continuously (without pauses). b) All parts of an object or equipment should operate at full load. c) Eliminate all idle and intermittent actions or work.
21	Skipping / Rushing through	a) Perform a process, or individual stages at very high speed to skip destructible or hazardous operations. b) Increase dramatically the speed or power in a process that may result in new useful properties of the system.

No.	Inventive Principle	Inventive Operator
22	Converting harm into benefit	a) Utilize harmful factors or negative environmental effects to obtain a positive effect. b) Remove a harmful factor by combining it with another harmful factor. c) Amplify a harmful action to such a degree that it is no longer harmful.
23	Feedback and automation	a) Introduce feedback to improve a process or action. b) If feedback already exists, change it (e.g. its magnitude or influence). c) Increase a degree of automation and controllability of the system, use adaptive feedback control and artificial intelligence. d) Utilize information and data processing.
24	Mediator	a) Introduce an intermediate object to transfer or carry out an action. b) Merge one object temporarily with another intermediate object that can be easily removed. c) Use an intermediary process or process step.
25	Self-service / Use of resources	a) Make the object serve itself and carry out supplementary and repair operations. b) Utilize waste resources, energy, or substances. c) Use available environmental resources: substances, energy, space, information, and data.
26	Copying and modelling	a) Use simple inexpensive copies instead of unavailable, expensive, fragile objects. b) Replace an object or process with its optical copies (graphical images, three-dimensional images, holograms). c) If visible optical copies are already used, move to infrared, ultraviolet, X-ray copies, optical or radio shadows. d) Use digital models and computer simulations. e) Use virtual reality, computer augmented reality, etc.
27	Disposability / Cheap short-living objects	a) Use cheap short-living objects or substances. b) Replace an expensive object by a multiple inexpensive one, forgoing certain qualities (e.g. longevity). c) Use one-way disposable or temporary objects. d) Create cheap short-living objects from available resources, such as waste, water, air, environment, etc.
28	Replacement of the mechanical working principle	a) Replace the mechanical working principle by electric, magnetic, or electromagnetic one. b) Use optical working principle (e.g. IR, UV, Laser, LED). c) Use an acoustic or sound system (e.g. ultrasonic, infrasonic, etc). d) Use thermal, chemical, olfactory (smell) or biological system. e) Use electromagnetic fields in conjunction with ferromagnetic particles, magnetic or electro-rheological fluids.
29	Pneumatic or hydraulic constructions	a) Use gas or liquid as working elements, for example gas and liquid flows, aero- and hydrostatics or dynamics, hydro-reactive systems, etc. b) Replace solid parts by gas or liquid (e.g. inflatable elements, air cushion, parts filled with liquids under pressure). c) Use negative pressure, partial vacuum, and vacuum chambers. d) Use fluidisation of powders, dusts or granulates in the air flow, for example in the fluidised bed. e) Use fluids and gases for heat and energy transfer: heat pipe, heat exchanger, vortex cooler tube, shock waves, cavitation, etc.

No.	Inventive Principle	Inventive Operator
30	Flexible shells or thin films	a) Replace traditional constructions with those made of flexible shells or thin films. b) Isolate the object or parts from its environment using flexible shells or thin films. c) Use piezoelectric foils. d) Apply flexible brushes for guiding, cleaning, vibration damping. e) Use membranes, membrane operations and processing.
31	Porous materials	a) Make an object or its surface porous, or add porous elements (inserts, covers, etc). Utilize objects with hollow spaces or cavities. b) If an object is already porous, fill the pores with a useful substance. c) Utilize capillary and micro-capillary effects in porous materials. d) Use the filler in combination with physical effects (e.g. ultrasound, electromagnetic field, temperature differences, osmosis, etc). e) Use structured porosity, like honeycombed structure, pipes or canals, capillaries on the molecular level.
32	Changing colour	a) Change the colour of an object or its external environment. b) Change the degree of transparency of an object or its external environment. c) Use coloured additives to observe an object or process which is difficult to see. d) If such additives are already being used, add luminescent traces or other tracer elements.
33	Homogeneity	a) Make objects interacting with a given object of the same material, or material with identical properties. b) The interacting objects should have similar properties such as size, weight, temperature, optical or magnetic properties, etc. c) Homogeneous or uniform distribution of material or properties (temperature, concentration, viscosity, etc).
34	Discarding and restoring	a) Reject or modify (discard, dissolve, evaporate, etc) a part of an object after it has completed its function or become useless. b) Restore any part of an object which has become exhausted or depleted directly in operation. c) Generate object or material just on time and on site, that can be more efficient and less expensive.
35	Transformation of the 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 process chemistry.
36	Phase transitions	a) Use phenomena accompanying the phase transitions of a substance (e.g. the emission or absorption of heat energy, density or volume changes, etc). b) Use the second-order phase transitions: shape memory of metals and polymers, transition beyond the Curie point in ferromagnetic substances, conversion of a crystalline structure, etc.

No.	Inventive Principle	Inventive Operator
37	Thermal expansion and contraction	a) Use thermal expansion or contraction of materials (solids, fluids or gases). b) Use constructions made of multiple materials with different coefficients of thermal expansion (e.g. bi-metals). c) Use heat shrinkable materials (e.g. heat shrinkable tubing). d) Use thermo-mechanical shape memory of metals and polymers.
38	Strong oxidants	a) Replace common air with oxygen-enriched air. b) Replace oxygen-enriched air with pure oxygen. c) Expose air or oxygen to ionising radiation, use ionized oxygen. d) Raise the ozone level. Replace ozonized (or ionized) oxygen with ozone. e) Use other strong or extreme oxidants.
39	Inert environment	a) Replace the normal environment with an inert one. b) Carry out the process in inert atmosphere of (e.g. helium or argon). c) Carry out the process in a vacuum. d) Use inert, protective or antioxidant coatings or additives. e) Use foams or foamed substances to protect or isolate objects.
40	Composite materials	a) Replace a homogeneous, uniform material with a composite one (e.g. carbon-fibre composite, laminates, etc). b) Take advantage of the anisotropic properties of the composite materials, like mechanical, electrical, thermal. c) Use additives to provide specific properties to the composites (e.g. fire retardant additives in polymer matrix composites). d) Use materials with composite microstructure, controllable by external field. e) Use a composition of materials in different aggregate states (e.g. mixture of liquid and gas).

Appendix F: RM5 Breakdowns

Table A.14: Detailed Breakdown of Cost and Performance (adapted from [282])

ID	Breakdown	50-Unit Farm	Basis (Equations Refer to Subsequent Row IDs)
1	CAPEX ($)	240,016,908	= 1.1 + 1.2 + 1.3 + 1.4 + 1.5 + 1.6
1.1	Development	10,558,725	= 1.1.1 + 1.1.2
1.1.1	Engineering	4,589,164	Percentage of CAPEX (2%)
1.1.2	Permitting	5,969,561	Average of PNNL estimates
1.2	Financial costs	0	= 1.2.1 + 1.2.2 + 1.2.3
1.2.1	Insurance	0	Not considered
1.2.2	Decommission	0	Percentage of installation cost (70%), depreciation
1.2.3	Other	0	Percentage of CAPEX (0%)
1.3	WEC	109,478,032	= 1.3.1 + 1.3.2 + 1.3.3
1.3.1	Hydrodynamic system	86,670,989	Weight (499 t), unit cost ($ 3,161/t), integration (10%)
1.3.2	PTO	22,561,677	= 1.3.2.1 + 1.3.2.2 + 1.3.2–3 + 1.3.2.3 + 1.3.2.4 + 1.3.2.5
1.3.2.1	Prime mover	19,208,071	Mass (32.92 t), unit cost ($ 10.61/kg), integration (10%)
1.3.2.2	Generator	1,467,120	Mass (908 kg), unit cost ($ 29.38/kg), integration (10%)
1.3.2.3	Storage	0	Included in the hydraulic prime mover
1.3.2.4	Power electronics	1,143,890	Mass (1.2 t), unit cost ($ 17.32/kg), integration (10%)
1.3.2.5	Transformer	742,597	Mass (1.59 t), unit cost ($ 8.49/kg), integration (10%)
1.3.3	Instrumentation & control	245,366	Unit cost (USD 4461), subsystem integration (10%)
1.4	BoP	91,009,936	= 1.4.1 + 1.4.2 + 1.4.3 + 1.4.4
1.4.1	Station-keeping	81,681,936	= 1.4.1.1 + 1.4.1.2 + 1.4.1.3 + 1.4.1.4 + 1.4.1.5
1.4.1.1	Anchors and piles	14,500,828	No./device (8), weight (13 t), unit cost ($ 2789/t)
1.4.1.2	Mooring lines	15,789,988	No./device (4), length (80 m), unit cost ($ 987/m)
1.4.1.3	Substructure	44,087,621	Weight (301 t), unit cost ($ 2,663/t), integration (10%)
1.4.1.4	Buoyancy	2,700,000	Bulk discount factor (0.9), unit cost ($ 60,000)
1.4.1.5	Connecting hardware	4,603,500	Bulk discount factor (0.9), unit cost ($ 102,300)
1.4.2	Grid connection	9,328,000	= 1.4.2.1 + 1.4.2.2 + 1.4.2.3 + 1.4.2.4
1.4.2.1	Umbilical	4,400,000	Length (40,000 m) and unit cost ($ 110/m)
1.4.2.2	Inter-array	2,880,000	Length (14,400 m) and unit cost ($ 200/m)
1.4.2.3	Export	1,200,000	Length (6000 m) and unit cost ($ 200/m)
1.4.2.4	Connectors	848,000	Percentage of cable cost (10%)
1.4.3	Offshore substation	0	Not considered
1.4.4	Onshore infrastructure	0	Not considered
1.5	Transp., inst. & commission	23,320,215	= 1.5.1 + 1.5.2 + 1.5.3 + 1.5.4
1.5.1	Transport	1,487,500	Unit cost ($ 29,750)
1.5.2	Installation WEC	3,854,375	Days (55 days), rate ($ 70,080/day)
1.5.3	Installation BoP	14,123,965	= 1.5.3.1 + 1.5.3.2 + 1.5.3.3 + 1.5.3.4
1.5.3.1	Station-keeping	8,852,950	Days (127 day), rate ($ 69,483/day)
1.5.3.2	Grid connection	4,503,815	Days (50 day), rate ($ 90,949/day)

ID	Breakdown	50-Unit Farm	Basis (Equations Refer to Subsequent Row IDs)
1.5.3.3	Offshore substation	0	Not considered
1.5.3.4	Onshore infrastructure	767,200	Cable landing distance (500 m), unit cost ($ 1,534/m)
1.5.4	Commissioning	3,854,375	Percentage of WEC installation (100%)
1.6	Dedicated O&M vessels	5,650,000	Number (1), vessel cost ($ 5.65m)
2	Annual OPEX ($)	5,870,427	= 2.1 + 2.2 + 2.3
2.1	Site lease and insurance	2,414,582	Lease cost (USD 120,000), percentage of CAPEX (1%)
2.2	Environmental monitoring	1,785,000	Data taken from PNNL study
2.3	O&M	1,670,845	= 2.3.1 + 2.3.2
2.3.1	Scheduled	1,009,692	Staff (6.5), salary ($51,491/year), consumables ($13,500)
2.3.2	Unscheduled	661,153	Days (109), rate ($5,680/day), spares ($24,830), no. (1.75)
3	FCR (%)	0.11	= 3.1/(1 − 1/(1 + 3.1) ^ 3.2)
3.1	Discount rate (%)	0.09	= 3.1.1 + 3.1.2
3.1.1	Debt (%)	0.05	Return on debt (9.5%), percentage (50%)
3.1.2	Equity (%)	0.04	Return on equity (8.1%), percentage (50%)
3.2	Project lifetime (years)	20	n/a
4	AEP (kWh)	44,101,201	= 8,766 × N × 4.1 × 4.2 × 4.3
4.1	Rated power (kW)	360	n/a
4.2	Capacity factor (%)	0.29	= 4.2.1 × 4.2.2 × 4.2.3
4.2.1	Capture efficiency (%)	0.37	Average extracted power (132 kW)
4.2.2	Conversion efficiency (%)	0.82	NREL’s assumption
4.2.3	Transmission efficiency (%)	0.95	NREL’s assumption
4.3	Availability (%)	0.98	NREL’s assumption
5	LCOE ($/kWh)	0.72	= (1 × 3 + 2)/4

Table A.15: Propagation of Uncertainties and Corresponding Costs.

For assigned uncertainties, the associated Std and 80% confidence interval in Table 6.3 are used. Propagated uncertainties use eq. (26)-(28) as appropriate. Units of upper/lower bound as per breakdown.

ID	Breakdown	Uncertainty	Std	80% Conf Interval		Lower Bound	Upper Bound
1	CAPEX ($)	Propagated	11.4%	−12%	17%	210,033,907	281,374,854
1.1	Development	Propagated	17.3%	−18%	29%	8,704,876	13,563,431
1.1.1	Engineering	High	27.0%	−24%	51%	3,468,629	6,928,178
1.1.2	Permitting	Med/High	22.5%	−21%	40%	4,690,419	8,348,819
1.2	Financial costs	Propagated	0.0%	0%	0%	0	0
1.2.1	Insurance	None	0.0%	0%	0%	0	0
1.2.2	Decommission	None	0.0%	0%	0%	0	0
1.2.3	Other	None	0.0%	0%	0%	0	0
1.3	WEC	Propagated	21.6%	−21%	38%	86,709,892	150,851,161
1.3.1	Hydrodynamic system	High	27.0%	−24%	51%	65,508,563	130,845,643
1.3.2	PTO	Propagated	15.4%	−16%	25%	18,948,422	28,125,143
1.3.2.1	Prime mover	Medium	18.0%	−18%	30%	15,730,180	24,951,644
1.3.2.2	Generator	Medium	18.0%	−18%	30%	1,201,478	1,905,817
1.3.2.3	Storage	Medium	18.0%	−18%	0%	0	0
1.3.2.4	Power electronics	Medium	18.0%	−18%	30%	936,773	1,485,934
1.3.2.5	Transformer	Medium	18.0%	−18%	30%	608,139	964,647
1.3.3	Instrumentation and control	Medium	18.0%	−18%	30%	200,939	318,735
1.4	BoP	Propagated	14.7%	−15%	23%	77,004,901	112,141,127
1.4.1	Station-keeping	Propagated	16.3%	−17%	26%	68,002,855	103,257,710
1.4.1.1	Anchors and piles	High	27.0%	−24%	51%	10,960,166	21,891,640
1.4.1.2	Mooring lines	High	27.0%	−24%	51%	11,934,552	23,837,862
1.4.1.3	Substructure	High	27.0%	−24%	51%	33,322,761	66,558,293
1.4.1.4	Buoyancy	High	27.0%	−24%	51%	2,040,742	4,076,142
1.4.1.5	Connecting hardware	High	27.0%	−24%	51%	3,479,465	6,949,822
1.4.2	Grid connection	Propagated	10.5%	−12%	16%	8,239,279	10,793,785
1.4.2.1	Umbilical	Medium	18.0%	−18%	30%	3,603,318	5,715,683
1.4.2.2	Inter-array	Medium	18.0%	−18%	30%	2,358,536	3,741,174
1.4.2.3	Export	Medium	18.0%	−18%	30%	982,723	1,558,823
1.4.2.4	Connectors	Medium	18.0%	−18%	30%	694,458	1,101,568
1.4.3	Offshore substation	None	0.0%	0%	0%	0	0
1.4.4	Onshore infrastructure	None	0.0%	0%	0%	0	0
1.5	Transp., inst. & commission		11.0%	−12%	17%	20,485,546	27,191,364
1.5.1	Transport	Med/High	22.5%	−21%	40%	1,168,762	2,080,365
1.5.2	Installation WEC	Med/High	22.5%	−21%	40%	3,028,470	5,390,594
1.5.3	Installation BoP	Propagated	15.9%	−16%	26%	11,808,255	17,734,310
1.5.3.1	Station-keeping	Med/High	22.5%	−21%	40%	6,955,964	12,381,426
1.5.3.2	Grid connection	Med/High	22.5%	−21%	40%	3,538,749	6,298,877

ID	Breakdown	Uncertainty	Std	80% Conf Interval		Lower Bound	Upper Bound
1.5.3.3	Offshore substation	Med/High	22.5%	−21%	0%	0	0
1.5.3.4	Onshore infrastructure	Med/High	22.5%	−21%	40%	602,806	1,072,979
1.5.4	Commissioning	Med/High	22.5%	−21%	40%	3,028,470	5,390,594
1.6	Dedicated O&M vessels	High	27.0%	−24%	51%	4,270,441	8,529,704
2	Annual OPEX ($)	Propagated	9.0%	−10%	13%	5,271,888	6,642,826
2.1	Site lease and insurance	Low	13.0%	−14%	20%	2,079,003	2,897,679
2.2	Environmental monitoring	Low/Med	15.5%	−16%	25%	1,498,118	2,227,544
2.3	O&M	Propagated	19.5%	−19%	33%	1,349,152	2,223,782
2.3.1	Scheduled	High	27.0%	−24%	51%	763,156	1,524,314
2.3.2	Unscheduled	High	27.0%	−24%	51%	499,720	998,132
3	FCR (%)	Propagated	12.1%	−13%	18%	0.09	0.13
3.1	Discount rate	Propagated	19.1%	−19%	32%	0.07	0.12
3.1.1	Debt	High	27.0%	−24%	51%	0.04	0.07
3.1.2	Equity	High	27.0%	−24%	51%	0.03	0.06
3.2	Project lifetime	None	0.0%	0%	0%	20	20
4	AEP (kWh)	Propagated	35.6%	−29%	76%	31,118,603	77,555,818
4.1	Rated power (kWh)	None	0.0%	0%	0%	360	360
4.2	Capacity factor (%)	Propagated	23.3%	−22%	42%	0.22	0.40
4.2.1	Capture efficiency (%)	Medium	18.0%	−18%	30%	0.30	0.48
4.2.2	Conversion efficiency (%)	Low	13.0%	−14%	20%	0.71	0.98
4.2.3	Transmission efficiency (%)	Very low	7.0%	−8%	10%	0.87	1.00
4.3	Availability (%)	High	27.0%	−24%	51%	0.74	1.00
5	LCOE ($/kWh)		38.2%	−31%	84%	0.50	1.33

Table A.16: Component-based Learning and Future Cost Projections.

Upper bound from Table A.15. Units of Projection and Baseline as per breakdown.

ID	Breakdown	Upper Bound	Learning Rate		Category	Projection	Baseline
1	CAPEX ($)	281,374,854	Aggregated	3.9%	Mature	223,023,237	210,412,696
1.1	Development	13,563,431	Aggregated	8.0%	Evolving	8,389,156	5,399,407
1.1.1	Engineering	6,928,178	Assigned	7.5%	Evolving	4,409,418	2,414,626
1.1.2	Permitting	8,348,819	Assigned	12.0%	Emerging	3,979,737	2,984,781
1.2	Financial costs	0	Aggregated	0.0%	Mature	0	0
1.2.1	Insurance	0	Assigned	5.0%	Mature	0	0
1.2.2	Decommission	0	Assigned	6.0%	Evolving	0	0
1.2.3	Other	0	Assigned	5.0%	Mature	0	0
1.3	WEC	150,851,161	Aggregated	6.7%	Evolving	100,817,663	96,237,347
1.3.1	Hydrodynamic system	130,845,643	Assigned	8.0%	Evolving	80,700,943	76,546,193
1.3.2	PTO	28,125,143	Assigned	5.9%	Evolving	19,833,205	19,472,556
1.3.2.1	Prime mover	24,951,644	Assigned	8.0%	Evolving	16,708,154	16,708,154
1.3.2.2	Generator	1,905,817	Assigned	3.7%	Mature	1,531,727	1,284,397
1.3.2.3	Storage	0	Assigned	5.0%	Mature	0	0
1.3.2.4	Power electronics	1,485,934	Assigned	20.0%	Emerging	831,920	831,920
1.3.2.5	Transformer	964,647	Assigned	4.0%	Mature	761,404	648,084
1.3.3	Instrumentation & control	318,735	Assigned	2.0%	Mature	283,516	218,599
1.4	BoP	112,141,127	Aggregated	4.1%	Mature	88,247,013	84,640,133
1.4.1	Station-keeping	103,257,710	Assigned	4.5%	Mature	78,919,013	75,312,133
1.4.1.1	Anchors and piles	21,891,640	Assigned	7.0%	Evolving	14,375,068	13,281,286
1.4.1.2	Mooring lines	23,837,862	Assigned	7.0%	Evolving	15,789,988	15,789,988
1.4.1.3	Substructure	66,558,293	Assigned	8.0%	Evolving	41,050,790	38,937,360
1.4.1.4	Buoyancy	4,076,142	Assigned	6.0%	Evolving	2,847,752	2,700,000
1.4.1.5	Connecting hardware	6,949,822	Assigned	6.0%	Evolving	4,855,416	4,603,500
1.4.2	Grid connection	10,793,785	Assigned	2.5%	Mature	9,328,000	9,328,000
1.4.2.1	Umbilical	5,715,683	Assigned	6.0%	Evolving	4,400,000	4,400,000
1.4.2.2	Inter-array	3,741,174	Assigned	5.0%	Mature	2,880,000	2,880,000
1.4.2.3	Export	1,558,823	Assigned	5.0%	Mature	1,200,000	1,200,000
1.4.2.4	Connectors	1,101,568	Assigned	6.0%	Evolving	848,000	848,000
1.4.3	Offshore substation	0	Assigned	6.0%	Evolving	0	0
1.4.4	Onshore infrastructure	0	Assigned	2.0%	Mature	0	0
1.5	Transp., inst. & commission	27,191,364	Aggregated	4.4%	Mature	20,937,816	20,045,808
1.5.1	Transport	2,080,365	Assigned	6.0%	Evolving	1,487,500	1,487,500
1.5.2	Installation WEC	5,390,594	Assigned	7.0%	Evolving	3,763,500	3,763,500
1.5.3	Installation BoP	17,734,310	Assigned	6.6%	Evolving	11,920,737	11,031,308
1.5.3.1	Station-keeping	12,381,426	Assigned	10.0%	Evolving	6,723,055	6,622,419
1.5.3.2	Grid connection	6,298,877	Assigned	6.0%	Evolving	4,400,641	3,641,689
1.5.3.3	Offshore substation	0	Assigned	6.0%	Evolving	0	0

ID	Breakdown	Upper Bound	Learning Rate		Category	Projection	Baseline
1.5.3.4	Onshore infrastructure	1,072,979	Assigned	5.0%	Mature	797,040	767,200
1.5.4	Commissioning	5,390,594	Assigned	6.0%	Evolving	3,766,079	3,763,500
1.6	Dedicated O&M vessels	8,529,704	Assigned	10.0%	Evolving	4,631,589	4,090,000
2	Annual OPEX ($)	6,642,826	Aggregated	3.9%	Mature	5,270,454	4,478,928
2.1	Site lease and insurance	2,897,679	Assigned	8.0%	Evolving	1,787,185	1,102,959
2.2	Environmental monitoring	2,227,544	Assigned	4.0%	Mature	1,785,000	1,785,000
2.3	O&M	2,223,782	Aggregated	4.5%	Mature	1,698,269	1,590,969
2.3.1	Scheduled	1,524,314	Assigned	7.0%	Evolving	1,000,935	952,317
2.3.2	Unscheduled	998,132	Assigned	6.0%	Evolving	697,334	638,652
3	FCR (%)	0.13	Aggregated	2.0%	Mature	0.11	0.11
3.1	Discount rate	0.12	Aggregated	3.5%	Mature	0.10	0.09
3.1.1	Debt	0.07	Assigned	10.0%	Evolving	0.05	0.05
3.1.2	Equity	0.06	Assigned	10.0%	Evolving	0.04	0.04
3.2	Project lifetime	20	Aggregated	0.0%	Mature	20	20
4	AEP (kWh)	31,118,603	Aggregated	−6.2%	Evolving	44,071,015	44,071,015
4.1	Rated power (kWh)	360	Assigned	0.0%	Mature	360	360
4.2	Capacity factor (%)	0.22	Aggregated	−4.4%	Mature	0.29	0.29
4.2.1	Capture efficiency (%)	0.30	Assigned	−10.0%	Evolving	0.37	0.37
4.2.2	Conversion efficiency (%)	0.71	Assigned	−6.0%	Evolving	0.82	0.82
4.2.3	Transmission efficiency (%)	0.87	Assigned	−2.0%	Mature	0.95	0.95
4.3	Availability (%)	0.74	Assigned	−5.0%	Mature	0.98	0.98
5	LCOE ($/kWh)	1.33	Aggregated	10.6%	Emerging	0.69	0.62

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PUBLICATIONS

The PhD process requires actively disseminating the findings of the research in the form of reports, conference communications, peer-reviewed journal publications or books. In this chapter, the main research outcomes related to the subject of this thesis are listed.

JOURNAL PAPERS

P. Ruiz-Minguela, D. R. Noble, V. Nava, S. Pennock, J. M. Blanco, H. Jeffrey. "Estimating Future Costs of Emerging Wave Energy Technologies". *Sustainability*, vol 15, nº 1, p. 215, Dec. 2022. https://doi.org/10.3390/su15010215

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ETIP OCEAN: European Technology and Innovation Platform for Ocean Energy. EU H2020, no 727483, 2019-2021. https://cordis.europa.eu/project/id/727483/results

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OPERA: Open Sea Operating Experience to Reduce Wave Energy Cost. EU H2020, no 654444, 2016-2019. https://cordis.europa.eu/project/id/654444/results

J. Pablo Ruiz Minguela
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Supervisors: Prof Jesús María Blanco Ilzarbe and Dr Vincenzo Nava

Universidad del País Vasco / Euskal Herriko Unibertsitatea
Energy Engineering Department
Plaza Ingeniero Torres Quevedo, 1
E-48013 Bilbao

TECNALIA, Basque Research and Technology Alliance (BRTA)
Offshore Renewable Energy Group
Energy, Climate and Urban Transition Unit
Parque Científico y Tecnológico de Bizkaia, Astondo Bidea, Edificio 700
E-48160 Derio

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