Renewable and Sustainable Energy Reviews 132 (2020) 110011

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

A systematic approach for selecting suitable wave energy converters for potential wave energy farm sites

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A R T I C L E I N F O

Keywords:
Wave energy
Site selection
Wave energy converter (WEC)
WEC classification
Site matching
Site assessment

A B S T R A C T

The ocean covers approximately 70% of the earth's surface and contains an immense source of renewable energy, in terms of ocean waves. However, this resource is unevenly distributed throughout the world, and so, therefore, converting waves into a useful form of energy will require the identification of potential Wave Energy Farm (WEF) locations. This should be undertaken in tandem with selecting an appropriate Wave Energy Converter (WEC), as the characteristics of these devices are critical in capturing the available wave power. Therefore, this paper describes a three-stage systematic approach that was developed and implemented in order to select the most suitable WEC(s) for marine areas identified as optimal for WEFs. As this sector is evolving rapidly, the first stage identified all WECs currently in development and proposed classifying these devices in a practical and meaningful manner. The second stage developed a procedure for identifying generic WEF locations by integrating the multiple dimensions of sustainable development and the technical limitations of the sector, within a geographic information systems framework. Lastly, the third stage incorporates the results from the previous two stages. The devices considered for further analysis were reduced based on commercial viability, whilst the available power was quantified and characterised at each of the optimal WEF sites. Thereafter, appropriate techno-economic performance indicators were identified to rank and determine the optimal device for a specific location.

1. Introduction

Ensuring global access to affordable and clean energy by 2030 is the seventh of the 17 United Nation's Sustainable Development Goals. However, the world is currently falling short on all of the clean energy targets, and as a result, approximately one billion people are still living without access to electricity [1].

Ocean wave energy is considered to be one of the most promising sources of clean, reliable, and renewable energy [2], and it is estimated that there is a theoretical global wave energy potential of 32,000 TWh available per year [3]. Moreover, with approximately 40% of the world's population residing in coastal areas [4], this provides additional opportunities for the deployment of Wave Energy Converters (WECs) for distributed generation.

Compared to other renewable energy sources, wave energy is more predictable, more constant, has a lower visual and environmental impact, and most significantly, a higher energy intensity [5]. However, this sector is still relatively immature compared to that of wind and solar [6], and despite considerable research and development, there are a significant number of competing technologies, which show no signs of converging to a preferred design [7].

1.1. Developmental Stages

In order to standardise the ad-hoc approach to WEC development that led to this divergence in technology, slow rate of development as well as numerous device failures and considerable investment losses over the years, the International Structured Development Plan was established by the International Energy Agency–Ocean Energy Systems (IEA–OES) group [8]. This plan incorporates Technology Readiness Levels (TRLs) into a five-stage approach, which sets out the requirements for a WEC concept to achieve commercialisation (Fig. 1(a)). TRLs are internationally recognised and widely accepted as a benchmarking tool for tracking the advancement of emerging technologies [8], and are commonly comprised of nine development levels with the ninth level representing the most mature technology.

As seen in Fig. 1(b), utility companies Electricity Supply Board International (ESBI) and Vattenfall further proposed that TRLs should not only be defined in terms of the technology's readiness to convert ocean

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https://doi.org/10.1016/j.rser.2020.110011
Received 20 March 2020; Received in revised form 15 June 2020; Accepted 15 June 2020
Available online 17 July 2020

Nomenclature

Acronyms

A1	Auckland 1
A2	Auckland 2
A3	Auckland 3
AEP	Annual Energy Production, [Wh]
AoI	Area of Interest
CAPEX	CAPital EXpenditure, [$/kW]
CWR	Capture Width Ratio
DD	Decimal Degrees
EEZ	Exclusive Economic Zone
ESBI	Electricity Supply Board International
IEA-OES	International Energy Agency — Ocean Energy Systems
G1	Greymouth 1
G2	Greymouth 2
G3	Greymouth 3
GIS	Geographic Information System
I1	Invercargill 1
I2	Invercargill 2
I3	Invercargill 3
LCOE	Levelised Cost of Electricity
MCA	Multi-Criteria Analysis
MPA	Marine Protected Area
NP1	New Plymouth 1
NP2	New Plymouth 2
NP3	New Plymouth 3
NZ	New Zealand
OPEX	OPerating EXpenditure, [$/kW]
OWC	Oscillating Water Column
PIA	Potential Installation Areas
PTO	Power Take-Off
SS	Suitability Scale
TPL	Technology Performance Level
TRL	Technology Readiness Level
UK	United Kingdom
USA	United States of America
WAVEPLAM	WAVe Energy PLAnning and Marketing
WEC	Wave Energy Converter
WEF	Wave Energy Farm

Symbols

B	WEC characteristic dimension, [m]
C	constraint, [%]
C_f	capacity factor, [%]
H_{m0}	spectral significant wave height, [m]
n	technology lifetime, [years]
P	resource scatter diagram, [%]
p	WEC power matrix, [W]
P_E	WEC average power output, [W]
P_W	wave resource, [W/m]
R	restriction, [%]
r	discount rate, [%]
R_C	WEC rated capacity, [W]
T_e	energy wave period, [s]
t	year from start of project, [−]
w	weighting, [%]

Greek symbols

ρ	density, [kg/m^3]
Σ	sum, [−]
Π	product, [−]

Metric units

g	gram
h	hour
k	kilo
m	metre
s	second
T	tera
W	watt

wave energy and export it to the grid ('functional readiness') but also address the project lifecycle requirements such as operational and supply chain readiness, and risk and cost reduction ('lifecycle readiness') [9].

Each of the stages proposed in the IEA–OES structured programme can be equated to specific ESBI and Vattenfall defined TRL(s) (with the exception of TRL 1, 2, and 9). This has been shown in Fig. 1 by utilising a distinct colour for each of the five development stages in the IEA-OES structured programme and relating it to the relevant ESBI and Vattenfall TRLs.

Whilst TRLs are predominately used to rate the technical maturity of a device, Weber [11] introduced the complementary Technical Performance Levels (TPLs). This scale evaluates the techno-economic potential of a WEC by assessing cost drivers such as environmental, social and legal acceptability; power absorption and conversion; system availability (including the device's survivability mode); capital expenditure as well as lifecycle operational expenditure [11]. Similarly to the TRL scale, TPLs are categorised into nine levels with the ninth level representing an economically viable and competitive device.

1.2. Classification Schemes

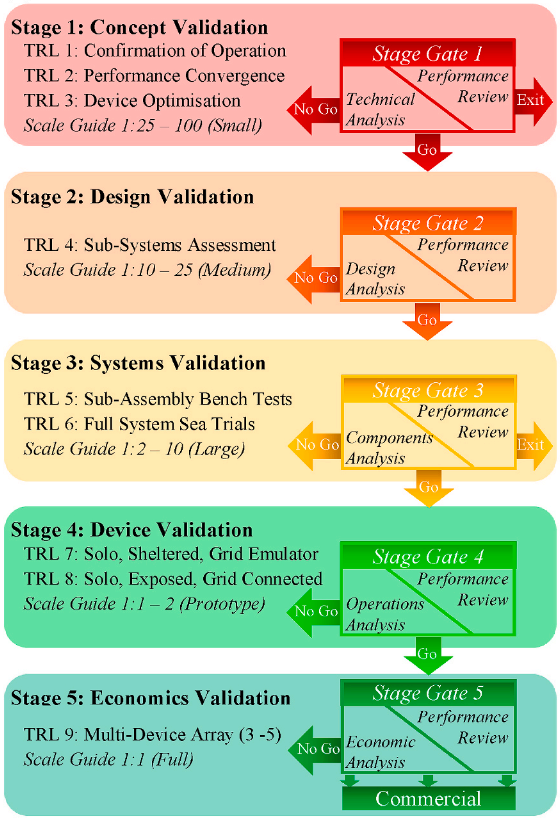
As wave energy technology development stages vary widely, so do the proposed classification schemes. Traditionally WECs have been classified according to operating principle (overtopping device, oscillating water column, and wave-activated bodies) [12], location (shoreline, nearshore and offshore; floating, submerged or bottom-standing), directional alignment (terminators, attenuators, and point absorbers) and Power Take-Off (PTO) systems (mechanical, hydraulic, pneumatic, and directly electrical) [13].

However, as the sector has advanced, numerous approaches have been proposed in the literature that attempts to adapt this traditional WEC classification system to include the development of novel and unconventional devices. Drew et al. [14] introduced a variation of the traditional classification scheme with the addition of the submerged pressure differential and oscillating wave surge converter and the removal of the wave-activated bodies from the operating principle category. Whereas the European Marine Energy Centre [15] and Li and Yu [16] identified eight and five main WEC types, respectively. These classification schemes appear to be various combinations of the main categories proposed by Falcão [12], Falnes [13], and Drew et al. [14], with the addition of the rotating mass [15], bulge wave [15] and membrane [16] device types.

More recently, Lehmann et al. [17] have proposed that a wide range of wave energy technology can be classified by using five main categories: working principle (oscillating water column, heaving buoy, submerged pressure differential, wave activated bodies, bulge wave, oscillating wave surge, rotating mass and cycloidal wave absorber); location (shore-based, nearshore, and offshore); orientation (point absorber, attenuator, and terminator); PTO system (hydraulic, direct drive, hydro, and pneumatic); and TRLs.

Alternative categorisation based on the referencing configuration

(a)



(b)

TRL	Functional Readiness	Lifecycle Readiness
1	Basic principles observed and reported.	Potential uses of technology identified.
2	Technology concept formulated.	Market and purpose of technology identified.
3	Analytical and experimental critical function and/or characteristic proof-of concept *(Scale Guide 1:25 - 100)*	Initial capital cost and power production estimates/targets established.
4	WEC component and/or basic WEC subsystem validation in laboratory environment. *(Scale Guide: >1:25)*	Preliminary lifecycle design: targets for manufacturable, deployable, operable and maintainable technology.
5	WEC component and/or basic WEC subsystem validation in relevant environment. *(Scale Guide 1:4 - 15)*	Supply-chain mobilisation: Procurement of subsystem design, installation feasibility studies, cost estimations, etc.
6	WEC prototype demonstration in relevant environment. *(Scale Guide >1:4)*	Customer interaction: consider customer requirements to inform design. Inform customer of likely project site constraints.
7	WEC prototype demonstration in operational environment. *(Scale Guide 1:2)*	Ocean operational readiness: management of ocean scale risks, marine operations, etc.
8	Actual full-scale WEC completed and qualified through test and demonstration. *(Scale Guide 1:1)*	Actual marine operations completed and qualified through test and demonstration.
9	Operational performance and reliability demonstrated for an array of WECs. *(Scale Guide Multiple 1:1)*	Fully de-risked business plan for utility scale deployment of arrays.

Fig. 1. Industry proposed WEC development protocols: (a) the international structured five-stage development protocol, modified from Holmes and Nielsen [8]; (b) ESBI and Vattenfall Wave Energy Systems TRLs, defined in terms of both functional readiness and lifecycle readiness [9,10].

(self-referencing or seabed/shoreline referencing) and mode(s) of motion (heave, pitch, and/or surge) of the WECs primary conversion component has been proposed by the EquiMar project [18]. Whereas Margheritini et al. [19] recommended a classification scheme based on the WECs expected environmental impact. This scheme classified the devices by: location (onshore, intermediate, and offshore); stability elements (anchors/moorings and foundations); PTO system; as well as the obstruction to the water column, and sea surface. Whilst many WECs can be accommodated within these numerous classification schemes; there are still a large number of device concepts that cannot be captured.

The lack of an all-encompassing taxonomy is an issue because a WEC will not perform the same in different locations, and likewise, different WEC designs perform differently at the same location [20]. This is due to the characteristics and tuning of the device [21]. Design characteristics such as the WEC's operational range and efficiency at various sea states are critical in quantifying the amount of energy that can be harvested at a specific site [22]. Whilst the technology's ability to be tuned to the dominant wave frequency will maximise its energy capture [23]. Therefore, in determining if a wave energy project is feasible, it is vital that the most suitable WEC is selected for the potential Wave Energy Farm (WEF) site [20], and this selection process can be streamlined by classifying devices appropriately.

1.3. Site Selection

Before attempting to determine the most suitable device(s) for a potential site, initial deployment locations need to be identified and assessed, as wave energy is unevenly distributed throughout the world [6]. Nobre et al. [24], Galparsoro et al. [25], and the European Union's WAVEPLAM (WAVe Energy PLAnning and Marketing) project [26] proposed using Multi-Criteria Analysis (MCA) within a Geographic Information System (GIS) framework to produce maps that depicted areas of varying suitability for generic WEFs. Nobre et al.'s [24] approach, implemented along the Portuguese south-west coast, classified the relevant site selection criteria as restrictions or weighted factors. These restrictions represented non-installation areas and were omitted from the analysis; whereas the weighted factors were assessed on their ability to affect the installation of a WEF. This differed slightly from the methods proposed by Galparsoro et al. [25], demonstrated within the Basque Continental Shelf (Spain), and the WAVEPLAM project [26], which both firstly used three main categories (socioeconomic, environmental, and technical) to identify the relevant site selection factors, and instead of omitting the exclusion factors from further analysis, these areas were assigned a value of zero. In addition, as a generalised site selection methodology was introduced by the WAVEPLAM project [26], a comprehensive list of all necessary information was provided, whereas Galparsoro et al. [25] and Nobre et al. [24] proposed site-specific selection criteria.

Subsequently, studies conducted by Le et al. [27], Chakraborty [28], and Ghosh [5] integrated multi-criteria decision making techniques with GIS to determine optimal generic WEF locations. Le et al.'s [27] method, implemented in Tasmanian coastal waters, classified the identified site selection criteria as ocean features, marine uses and facilities. However, the factors in this method were all considered to be limiting, and so, therefore, potentially the most suitable WEF location could be in direct conflict with an existing marine use. Whilst, the approach outlined by Chakraborty [28], demonstrated at multiple marine energy test sites (in Australia, England, and Spain), and Ghosh [5], implemented at specific locations within the coastal environments of Japan and the United States of America (USA), only considered site selection criteria which would influence the wave energy potential (such as wave height, wave period, depth, and so forth). Neither attempted to incorporate social or

Table 1
Review of the scientific literature focused on the three main methods of site matching. For each method, the studies have been listed in reverse chronological order.

Study/Year	Device(s)	Performance Indicator(s)	Location(s)
Method 1			
Dalton et al. [30]/2010	Pelamis[e] — only WEC to have published power performance data (at the time).	Energy: Power Production Economic: Cost of Electricity, Net Present Value, Internal Rate of Return	Ireland, Portugal, Canada, USA
Method 2			
Amrutha et al. [31]/2019	[b]Oyster[e], Wave Dragon, Wave Star[e] —selected WECs that were suitable for nearshore locations.	Energy: Power Production, Capacity Factor, Capture Width	[d]India
[a]Iuppa et al. [32]/2015	[b]AquaBuoy[e], Pelamis[e], Wave Dragon, as well as seven generic devices numerically modelled by Babarit et al. [33].	Energy: Power Production, Capacity Factor	[d]Italy
Veigas et al. [34]/2015	[b]Archimedes Wave Swing, Pelamis[e], Wave Dragon, generic Oscillating Water Column (OWC)	Energy: Power Production	[d]Spain
Bozzi et al. [35]/2014	AquaBuoy[e], Pelamis[e], Wave Dragon—WECs that had a range of operating principles, reached an advanced stage of development and had published performance data.	Energy: Power Production, Capacity Factor, Coefficient of Variation	[d]Italy
Mota & Pinto [36]/2014	[b]Archimedes Wave Swing, Pelamis[e], Wave Dragon—WECs that had a range of operating principles.	Energy: Power Production, Capacity Factor	[c]Portugal
[a]Sierra et al. [37]/2014	[b]AquaBuoy[e], Pelamis[e], Wave Dragon	Energy: Power Production, Capacity Factor	[d]Spain
[a]Aoun et al. [38]/2013	[b]AquaBuoy[e], Pelamis[e], Wave Dragon—selected range of WECs that had published performance data.	Energy: Power Production, Capacity Factor	[c]Lebanon
[a]Silva et al. [39]/2013	[b]AquaBuoy[e], Oyster[e], Pelamis[e], Seawave Slot-Cone Generator[e], Wave Dragon—selected range of WECs.	Energy: Power Production	[c]Portugal
Vaquero et al. [40]/2013	[b]Ceto, Oceantec, Oyster[e], Pelamis[e], Pontoon Power Converter, Seabased, Seawave Slot-Cone Generator[e], Wave Dragon, Wave Star[e]—selected range of WECs.	Energy: Power Production, Capacity Factor, Capture Width	[d]Spain
Method 3			
[a]Rusu & Onea [41]/2017	Ceto[f], Ocean Energy Buoy, Oceantec[f], Pelamis[e], Pontoon Power Converter, Seabased, Sea Power, Wavebob[e], Wave Dragon, Wave Star[e]—selected range of WECs at an advanced stage of development.	Energy: Power Production, Capacity Factor, Capture Width	[d]Angola, Australia, Brazil, Canada, Chile, China, Denmark, Greenland, Iceland, Ireland, India, Indonesia, Madagascar, Mexico, New Zealand, Papua New Guinea, Peru, Philippines, Portugal, Russia, Senegal, South Africa, United Kingdom (UK), Uruguay, USA
[a]Vannucchi & Cappietti [42]/2016	Archimedes Wave Swing, Oyster[e], Pelamis[e], Wave Dragon, Oyster[e], Wave Star[e]—selected range of WECs at an advanced stage of development.	Energy: Power Production, Capacity Factor, Capture Width	[d]Ireland, Italy, France, Portugal
[a]Rusu [29]/2014	[b]AquaBuoy[e], Pelamis[e], Wave Dragon—selected range of WECs.	Energy: Power Production, Capacity Factor, Capture Width	[d]Portugal, Spain
O'Connor et al. [20]/2013	[b]Pelamis[e], Wave Star[e]	Energy: Power Production, Capacity Factor Economic: Cost of Electricity, Net Present Value, Internal Rate of Return	[d]Denmark, Greece, Ireland, UK, Spain, Portugal
[a]Babarit et al. [33]/2012	[b]Eight generic numerically modelled devices inspired by Ceto[f], Langlee[e], Ocean Energy Buoy, Oyster[e], Pontoon Power Converter, Seabased, Wavebob[e], Wave Star[e].	Energy: Power Production, Capture Width Ratio	[d]Ireland, France, Portugal, UK

[a] An external body funded the study.
[b] The initial WEC selection was not discussed in the study.
[c] The initial selection of the locations was not disclosed.
[d] The selection of the sites was based on the available resource and/or limited to technical parameters.
[e] Abandoned technology.
[f] Technology has evolved significantly since the publication of the study.

economic impacts, environmental aspects, or existing marine uses into the analysis.

None of these case studies were applied to an initial large area, and in fact, the WAVEPLAM guidance document [26] actively discouraged assessing large areas; such as a country's entire marine territory. However, the majority of these methodologies recognised that the available resource is not the only aspect to be used in the analysis, because the selection of an appropriate WEF site also requires an assessment of the technical limitations, potential economic and social impacts, and environmental considerations.

1.4. Site Matching

As stated in Section 1.2, an important aspect to consider when selecting a suitable location for the deployment of a WEF is determining which wave energy technology would be more appropriate for the particular conditions encountered at that potential site [29]. A review of the literature identified three main methods for matching wave energy devices to potential marine energy sites: (1) evaluating and comparing the performance of a single technology type at different locations; (2) evaluating and comparing the performance of a range of technology types in a specific area; and (3) evaluating and comparing the performance of different technology types at a range of sites. In this paper, if multiple locations were investigated within a country's Exclusive

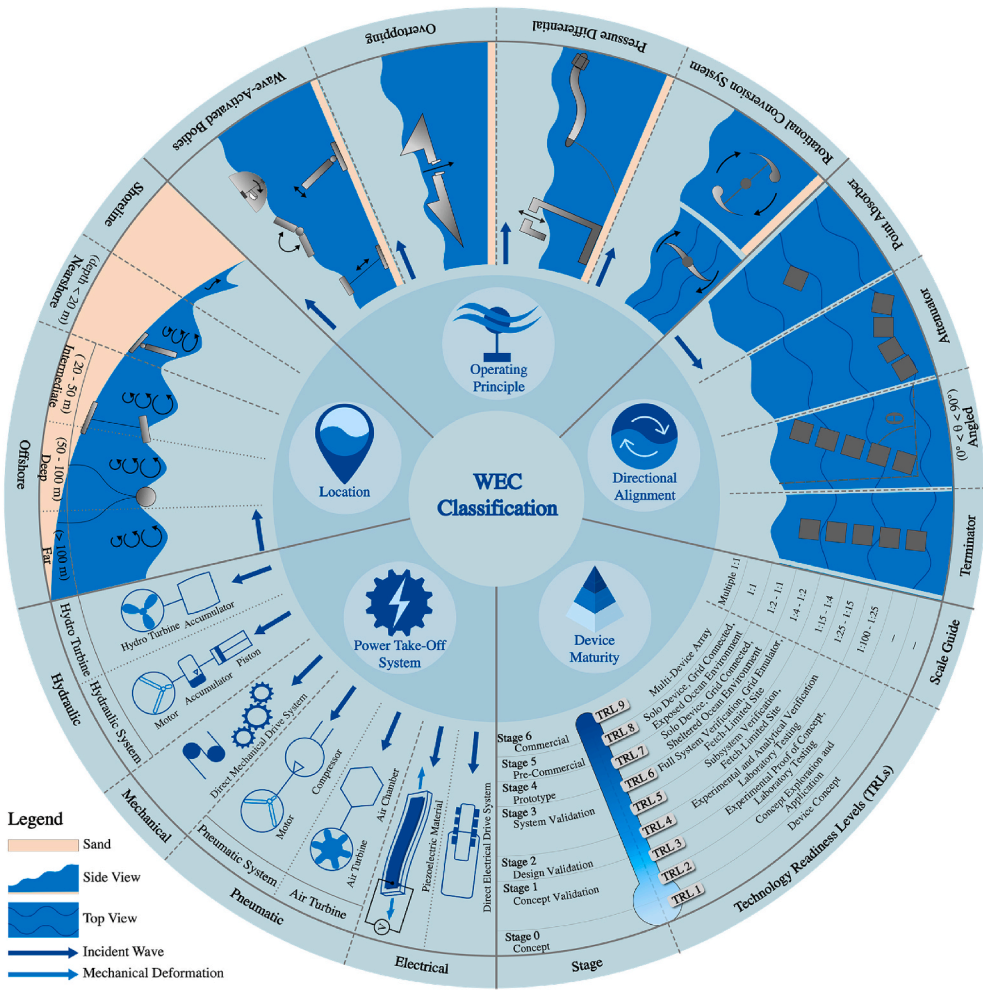


Fig. 2. Proposed WEC classification system comprised of five main categories: Operating Principle, Directional Alignment, Device Maturity, PTO System, and Location.

Economic Zone (EEZ), this was defined as a single 'specific area' (Method 2). Table 1 provides an overview of the literature pertaining to the three site matching methodologies.

As seen in Table 1, a significant number of the case studies were based in the Northern Hemisphere (predominately along the Atlantic coast of Europe), and were limited to assessing the energy performance of the WEC(s) only. Furthermore, the majority of these case studies selected the locations based solely on the available resource and/or technical limitations (ocean depth, distance to shore, etc.). Whilst the initial selection of the wave energy technology, existing or generic, was generally not discussed, and as this is a rapidly evolving sector, the development of several of the 'existing' WECs has since been abandoned.

1.5. Research Aim

Three main gaps have been identified from the literature. Firstly, the absence of an adaptable taxonomy, which has distinct containing classes, that is both analytical and able to accommodate future wave energy technologies. Secondly, a lack of a flexible broad-based method that determines optimal locations, from an initial large study area, for generic wave energy projects. Thirdly, the need for a systematic site matching methodology, which includes the initial identification of devices that could potentially be suitable for these deployment locations.

This research aims to develop a framework that can be implemented in order to identify optimal WEF sites (that is applicable at multi-scale) and then subsequently, the most suitable WEC(s) for these locations. The approach proposes the use of five main dimensions to assist in determining the relevant site selection criteria, limiting conditions to reduce the initial area of interest, and spatial MCA to conduct the analysis. The proposed site selection methodology will be applied to a Southern Hemisphere case study; New Zealand. A review of the current wave energy technologies in development will also be undertaken, and five main categories (with appropriate descriptors) will be proposed to classify these devices in a meaningful way. An initial screening of the WECs based on advanced maturity level will then be applied, and thereafter, performance comparison metrics will be proposed and discussed.

2. Material and Methods

The proposed methodology is comprised of three main stages, Stage 1: WEC Identification, Stage 2: Site Selection, and Stage 3: Site Matching. The first stage identified all WECs currently in development, which were then further classified according to five proposed main categories. The second stage determined the most suitable locations for the deployment of generic WEFs by acquiring, preparing, and analysing the relevant spatial data in accordance with the five proposed main dimensions. The third stage assessed the sites (established in Stage 2), utilised an advanced technical maturity to reduce the number of devices (identified in Stage 1) for further analysis, and then discussed which techno-economic metrics would be appropriate for the evaluation of the WEC's performance, and therefore, its suitability for the potential WEF

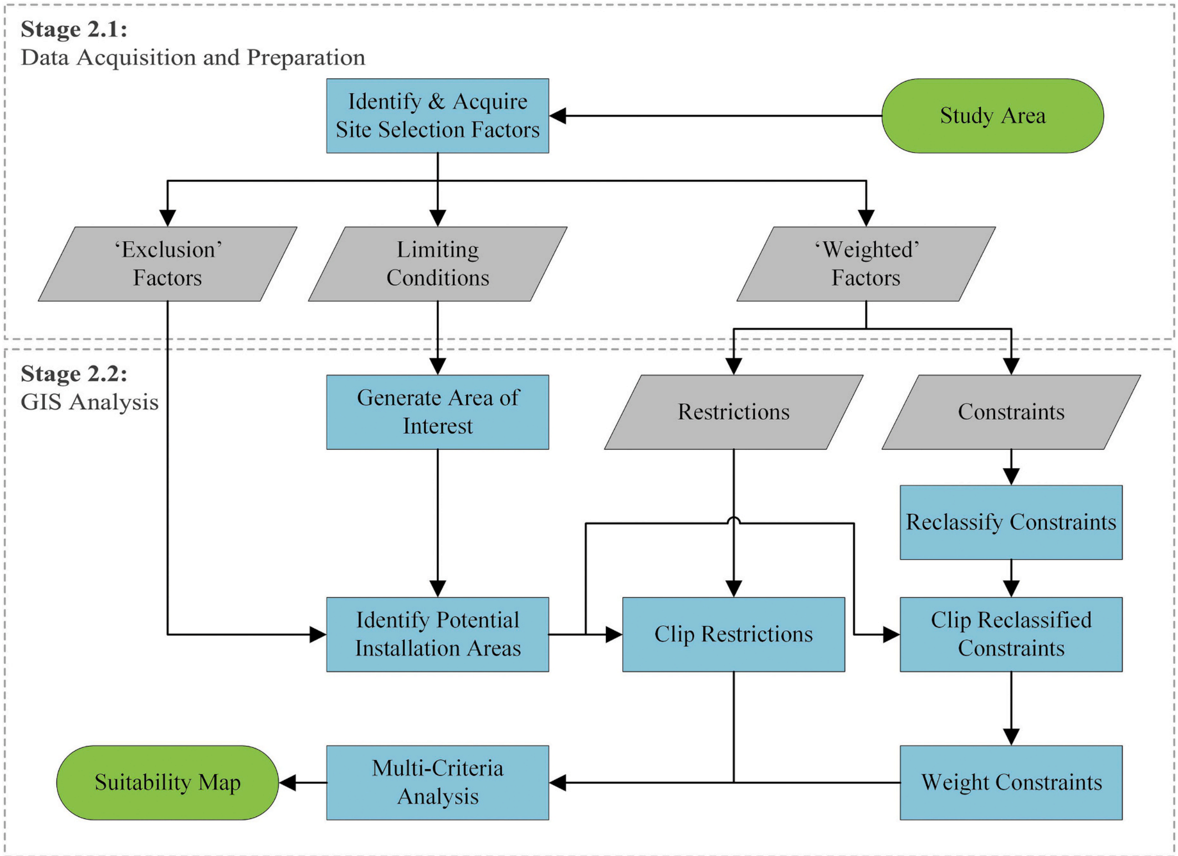


Fig. 3. The site selection methodology utilised to identify locations with optimal conditions (maximum resource and least constraints) for a generic WEF.

locations.

2.1. Stage 1: WEC Identification

In order to select the most appropriate device for potential WEF locations, all the WECs currently under development had to be identified. Technologies that utilise ocean waves to generate electricity, desalinate seawater, pump or heat water, propel ships [13], and produce liquid fuel [43] have been proposed in the literature, patented and developed in industry. However, for the purpose of this study, only devices that generate electricity were considered.

Therefore, this stage required the development of a database, which was created by combining the relevant information available on the European Marine Energy Centre [44], Open Energy Information [45], and Open Wave Energy Project [46] websites. Only the developer's name, location and device(s) were recorded. However, once this initial database was compiled then each company was investigated further, to ensure that they were actively developing a WEC. This required the status of the company to be determined (active, dissolved, etc. — not possible for all countries), as well as a review of the developer's website and social media platforms (Twitter, Facebook, LinkedIn, and YouTube).

For companies that had little to no online footprint, the relevant patents, journal publications and online newspapers articles were examined. If the aforementioned methods could not be applied, then the WEC developers were emailed directly. Developers were considered 'inactive' if they did not respond, no explicit information could be found regarding the status of the device/developer, and/or social media platforms and websites had not been updated within the last five years.

2.1.1. WEC Classification

The database was then expanded, by recording the classification of the technology, for companies that were established as actively developing a device (or devices). As stated in Section 1.2, WECs are most commonly classified according to directional alignment, location, operating principle, and PTO system. The approach proposed in this paper utilised an adapted (and in some cases, redefined) version of these categories with the addition of a class that described the device's maturity (Fig. 2).

Operating Principle. The mode of energy extraction employed by a WEC is referred to as its operating principle. The methods for harvesting wave energy vary widely, which has led to an extensive range of device types that, according to Falcão [12], can be grouped into three main categories. Namely, wave-activated bodies (also referred to as oscillating bodies), overtopping devices, and OWCs. However, a review of current WECs led to the discovery of a class of devices, which convert wave energy directly into rotational work (in either the vertical or horizontal plane), therefore leading to the formation of the 'Rotational Conversion System' category. A 'Pressure Differential' category was also established in place of the OWC, as only devices that utilise a difference in air pressure are included in the OWC class. Whereas, the new pressure differential category consists of any device that uses a fluid (gas and/or liquid) pressure difference. Therefore WECs that were classified as submerged pressure differential, bulge wave [15], and membrane [16] form part of this new category.

Directional Alignment. Wave energy technologies may also be classified according to size and orientation [13]. If the device has small dimensions with respect to a typical wavelength, the WEC is called a point absorber. Whereas, a large device with the longest dimension comparable to or larger than a typical wavelength, is referred to as a line absorber. A line absorber is more commonly known as an attenuator (longest dimension aligned parallel to the prevailing wave direction) or terminator (longest dimension aligned perpendicular to the prevailing wave direction). When reviewing the devices currently in development, a new descriptor was required to define line absorbers that were neither parallel nor perpendicular to the wave propagation direction but positioned at an angle, hence the addition of the 'Angled' sub-category.

Device Maturity. Given the nascent state of the ocean wave energy sector, the addition of a category that specifies the maturity of devices in development will provide insight into the global market status as well as identify WECs that are near or at commercialisation (which is required for the next stage of this method). This category was primarily based on the TRLs proposed by ESBI and Vattenfall [10], which have been integrated into a seven-stage developmental plan. The inclusion of two additional stages accounts for yet-to-be-proven device ideas/concepts ('Stage 0'-TRL 1), and commercially viable technology ('Stage 6'-TRL 9). Devices identified as being at Stage 0 were not included in the database.

TPLs were not incorporated into this category as this metric is not yet widely implemented (or even known), and funding opportunities, as well as the commercial ability of WECs, are currently defined in terms of TRLs [47]. However, funding agencies such as the USA's Department of Energy are transitioning towards a more holistic evaluation process, which would include incorporating performance indicators such as TPLs [48]. Therefore once TPLs become more commonplace in this industry, the Device Maturity category will be expanded to include this metric.

PTO System. The mechanism which converts the energy harvested from ocean waves into useable electricity is referred to as the PTO system. The PTO system is of great importance as it affects the power conversion efficiency of the device, thereby impacting its economic performance. A number of PTO systems exist, however, for this category, seven main types, five of which were identified by Têtu [49], have been incorporated into the four general energy conversion mechanisms (electrical, pneumatic, mechanical, and hydraulic) proposed by Falnes [13]. The addition of the sixth and the seventh PTO takes into account the 'Piezoelectric Material' utilised by the technology formerly referred to as bulge wave as well as the recently identified 'Pneumatic System', which is mainly comprised of a compressor and pneumatic motor.

Location. The fundamental design of the device is dependent on the installation site and resource availability at that location [50]. The intended WEC location will also determine the type of mooring system/foundations to be used. This category was based on the nomenclature proposed by the Strategic Initiative for Ocean Energy [50].

2.2. Stage 2: Site Selection

Determining feasible locations to deploy, operate and maintain a WEF is a considerable undertaking, and an extensive amount of information is required to conduct an informed evaluation [26]. Therefore, as seen in Fig. 3, the principal steps in the site selection procedure were grouped into two distinct sub-stages, Stage 2.1: Data Acquisition and Preparation and Stage 2.2: GIS Analysis. In the Data Acquisition and Preparation sub-stage, the general area of interest was established, and the relevant geospatial data was identified, assembled, and prepared. This spatial data was then integrated and modelled in a GIS system, in Stage 2.2, to identify suitable areas for wave energy projects; regardless of the size of the initial study area.

ArcGIS Desktop 10.5.1 was used to implement the proposed site selection approach. It is an appropriate tool for this methodology as it is able to capture, store, maintain, process, analyse, and display geospatial data [51]. This software package is comprised of numerous applications; however, for this method, only ArcCatalog and ArcMap were utilised. ArcCatalog is a data-management application, whereas ArcMap's functionalities range from creating maps to spatially modelling and analysing the geographic data [51].

2.2.1. Stage 2.1: Data Acquisition and Preparation

The steps proposed in the first sub-stage defined the study area, and to encourage a sustainable outcome, by avoiding the development of projects in inappropriate areas, all pertinent and available information was identified and gathered. Sustainability in reference to sustainable development is commonly defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own" [52] and is comprised of the integration of three main dimensions: social inclusion, economic prosperity, and environmental protection [53]. These dimensions, with the addition of a technical and cultural dimension, form the framework for identifying the relevant site selection criteria.

Cultural Dimension. Approximately 27 million people from 87 different countries make up the coastal indigenous communities around the world [54]. These communities are intrinsically linked with the marine environment as it forms part of their cultural heritage and identity [54]. Therefore marine areas of cultural significance or that contribute to the food sovereignty of these communities were considered cultural factors.

Economic Dimension. For the purpose of this study, economic factors were defined as activities that occur in, or uses, the marine environment, which made a direct economic contribution to the study area.

Environmental Dimension. Due to the immature nature of the ocean energy sector, the effects of a WEF on the marine environment, such as the risk of collision between marine animals and the moving parts of WECs, are currently unknown [55]. Furthermore, these potential environmental impacts will also vary depending on the former condition of the receiving environment. For instance, a number of maritime areas have severely deteriorated due to industrial marine activities, whilst untouched marine environments are regarded as more vulnerable. Hence, their protection and preservation are prioritised [26]. Therefore Marine Protected Areas (MPAs), which were established to protect and maintain marine ecosystems and biodiversity, were considered environmental factors.

Social Dimension. The coastal and marine environment provides opportunities for discovery, leisure and contemplation. However, a WEF could potentially interact with or transform these activities, thereby impacting the local lifestyle and negatively influencing public perception [26]. In this approach, only submarine archaeology was considered. However, once suitable WEF locations have been identified, it is recommended that areas of popular recreational activities, such as bathing and surfing, should be identified and used to refine the site selection further.

Technical Dimension. Technical parameters that could influence a WEF installation include the wave climatology (wave resource), ocean features (bathymetry), infrastructure and logistics (grid availability and port facilities), as well as existing marine applications (dredged areas, dumping grounds, military exercise areas, and submarine cables and pipelines) [26].

These site selection factors were then further classified as 'Limiting Conditions', 'Exclusion Factors' and 'Weighted Factors'. The Limiting Conditions delineated the preliminary areas which were viable for wave energy projects, and therefore reduced the size of the initial study area. The Exclusion Factors were considered incompatible with a WEF and were eliminated from further analysis, whilst the Weighted Factors were criteria that had the potential to impact a WEF (either negatively or positively) and were weighted according to their relevance.

As part of this sub-stage, once the relevant site selection considerations were identified, and further categorised, the corresponding spatial datasets had to be sourced and assembled into a database in ArcCatalog. Geospatial data are commonly stored in either a raster or vector structure [51]. In a vector structure, coordinates are used to establish the locations of points, lines, and polygons, which represent discrete map features [51]. Whereas in a raster structure, the geographic space is divided into a regular grid of cells, and each cell is allocated the value of the map feature that dominates that cell [51].

Each of these geographic datasets, which were stored in a vector structure, was then reviewed to determine which required further processing. This included ensuring that the dataset was accurate and up-to-date, projecting datasets to the recommended coordinate system for the study area, as well as splitting or merging existing datasets. Developing the database was a crucial and time-consuming aspect of the procedure,

Table 2
The project constraints that are considered instrumental in determining the most optimal sites for wave energy projects.

Constraint	Weight (%)
Available Wave Energy Resource	60
Distance to Ports	30
Distance to Power Grid	10

as the completeness and quality of the datasets utilised in the spatial analysis determined the accuracy of the resulting suitability map.

2.2.2. Stage 2.2: GIS Analysis

The GIS analysis was conducted in ArcMap, where the vector datasets assembled in Stage 2.1 were displayed as layers. In this sub-stage, the initial processing and analysis procedures were conducted using input layers with a vector structure, whilst the final operation, spatial MCA, required raster input layers.

The first process to be undertaken was to generate a smaller, more manageable Area of Interest (AoI) vector layer from the initial broad study area. Therefore only regions with ocean depths less than 250 m and that had a resource greater than 20 kW/m were considered for further analysis. These parameters were selected as the limiting conditions, as the maximum ocean depth suitable for the installation of WECs ranges from 50 m [27] to 500 m [56] in the literature, and WEFs are only considered viable in locations where the potential wave power is greater than 20 kW/m [56,57].

Then in order to determine the potential areas for the installation of WECs, the exclusion factors were merged to create a single non-installation-areas layer. This layer was spatially removed from the AoI layer, resulting in a Potential Installation Areas (PIA) vector layer.

To perform the final process, spatial MCA required the development of a suitability model (Equation (1)). This model combined the weighted factors, further categorised as constraints and restrictions, to generate a suitability map that identified the most optimal WEF locations by utilising a Suitability Scale (SS), which ranged from 1 (unsuitable locations) to 100 (very suitable locations).

The SS equation is defined as follows:

$$SS = \left(\sum_{i=1}^{n} w_i C_i\right) \prod_{j=1}^{m} R_j \quad (1)$$

where C_i and R_j referred to the (reclassified) constraints and restrictions, which were stored in a raster structure, with w_i representing the weight assigned to the individual constraints. These weightings were based on the importance of each constraint, and the total weight for all constraints was equal to 100%.

Constraints. Practical constraints associated with a WEF took into account the relative ease with which the WEC arrays could be installed, operated and maintained (distance to a port); the ability of the technology to generate electricity from the natural resource (available wave energy resource); and exporting the electricity to the local distribution network or the national transmission grid (distance to the power grid). As these constraints contain different features and measuring units, they had to be reclassified to a common comparable scale. In this scale, low values represented areas of poor resource or great distances from the ports or power grid, whilst high values represented areas with an excellent resource or close proximity to ports or power grid.

These reclassified constraints were then assigned a weight in accordance with their relative economic impact on the project (Table 2). The available wave resource received the highest weighting as it has the greatest influence on the economics of the project. This was followed by the distance to ports, as a WEF will require servicing over its lifespan. The distance to power grid constraint was ranked the lowest as the costs associated with connecting to the power grid (underwater and overland transmission lines) are considered one-off capital costs. The proposed weightings were provided by a wave energy expert (William Dick, personal communication, April 29, 2019), which also corresponded with the values provided in the literature [24]. However, it should be noted that these values are quite subjective and should be adjusted according to the situation being analysed (small island community vs coastal country) and also potentially as the sector matures.

Restrictions. Factors that were not incompatible with a WEF, but could negatively influence the local economy, or public perception were considered restrictions. Therefore these locations were considered less suitable for wave energy projects and were assigned a limiting value based on the perceived importance of these areas with the local stakeholders.

Before applying the suitability model, new raster layers had to be created from the restriction and reclassified constraint raster layers that were contained within the PIA vector layer. The resulting 'clipped' (cropped) restriction and reclassified constraint raster layers were then inputted into Equation (1) to identify the most optimal WEF locations.

2.3. Stage 3: Site Matching

In order to select the most suitable WEC(s) for potential WEF sites requires a systematic approach, which was comprised of three sub-stages. The first sub-stage, Stage 3.1: Site Assessment, quantified and characterised the resource available at the potential WEF location(s). The second sub-stage, Stage 3.2: Preliminary WEC Screening reduced the number of devices for further analysis based on advanced technical maturity. Whilst Stage 3.3: WEC Assessment identified appropriate power and economic performance metrics to compare and rank the selected devices at these specific sites.

2.3.1. Stage 3.1: Site Assessment

The first step in assessing the wave climates at the locations identified in Stage 2.2 was to quantify the available resource, thereby identifying the most attractive sites in terms of potential electricity production. Two wave parameters that are fundamental in calculating the omnidirectional wave power (per metre of wave crest), P_W, are the spectral significant wave height, H_{m0}, and energy wave period, T_e [55]:

$$P_W = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e \quad (2)$$

where ρ is the density of seawater (1025 kg/m^3), and g is the acceleration due to gravity (9.81 m/s^2).

However, as stated in Section 1.2, the amount of energy that can be harvested from a site is dependent on the WEC characteristics being analysed, such as its efficiency at various sea states [22]. Therefore, the resource should be further characterised in terms of its sea states. This was achieved by constructing omnidirectional scatter diagrams (bivariate histograms) [58], which typically plot H_{m0} against T_e in tabular form, where the relative frequency of occurrence of a $H_{m0} - T_e$ pair (sea state) is represented in each bin. In this study, the H_{m0} and T_e bins were defined in 0.5 m and 1.0 s intervals [58], respectively.

2.3.2. Stage 3.2: Preliminary WEC Screening

Once all the relevant information had been recorded in the developer database (Stage 1), WECs that had reached TRL 7 (Stage 4) or above, were selected for further analysis. At this TRL, the device and its subsystems (PTO and control systems, foundations and moorings, and primary mover) have been validated; energy production has been verified; and survivability has been demonstrated [10].

2.3.3. Stage 3.3: WEC Assessment

As the wave energy sector is characterised by a wide range of technologies, appropriate performance metrics are required in order to compare and rank the devices. Since the ultimate objective of any power generating plant is to produce and supply electricity, an integral

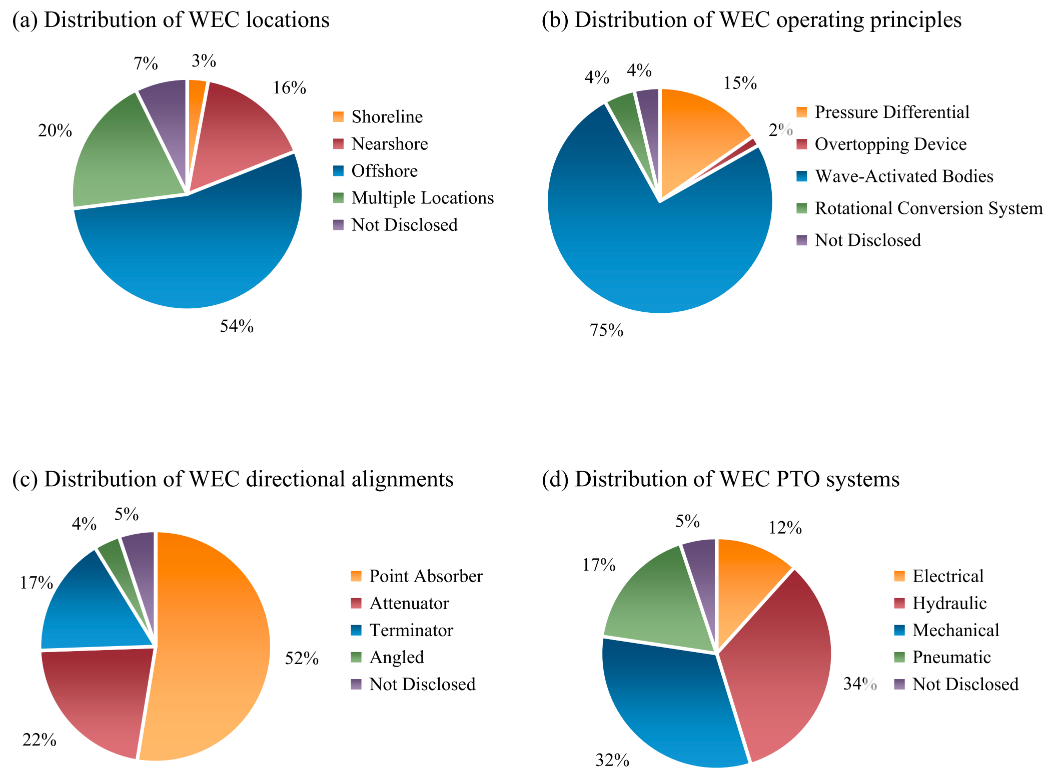


Fig. 4. The distribution of wave energy technology identified as active, according to four of the proposed classification categories: (a) Location; (b) Operating Principle; (c) Directional Alignment; and (d) PTO System.

parameter to consider would be the average power output (P_E) of the WEC. This is dependent on its geometry, PTO, and control strategies as well as the local wave resource [33], and is calculated as follows [29]:

$$P_E = \frac{1}{100} \sum_{i=1}^{n_T} \sum_{j=1}^{n_H} P_{ij} p_{ij} \tag{3}$$

where P_{ij} indicates the percentage occurrence (of the $H_{m0} - T_e$ pair) that corresponds to the bin defined by row i and column j of the resource scatter diagram. p_{ij} refers to the expected power output of the same sea state of the WECs power matrix, while n_T and n_H refer to the number of horizontal and vertical bins, respectively.

However, devices vary in terms of size and rated capacity, and so, therefore, it would be more appropriate to compare normalised power performance by utilising indicators such as the Capture Width Ratio (CWR) and capacity factor (C_f).

CWR. This parameter represents the effectiveness of the WEC to capture the energy contained within the ocean waves [59] and is determined by [60]:

$$CWR = \frac{P_E}{BP_W} \tag{4}$$

where B is the characteristic dimension of the WEC (most commonly the device's width [60]).

C_f. The average usage of the WEC's installed capacity is described by the C_f [59], which corresponds to the ratio between the average electrical power generated and the rated peak power [61]. This commonly used metric is computed by Ref. [62]:

$$C_f = 100.\frac{P_E}{R_C} \tag{5}$$

where R_C indicates the WEC's rated capacity.

Whilst these power performance metrics are essential in assisting in the selection of an appropriate device for a particular location, it does not include cost and so, therefore, are insufficient for evaluating the technology's investment potential [61].

The Levelised Cost of Electricity (LCOE) is a standard cost metric for quantifying the economic performance of an electricity-generating technology [47]. This parameter takes into consideration the capital costs, the operation and maintenance costs over the project's lifespan, as well as the technology's cumulative energy yield. Therefore, it will be used to measure the cost-performance of the selected WECs.

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEP_t}{(1+r)^t}} \tag{6}$$

where *CAPEX* refers to the project's Capital Expenditures and *OPEX* the project's Operational Expenditures, r refers to the discount rate, t is the year from the start of the project, n is the project life expectancy, and *AEP* is the Annual Energy Production [63], $AEP = C_f(365)(24)$.

As the methodology compares conflicting criteria, it will be necessary to utilise multi-criteria decision-making analysis to prioritise and rank the most optimal (WEC) solutions for a proposed WEF site.

2.4. Case Study

The procedures proposed in Stage 2 and 3 were applied to an NZ case study. NZ is an island country that is comprised of two main landmasses (the North and South Islands separated by Cook Strait) and over seven hundred smaller islands [64]. It is an ideal case study as it is in a prime position to develop wave energy projects. Firstly, as this island nation is quite isolated, its shores are exposed to high energy wave conditions, approximately 25 kW/m [65], from the surrounding Southern and Pacific oceans and the Tasman Sea [66]. Secondly, NZ has an extensive marine area, as it has the sixth-largest EEZ in the world [67], and lastly,

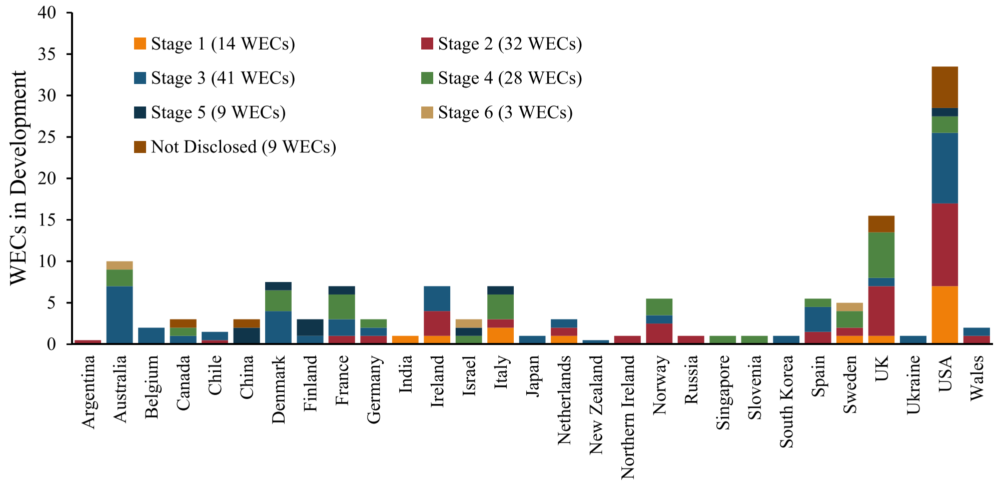


Fig. 5. Global distribution and status of WECs based on the proposed seven-staged approach (with the exclusion of Stage 0—TRL 1).

over 70% of the population resides within 10 km of the coast [68], which provides additional opportunities for distributed generation.

3. Stage 1: WEC Identification

The initial database identified 272 companies that were developing a total of 295 WECs. However, once each of these companies were reviewed, this number significantly reduced to 123 companies developing a total of 137 devices (with eleven of these companies developing more than one WEC).

The majority of these devices are currently being developed specifically for the offshore ocean environment (Fig. 4(a)). The advantage of these offshore WECs is that they can extract greater amounts of energy due to the higher energy content in deeper water waves [6]. In addition, suitable areas for wave device installation in deep water are considerably greater than the areas available for nearshore and shoreline device deployment [50], which has led to a growing market for these types of devices. However, these devices are more challenging to construct, operate and maintain and therefore, costs are significantly increased [14]. Furthermore, these devices need to be designed to survive the most extreme conditions due to the increased wave height and energy content in deep water waves. These complications have hindered their development, and as a result, almost 65% of the WECs currently being developed for the offshore environment are only at Stage 3 or below with regards to device maturity.

Offshore devices are predominately based on the wave-activated bodies working principle [12]. This principle of operation also encompasses a broad range of WECs, that vary from single-to multi-body systems, which can be either floating or fully submerged [12]. Therefore, as seen in Fig. 4(b), this is currently the prevailing technology type in the ocean wave sector.

In terms of directional alignment (Fig. 4(c)), the most common WEC currently in development is the point absorber (with a 52% majority). This device is able to capture energy from all directions, which is usually converted by a mechanical and/or hydraulic PTO system to a linear or rotational motion to drive electrical generators [6]. Consequently, as seen in Fig. 4(d), the most common methods of energy conversion are based on the hydraulic (hydro turbine or hydraulic system) and mechanical (direct drive system) PTO systems.

The international development status of WECs, based on the proposed seven-staged approach, is depicted in Fig. 5. As seen in this figure, the majority of devices (64%) are currently only at Stage 3 (TRL 5–6) or below. This can be attributed to the exponential increase in costs associated with advancing the technology readiness of the device from Stage 3 (TRL 5–6) to Stage 4 (TRL 7), as a twofold increase in spending is

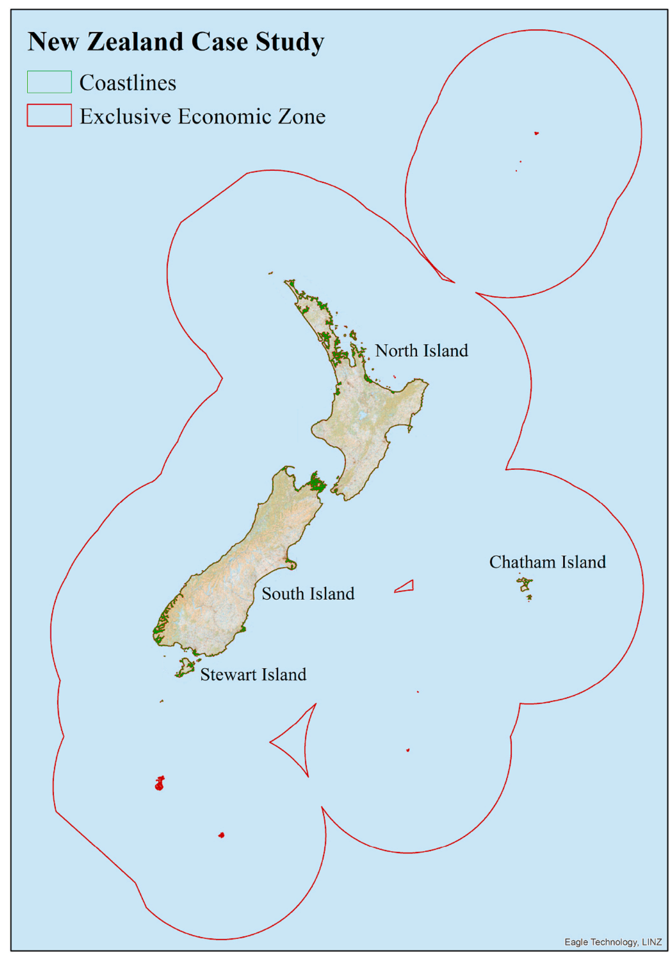


Fig. 6. The initial marine area proposed for the NZ case study.

expected [10]. Also, in some cases, the developer will deliberately remain at laboratory testing scale (1:100–1:15) in order to optimise the WEC's technical and economic performance, rather than devoting the resources to prematurely scaling-up the device for ocean deployment.

Fig. 5 also shows the global distribution of individual WEC development. As shown in this graph, the industry is currently dominated by the USA (with 33.5 devices) and the UK (with 15.5 devices), both of which have significant wave energy resources coupled with the

Table 3
The relevant site selection factors identified according to the proposed cultural, economic, environmental, social, and technical dimensions.

Dimension	Factor	Classification	Data Source
Study Area	Coastline	–	[73]
	Exclusive Economic Zone	–	[74]
Cultural	Mātaitai Reserves	Exclusion	[a]
	Taiāpure	Exclusion	[75]
Economic	Marine Farms (Aquaculture)	Exclusion	[76]
	Settlement Areas (Aquaculture)	Exclusion	[77]
	Commercial Fisheries	Exclusion	[b]
	Offshore Installations	Exclusion	[78,79]
	Seabed Mining	Exclusion	[80]
	Shipping (Routes)	Exclusion	[c]
Environmental	Benthic Protection Areas	Exclusion	[81]
	Hauraki Gulf Marine Park	Weighted (*Restriction*)	[b]
	Marine Mammal Sanctuaries	Weighted (*Restriction*)	[82] [83]
	Marine Protected Areas	Exclusion	[84]
	Marine Reserves	Exclusion	[85]
	Seamount Closure Areas	Exclusion	[86]
Social	Submarine Archaeology	Weighted (*Restriction*)	[87–90]
Technical	Bathymetry	Limiting Condition	[91]
	Dredged Areas	Exclusion	[92,93]
	Dumping Grounds	Exclusion	[94–96]
	Grid Availability	Weighted (*Constraint*)	[d]
	Military Exercise Areas	Exclusion	[97]
	Commercial Ports	Weighted (*Constraint*)	[98]
	Submarine Cables	Exclusion	[99]
	Submarine Cables & Pipelines Protection Zones	Exclusion	[84] [100–103]
	Wave Energy Resource	Limiting Condition; Weighted (*Constraint*)	[e]

[a] Ministry for Primary Industries, personal communication, December 22, 2018.
[b] Fisheries NZ, personal communication, March 12, 2019.
[c] Maritime NZ, personal communication, March 4, 2019.
[d] Transpower, personal communication, May 6, 2019.
[e] MetOcean Solutions, personal communication, November 23, 2017.

manufacturing capability [69]. However, in terms of technology maturity, the UK is in the lead with 5.5 devices at Stage 4 or above, followed by France and Italy, with four devices each (at Stage 4 or above). It should be noted that in this study, if a developer was based in two or more countries, 0.5 of the device was allocated to each of these countries.

As the wave energy sector is continually evolving, it is recommended that in order to maintain the database, it should be updated continuously (at least every six months).

4. Stage 2: Site Selection—NZ Case Study

4.1. Stage 2.1: Data Acquisition and Preparation

To demonstrate that the proposed site selection methodology is valid at any scale, especially large scale, the initial study area (Fig. 6) was defined as all the marine waters contained between NZ's coastline and EEZ; approximately 4.1 million km^2.

The site selection considerations applicable to this case study are depicted in Table 3. These criteria were identified according to the five main dimensions proposed in Section 2.2.1, and depending on its potential to condition or influence the project, were classified further as limiting conditions, and exclusive or weighted factors. Based on the site selection factors proposed by Galparsoro et al. [25], Le et al. [27], Nobre et al. [24], and the WAVEPLAM project [26], it was found that the proposed economic, social and technical criteria were widely applicable, whilst the recommended cultural and environmental factors are unique to NZ.

Cultural Factors. The importance of oceans to the Māori tribes, NZ's indigenous people, is managed through the establishment of mātaitai reserves (traditional fishing grounds) and taiāpure (traditional fishing grounds as well as areas of special cultural or spiritual significance) [70].

Environmental Factors. There are three levels of marine protection in NZ: marine reserves (the highest protection level); MPAs; and other marine protection tools (which includes benthic protection areas, seamount area closures, marine mammal sanctuaries and the Hauraki Gulf marine park) [71]. Additional environmental aspects that should be considered, once these general WEF installation regions have been identified, are coastal areas of outstanding natural character, features, and landscapes [72].

The corresponding GIS database was then developed using spatial data from the sources referred to in Table 3. The majority of the site selection factors were readily available in a GIS format and only required minimal changes. These modifications included transforming the geospatial data into the same projected coordinate system (NZ Continental Shelf Lambert Conformal 2000—the recommended coordinate system for NZ's continental shelf [104]), ensuring the shapefiles were up-to-date (by referring to the relevant NZ nautical charts and/or legislation), and clipping the features to the defined study area.

However, several geographical datasets had to be created in ArcMap. These included the commercial fisheries, shipping routes, military exercise areas and submarine cable and pipeline protection areas.

Commercial Fisheries. A commercial fishing intensity raster layer, comprised of 5 km^2 grid cells, was provided by Fisheries NZ. These cells were assigned a value that ranged from 1 (low catch) to 10 (high catch). In order to generate the commercial fisheries vector layer, the cells containing a high-intensity ranking (values ranging from 7 to 10), were identified, and then converted to the appropriate vector format.

Shipping (Routes). As NZ does not have mandatory shipping lanes, a popular shipping routes vector layer was created from the Automatic Identification System ship tracking data provided by Maritime NZ. A statistical analysis tool was used to determine areas of statistically significant spatial clusters of shipping track lines in a fishnet grid comprised of 5 km^2 cells, thereby identifying routes that were most frequented by commercial ships.

Military Exercise Areas. The military exercise areas vector layer was created from the coordinates provided in the Annual NZ Notices to Mariners regarding the firing and bombing practices as well as defence exercises that take place off the coast of NZ [97].

Submarine Cables & Pipelines Protection Zones. NZ has designated cable and pipeline protection zones [105] within its territorial seas, several which qualify for 'Type 2 MPA' status, as defined by NZ's Ministry of Fisheries and Department of Conservation [71]. However, for this study MPAs are categorised as environmental factors, which as stated in Section 2.2.1 are areas which have been established to provide protection to marine habitats and ecosystems. Therefore, the cable protection zones included in the original MPA spatial dataset were exported to a new vector layer, which was then further amended to include cable protection zones that were not classified as Type 2 MPAs. These additional areas were created from the coordinates provided in the relevant NZ legislation (Table 3).

Furthermore, designated cable protection zones have not been delineated within NZ's EEZ. Therefore a spatial dataset with the recommended one nautical mile buffer [106] on either side of the relevant submarine cables was also generated.

4.2. Stage 2.2 GIS Analysis

This initial study area of 4,163,866 km^2 was significantly reduced to a reasonable AoI of only 131,613 km^2 in size (3% of the initial study

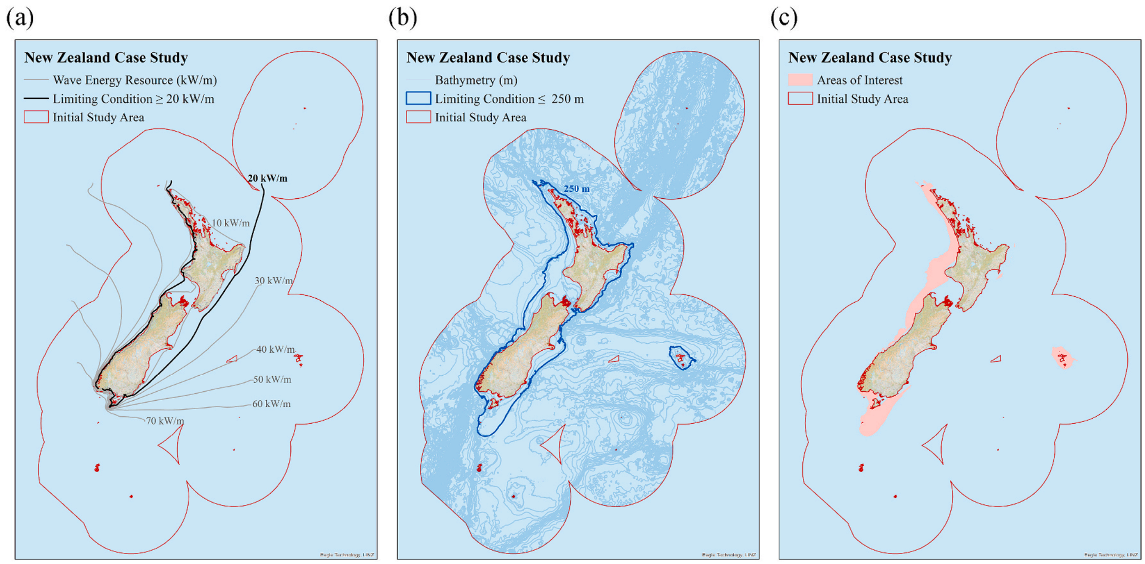


Fig. 7. The (a) minimum and (b) maximum limiting conditions that were applied to generate the significantly reduced (c) AoI layer.

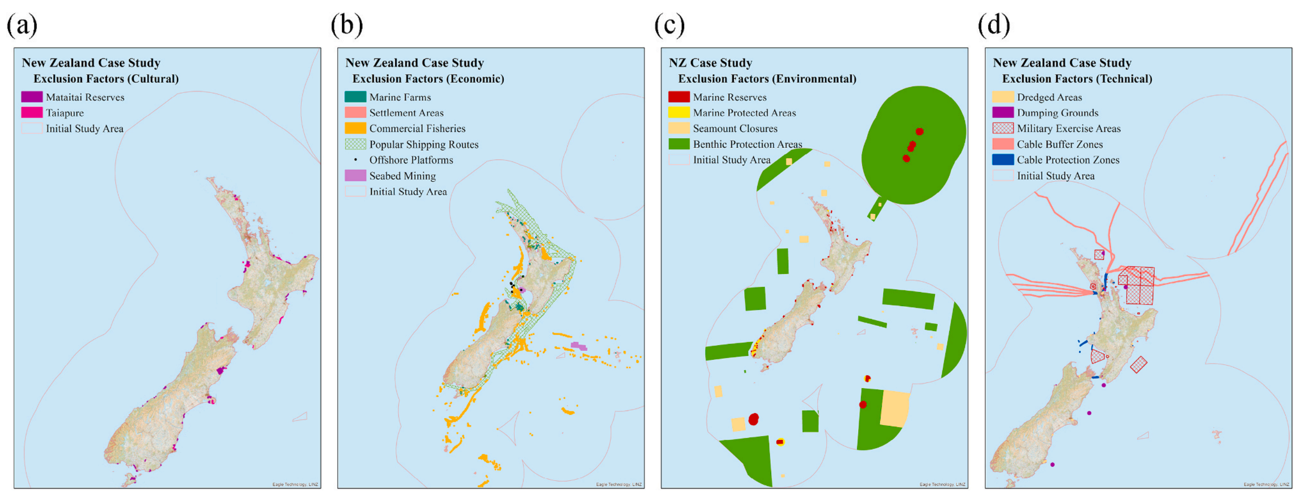


Fig. 8. Visualisation of the (a) cultural, (b) economic, (c) environmental, and (d) technical activities incompatible with a WEF.

area), by applying the limiting conditions depicted in Fig. 7(a) and (b), respectively. However, as NZ is an archipelago, the limiting conditions were only applied to the inhabited islands [107]; North and South Island, Chatham Island, and Stewart Island (Fig. 6).

The resulting AoI is predominately limited to the north-west and southern coastal areas of North and South Island, whilst almost entirely surrounding Stewart and Chatham Island (Fig. 7(c)). Most areas along the north- and south-east coasts (of North and South Island) were excluded due to the combination of low wave resource and large ocean depths. These areas also coincided with the majority of marine applications in NZ, Fig. 8(b) and (d), and thus would have been excluded from further analysis regardless.

As seen in Fig. 8(a–d), a large proportion of NZ's coastal and shallow waters are committed to other uses, which are considered incompatible with WEFs.

These exclusion factors were clipped to the AoI layer and merged to create a new layer that depicted areas in direct conflict with wave energy projects; Fig. 9(a). The incompatible areas were then erased from the AoI layer, Fig. 9(b), thereby resulting in the PIA layer depicted in Fig. 9(c). The elimination of the exclusion factors decreased the area for further analysis from 131,613 km^2 to 111,529 km^2; an additional 15% reduction.

The weighted factors, categorised as constraints and restrictions (Table 3), were then combined to develop the WEF suitability map.

Constraint. The constraint raster layers were generated from the vector datasets pertaining to grid availability, commercial ports, and the wave energy resource. A straight line tool was applied to the ports and grid connection points that were within 50 km of the PIAs. These newly generated constraint layers contained distance data (in km) from the grid/port location to 100 km offshore (at a 1 km resolution). Whereas the wave energy resource contour lines were interpolated, in order to determine the available resource (in kW/m), at any location, within the extent of the PIA (also at a 1 km resolution).

As a first approach, the distance constraints were reclassified by utilising the quantile classification scheme, whilst the geometric interval method was used to reclassify the available resource constraint. These data classification methods were selected as they are best suited for linearly distributed data (the distance constraints) and continuous data (the resource constraint) [108]. Thereafter, the reclassified constraint layers were clipped to the PIA layer, resulting in the layers depicted in Fig. 10(a–c).

Restriction. The Hauraki Gulf Marine Park, marine mammal sanctuaries, and NZ's submarine archaeology (shipwrecks) were identified as potential restrictions. However, as seen in Fig. 11(a), the Hauraki Gulf

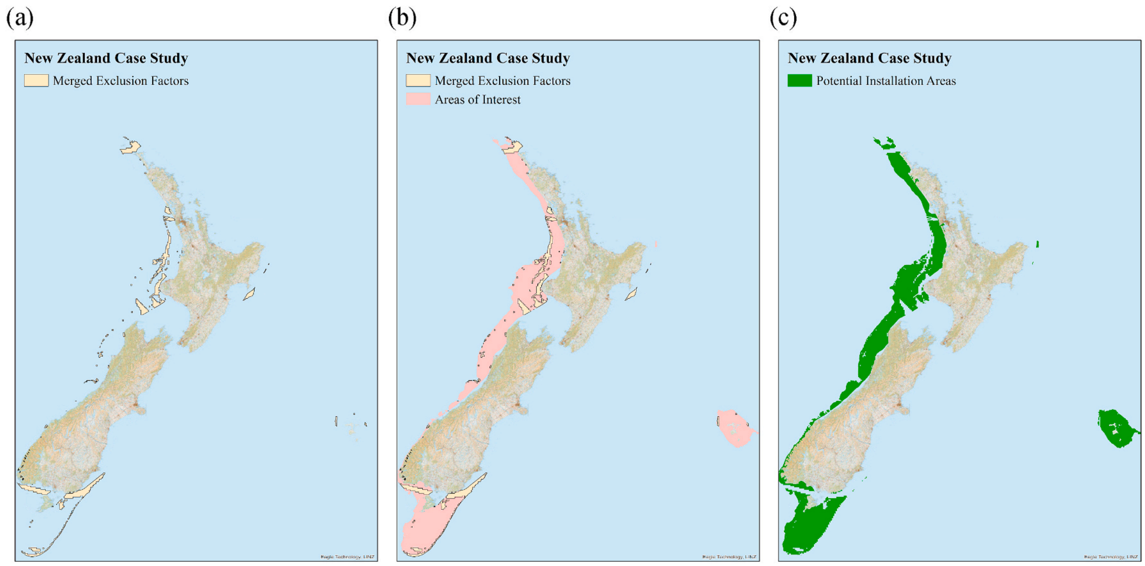


Fig. 9. The (a) exclusion factors were merged to create a non-installation areas layer, which was (b) spatially removed from the AoI layer to generate (c) the PIAs for WEFs in NZ.

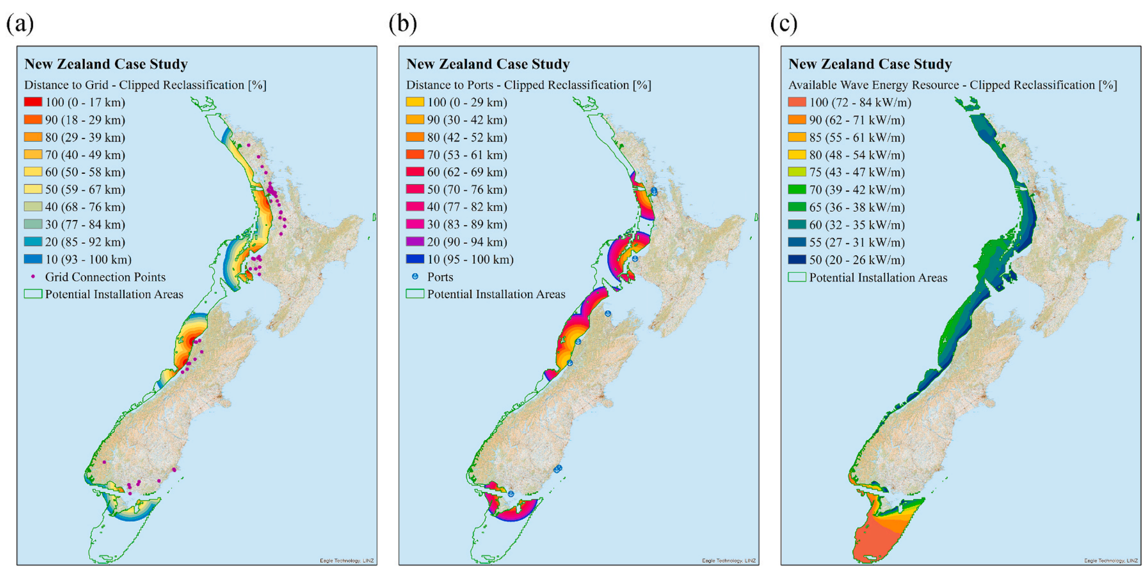


Fig. 10. The reclassified and clipped (a) distance to grid, (b) distance to ports, and (c) available wave energy resource constraints utilised in the suitability model.

Marine Park does not fall within the PIAs, and therefore, was not included in the suitability model.

The remaining marine mammal sanctuary and submarine archaeology vector layers had to be processed further to generate the restriction raster layers required for the SS equation. Therefore, the marine mammal sanctuaries were clipped to the PIA layer and converted to a raster (Fig. 11(b)). Whereas a new vector layer containing 500 m buffers around the shipwrecks that were within 500 m of the PIA layer was created, and then also converted to a raster. These clipped restrictions were preliminarily assigned a limiting value of 0.8, as more detailed information was not available. As the constraints identify the general areas that are most suitable for WEFs, this 20% reduction in the final SS value in these restriction zones, would not significantly alter the final results.

To produce the final suitability map depicted in Fig. 12, the SS model, Equation (1), was executed in two parts. The first part of the equation used the weighted overlay tool to sum the weighted clipped and reclassified constraints, which generated a preliminary suitability raster layer. The second part of the equation then used the raster calculator to multiply the clipped restrictions and the preliminary suitability raster, which resulted in the final suitability map (Fig. 12) with SS values lowered accordingly in the restriction zones.

These SS values were only calculated for areas that contained all three constraints. Therefore, PIAs surrounding Chatham Island were excluded from the suitability model as the relevant spatial datasets could not be acquired.

5. Stage 3: Site Matching—NZ Case Study

5.1. Stage 3.1 Site Assessment

The relevant details pertaining to the 12 sites identified as optimal WEF locations (Fig. 12) are presented in Table 4. The depth of these sites ranged from 47.3 m (I1) to 149.8 m (I3), and so, therefore, WECs considered for these locations would have to be able to operate in offshore conditions (Fig. 2). Furthermore, as a minimum of ten years of

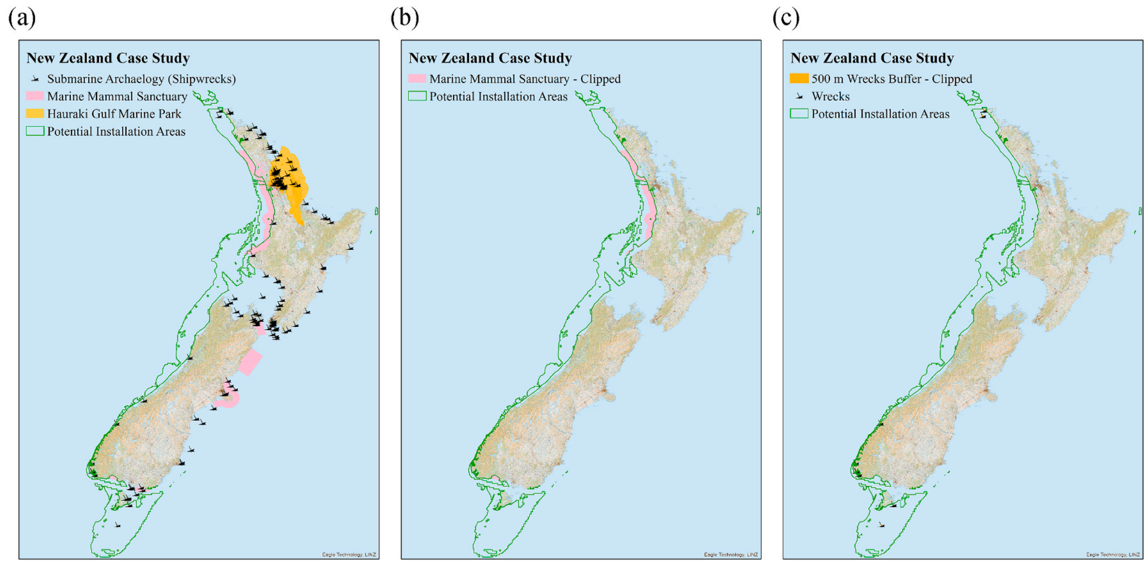


Fig. 11. The (a) social and environmental factors classified as potential restrictions, which were further processed to generate the clipped (b) marine mammal sanctuary and (c) 500 m (ship)wreck buffer restriction raster layers.

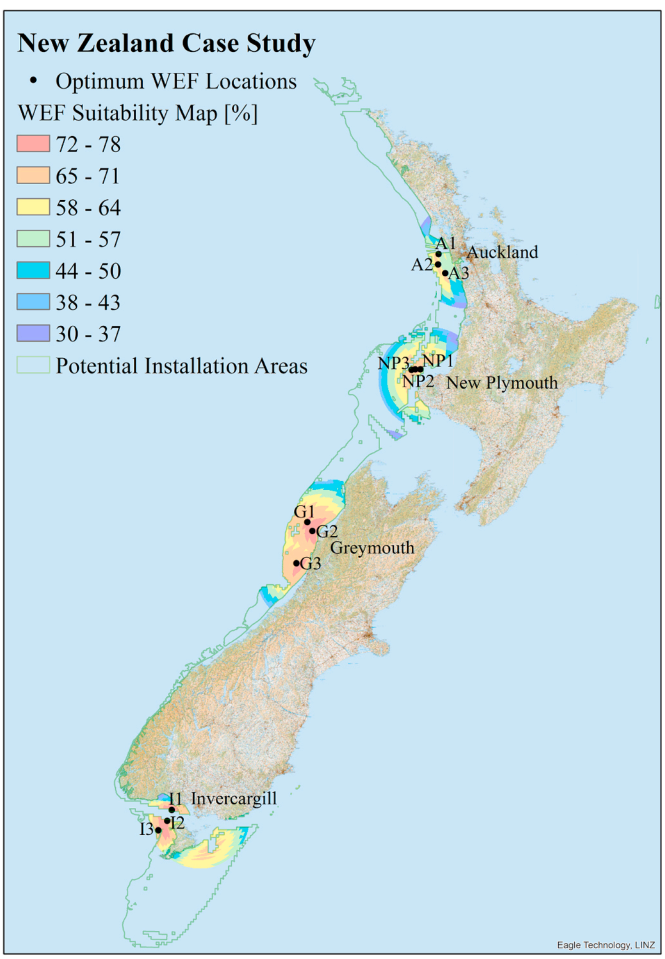


Fig. 12. The final suitability map indicating the most optimal locations for WEFs in NZ are offshore Auckland, New Plymouth, Greymouth, and Invercargill.

Table 4
The coordinates and depth values of the study sites (Fig. 12) considered suitable for the installation of WEFs. The latitude and longitude values are expressed in Decimal Degrees (DD).

Location	Latitude [DD]	Longitude [DD]	Depth [m]
Auckland 1 (A1)	−36.9	174.2	69.9
Auckland 2 (A2)	−37.1	174.2	90.6
Auckland 3 (A3)	−37.2	174.3	79.3
New Plymouth 1 (NP1)	−38.9	173.8	127.3
New Plymouth 2 (NP2)	−38.9	173.7	130.0
New Plymouth 3 (NP3)	−38.9	173.6	131.0
Greymouth 1 (G1)	−41.7	171.3	137.0
Greymouth 2 (G2)	−41.6	171.2	147.7
Greymouth 3 (G3)	−42.3	171.0	99.3
Invercargill 1 (I1)	−46.4	167.7	47.3
Invercargill 2 (I2)	−46.6	167.6	68.8
Invercargill 3 (I3)	−46.8	167.3	149.8

wave data are required to reliably assess each site [109], 20 years of H_{m0} and T_e data (from January 1993 to December 2012) were obtained from the recently published NZ Wave Data Tool [110]. This tool is a high-resolution (9 km) hindcast model that provides a range of 3-hourly integrated and partitioned wave parameters relating to the wave climate surrounding NZ [110].

The average power available year-to-year across the 20-year interval varied significantly for I1–I3 (Fig. 13), where I3 had a maximum range of 44 kW/m. All the other study sites (A1–G3) were much less variable over the same period of time, G3 only had a range of 11 kW/m, but had milder wave climates (relative to I1–I3).

As seen in Fig. 14, the average annual wave power over the 20 year-interval ranged from 28 kW/m at G3 to almost three times that at I3 (78 kW/m). Fig. 14 also depicts the seasonal distribution of the average wave power potential at all the locations, which behaved as expected; with a maximum and minimum wave power available in the winter (June, July, and August) and summer (December, January, and February) months, respectively. Across all the study sites, winter accounted for approximately 31% of the annual wave power, whilst summer provided only about 16% of the annual power output.

In order to determine the energy performance of the WECs (Equation (3)) at each of these study sites required the development of scatter diagrams. The scatter diagrams depicted in Fig. 15 plotted the percentage occurrence of the $H_{m0} - T_e$ pair over the entire 20-year time

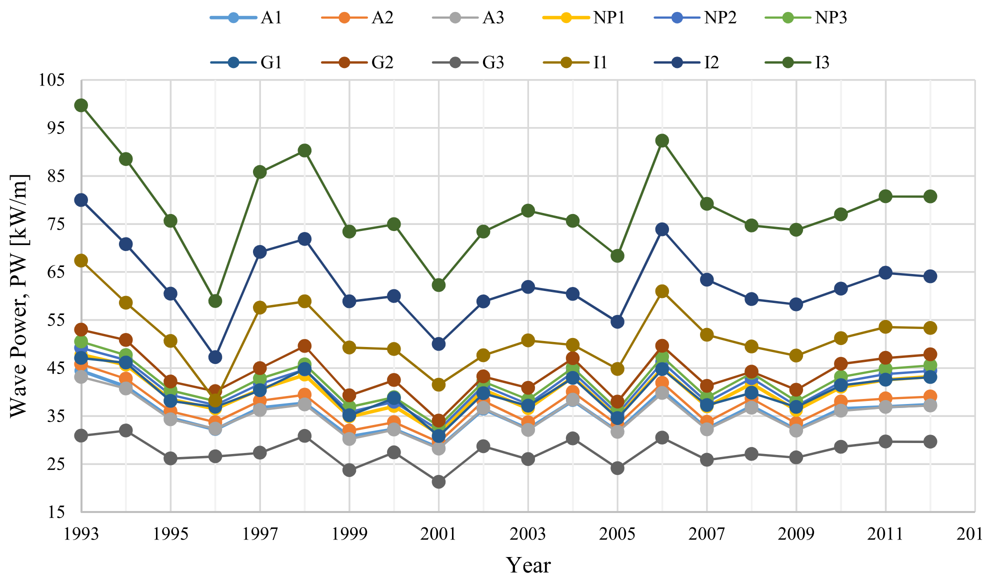


Fig. 13. The inter-annual variation of the average yearly power over a 20-year time horizon (January 1993–December 2012).

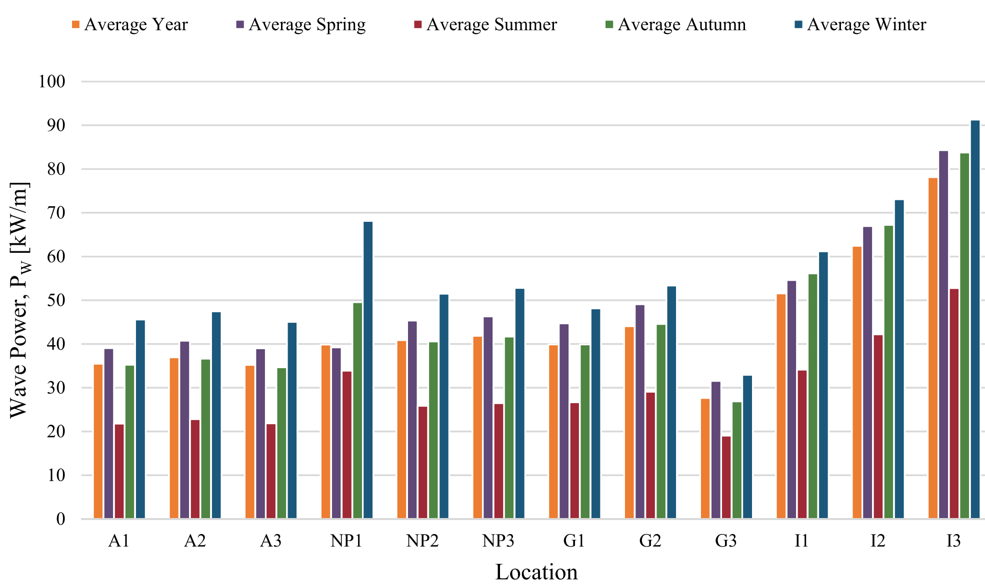


Fig. 14. Average yearly and seasonal wave power corresponding to the 20-year interval from January 1993–December 2012.

period. The H_{m0} bins were defined in 0.5 m intervals, which ranged from 0 to 16 m, and the T_e bins were defined in 1 s intervals that ranged from 0 to 20 s.

As seen in Fig. 15, NZ's wave climate was characterised by T_e that varied from 4 to 19 s (at all the sites), whilst H_{m0} varied from waves just greater than 0–9.5 m high, at the majority of the study sites (A1–G3). The H_{m0} at the offshore Invercargill locations (I1–I3) were significantly higher with waves reaching 13 m in height (I3). Regardless of the difference in H_{m0}, the majority of the sea states at all study sites were between 1 and 3.5 m for H_{m0} (~75%) and between 8 and 12 s for T_e (~80%). Therefore, WECs considered for the NZ wave climate should have a maximum efficiency for these prevalent sea states.

5.2. *Stage 3.2 WEC Screening*

A total of 40 devices were identified as being at Stage 4 (TRL 7) or above, from the 137 WECs currently in development. The developers of these devices are predominately based in Europe (69%), and the majority of these WECs are offshore (54%) wave-activated (82%) point absorbers (67%) that either utilise a hydraulic (44%) or mechanical (31%) PTO system.

6. Conclusions

An integrated site and device selection methodology has been developed and demonstrated in this paper, which was comprised of three main stages.

The first stage identified 137 WECs currently in development and utilised five main categories, including a technology maturity category, to classify current and future devices in a practical and meaningful manner.

The second stage implemented a site selection methodology that was applicable at any scale and was applied to an NZ case study. For this stage: (1) five main dimensions were utilised, which included a new cultural dimension, in order to determine the relevant site selection criteria; (2) limiting conditions were introduced to reduce the study area; (3) site selection criteria were classified as exclusion or weighted factors, and the exclusion factors were eliminated from further analysis;

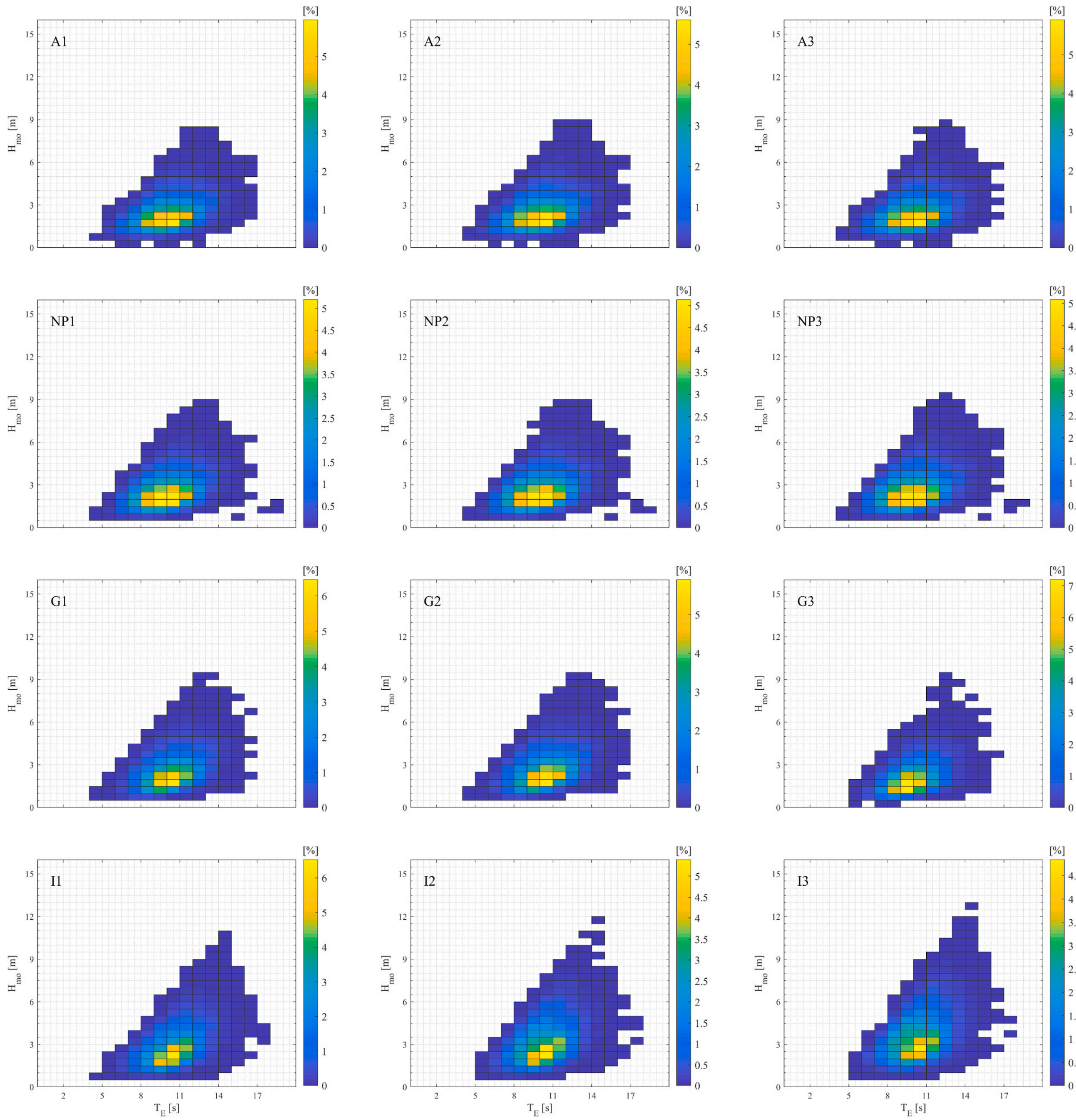


Fig. 15. Scatter diagrams of the H_{m01} and T_e parameters for each of the 12 potential WEF sites. The seas states correspond to a 20-year interval from January 1993 to December 2012.

and (4) a SS, which represented the spatial distribution of each area's suitability for a WEF, was developed by combining the relevant weighted factors. Based on these analyses, 12 optimal WEF locations, clustered in four regions, were identified along NZ's west coast. Namely, offshore Auckland (North Island), New Plymouth (North Island), Greymouth (South Island), and Invercargill (South Island).

As part of the third and final stage, the resource available at the 12 WEF sites was determined by analysing 20 years of hindcast data. The results showed that the average annual wave power ranged significantly from 28 kW/m (at Greymouth) to almost triple that at Invercargill (78 kW/m). In addition, 40 devices were selected for further analysis based on a high technology maturity level, and then four conflicting techno-economic performance metrics were proposed to quantitatively compare and rank the WECs for the specific sites identified in Stage 2.

Credit author statement

Danielle V. Bertram: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualization. **Amir H. Tarighaleslami:** Methodology, Writing – Original Draft, Writing – Review & Editing. **Michael R.W. Walmsley:** Supervision, Resources, Writing – Review & Editing. **Martin J. Atkins:** Writing – Review & Editing. **Graeme D.E. Glasgow:** Writing – Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank, World Health Organization. Tracking SDG7: the energy progress report. Washington: The World Bank; 2018.
[2] Xie J, Zuo L. Dynamics and control of ocean wave energy converters. Int J Dyna Contr 2013;1(3):262–76.
[3] Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Kadner S, Zwickel T, et al. Renewable energy sources and climate change mitigation: special report of the intergovernmental panel on climate change. Cambridge University Press; 2011.
[4] United Nations. Factsheet: people and oceans. 2017. https://www.un.org/sustainabledevelopment/wp-content/uploads/2017/05/Ocean-fact-sheet-package.pdf. [Accessed 7 June 2019].
[5] Ghosh S. Wave energy potential site selection based on MCDM and neural network analysis. In: Application of geographical information systems and soft computation techniques in water and water based renewable energy problems. Springer; 2018. p. 107–20.
[6] Czech B, Bauer P. Wave energy converter concepts: design challenges and classification. IEEE Ind Electron Mag. 2012;6(2):4–16.
[7] Hannon M, van Diemen R, Skea J. Examining the effectiveness of support for UK wave energy innovation since 2000: lost at sea or a new wave of innovation? Glasgow: University of Strathclyde, International Public Policy Institute; 2017.
[8] Holmes B, Nielsen K. Guidelines for the development & testing of wave energy systems. OES-IA Annex II Task 2.1 2010. Contract No.: Report T02.1.
[9] Fitzgerald J, Bolund B. Technology readiness for wave energy projects; ESB and Vattenfall classification system. In: Proceedings of the 4th international conference on ocean energy; 2012. Oct 17 -19; Dublin, Ireland.
[10] Fitzgerald J. ESB wave energy systems: technology readiness levels. 2012. Contract No.: ESBIoe-WAV-12-091 Rev.2.
[11] Weber J. WEC technology readiness and performance matrix–finding the best research technology development trajectory. In: Proceedings of the 4th international conference on ocean energy; 2012. Oct 17 -19; Dublin, Ireland.; 2012.
[12] Falcão AF. Wave energy utilization: a review of the technologies. Renew Sustain Energy Rev 2010;14(3):899–918.
[13] Falnes J. A review of wave-energy extraction. Mar Struct 2007;20(4):185–201.
[14] Drew B, Plummer AR, Sahinkaya MN. A review of wave energy converter technology. 2009.
[15] EMEC. Wave devices. 2019. http://www.emec.org.uk/marine-energy/wave-developers/. [Accessed 9 June 2019].
[16] Li Y, Yu Y-H. A synthesis of numerical methods for modeling wave energy converter-point Absorbers. Renew Sustain Energy Rev 2012;16(6):4352–64.
[17] Lehmann M, Karimpour F, Goudey CA, Jacobson PT, Alam M-R. Ocean wave energy in the United States: current status and future perspectives. Renew Sustain Energy Rev 2017;74:1300–13.
[18] Myers LE, Bahaj AS, Retzler C, Pizer D, Gardner F, Bittencourt C, et al. EquiMar deliverable D5. 2: device classification template. 2011.
[19] Margheritini L, Hansen AM, Frigaard P. A method for EIA scoping of wave energy converters-based on classification of the used technology. Environ Impact Assess Rev 2012;32(1):33–44.
[20] O'Connor M, Lewis T, Dalton G. Techno-economic performance of the Pelamis P1 and Wavestar at different ratings and various locations in Europe. Renew Energy 2013;50:889–900.
[21] Doyle S, Aggidis GA. Development of multi-oscillating water columns as wave energy converters. Renew Sustain Energy Rev 2019;107:75–86.
[22] Dunnett D, Wallace JS. Electricity generation from wave power in Canada. Renew Energy 2009;34(1):179–95.
[23] Coe RG, Michelen C, Eckert-Gallup A, Sallaberry C. Full long-term design response analysis of a wave energy converter. Renew Energy 2018;116:356–66.
[24] Nobre A, Pacheco M, Jorge R, Lopes MFP, Gato LMC. Geo-spatial multi-criteria analysis for wave energy conversion system deployment. Renew Energy 2008;34(1):97–111.
[25] Galparsoro I, Liria P, Legorburu I, Bald J, Chust G, Ruiz-Minguela P, et al. A marine spatial planning approach to select suitable areas for installing wave energy converters (WECs), on the Basque continental shelf (Bay of Biscay). Coast Manag 2012;40(1):1–19.
[26] EU WAVEPLAM Project. D3.1 methodology for site selection. 2009.
[27] Le P, Fischer A, Penesis I, Rahimi R. Aggregating GIS and MCDM to optimize wave energy converters location in Tasmania, Australia. In: Soft computing applications for renewable energy and energy efficiency. IGI global; 2015. p. 141–64.
[28] Chakraborty T. A MCDM-NBO approach for selection of installation location for wave energy power plants. In: Application of geographical information systems and soft computation techniques in water and water based renewable energy problems. Springer; 2018. p. 121–40.
[29] Rusu E. Evaluation of the wave energy conversion efficiency in various coastal environments. Energies 2014;7(6):4002–18.
[30] Dalton GJ, Alcorn R, Lewis T. Case study feasibility analysis of the Pelamis wave energy convertor in Ireland, Portugal and North America. Renew Energy 2010;35(2):443–55.
[31] Amrutha M, Kumar VS, Bhaskaran H, Naseef M. Consistency of wave power at a location in the coastal waters of central eastern Arabian Sea. Ocean Dynam 2019;69(5):543–60.
[32] Iuppa C, Cavallaro L, Foti E, Vicinanza D. Potential wave energy production by different wave energy converters around Sicily. J Renew Sustain Energy 2015;7(6):061701.
[33] Babarit A, Hals J, Muliawan MJ, Kurniawan A, Moan T, Krokstad J. Numerical benchmarking study of a selection of wave energy converters. Renew Energy 2012;41:44–63.
[34] Veigas M, López M, Romillo P, Carballo R, Castro A, Iglesias G. A proposed wave farm on the Galician coast. Energy Convers Manag 2015;99:102–11.
[35] Bozzi S, Archetti R, Passoni G. Wave electricity production in Italian offshore: a preliminary investigation. Renew Energy 2014;62:407–16.
[36] Mota P, Pinto JP. Wave energy potential along the western Portuguese coast. Renew Energy 2014;71:8–17.
[37] Sierra JP, Mösso C, González-Marco D. Wave energy resource assessment in Menorca (Spain). Renew Energy 2014;71:51–60.
[38] Aoun NS, Harajli HA, Queffeulou P. Preliminary appraisal of wave power prospects in Lebanon. Renew Energy 2013;53:165–73.
[39] Silva D, Rusu E, Soares CG. Evaluation of various technologies for wave energy conversion in the Portuguese nearshore. Energies 2013;6(3):1344–64.
[40] Vaquero AM, Ruiz FC, Rusu E. Evaluation of the wave power potential in the northwestern side of the Iberian nearshore. In: Guedes Soares C, López Peña F, editors. Developments in maritime transportation and exploitation of sea resources. vol. 1. London, UK: Taylor & Francis Group; 2013. p. 1011–9.
[41] Rusu L, Onea F. The performance of some state-of-the-art wave energy converters in locations with the worldwide highest wave power. Renew Sustain Energy Rev 2017;75:1348–62.
[42] Vannucchi V, Cappietti L. Wave energy assessment and performance estimation of state of the art wave energy converters in Italian hotspots. Sustainability 2016;8(12):1300.
[43] Leung S-F, Fu H-C, Zhang M, Hassan AH, Jiang T, Salama KN, et al. Blue energy fuels: converting ocean wave energy to carbon-based liquid fuels via CO2 reduction. Energy & Environmental Science; 2020.
[44] EMEC. Wave developers. 2017. http://www.emec.org.uk/marine-energy/wave-developers/. [Accessed 21 February 2018].
[45] OpenEI. Marine and hydrokinetic technology database. 2018. https://openei.org/wiki/Marine_and_Hydrokinetic_Technology_Database. [Accessed 21 February 2018].
[46] OWEP. Wave energy developers & projects. 2018. http://openwaveenergy.org/open-wave-energy-project-resource-and-industry/wave-energy-developers-a-projects.html. [Accessed 21 February 2018].
[47] Chozas J. International levelised cost of energy for ocean energy technologies. Ocean Energy Systems; 2015.
[48] Ocean Energy Systems. Annual report 2018 2018. 2018.
[49] Têtu A. Power take-off systems for WECs. In: Pecher A, Kofoed JP, editors. Handbook of ocean wave energy. London: Springer; 2017. p. 203–20.
[50] SI Ocean. Ocean energy: state of the art. 2012.
[51] Crosier S, Booth B, Dalton K, Mitchell A, Clark K. ARGIS 9 getting started with ArcGIS. United States: ESRI; 2004.
[52] Brundtland G, Khalid M, Agnelli S, Al-Athel S, Chidzero B, Fadika L, et al. Our common future. 1987.
[53] Strange T, Bayley A. Sustainable development: linking economy, society, environment. Paris: OECD Publishing; 2008.
[54] Cisneros-Montemayor AM, Pauly D, Weatherdon LV, Ota Y. A global estimate of seafood consumption by coastal indigenous peoples. PloS One 2016;11(12).
[55] Ingram D, Smith G, Bittencourt-Ferreira C, Smith H. Protocols for the equitable assessment of marine energy converters. first ed. UK: The Institute for Energy Systems; 2011.
[56] Lynch K, Murphy J, Serri L, Airoldi D. Site selection methodology for combined wind and ocean energy technologies in Europe.. In: Proceedings of the 4th International conference on ocean energy; 2012. Oct 17-19; Dublin, Ireland; 2012.
[57] Bahaj AS. Generating electricity from the oceans. Renew Sustain Energy Rev 2011;15(7):3399–416.
[58] International Electrotechnical Commission. Marine energy-wave, tidal and other water current converters-Part 101: wave energy resource assessment and characterization; IEC TS 62600–101. London, UK: International Electrotechnical Commission; 2015.
[59] Pecher A, Kofoed JP. Handbook of ocean wave energy. Springer London; 2017.
[60] Babarit A. A database of capture width ratio of wave energy converters. Renew Energy 2015;80:610–28.
[61] Dallman A, Jenne DS, Neary V, Driscoll F, Thresher R, Gunawan B. Evaluation of performance metrics for the wave energy prize converters tested at 1/20th scale. Renew Sustain Energy Rev 2018;98:79–91.
[62] Rusu E, Onea F. A review of the technologies for wave energy extraction. Clean Energy 2018;2(1):10–9.
[63] Water Power Technologies Office. Existing ocean energy performance metrics. Renewable Energy 2018.
[64] Walrond C. Natural environment - geography and geology. In: Te Ara - the encyclopedia of New Zealand [internet]; 2005. Available from: http://www.TeAra.govt.nz/en/natural-environment/page-1.
[65] Stevens C, Smith M, Gorman R. Ocean bounty: energy from waves and tides. Water & Atmos 2005;13(4):16–7.
[66] Gorman RM, Bryan KR, Laing AK. Wave hindcast for the New Zealand region: nearshore validation and coastal wave climate. N Z J Mar Freshw Res 2003;37(3):567–88.
[67] The Economist. Pocket world in figures 2019. London, UK: Profile Books; 2018.
[68] Statistics New Zealand. Are New Zealanders living closer to the coast?. 2006.
[69] Koca K, Kortenhaus A, Oumeraci H, Zanuttigh B, Angelelli E, Cantù M, et al. Recent advances in the development of wave energy converters. In: Proceedings

of the 10th European wave and tidal energy conference (EWTEC); 2013. Sep. 2–5; Aalborg, Denmark.
[70] De Freitas CR, Perry M. New environmentalism: managing New Zealand's environmental diversity. Springer Science & Business Media; 2012.
[71] Ministry of Fisheries, Department of Conservation. Marine protected areas: classification, protection standard and implementation guidelines. Wellington, NZ: Ministry of Fisheries, Department of Conservation; 2008.
[72] Department of Conservation. New Zealand coastal policy statement 2010. Wellington, NZ: Department of Conservation; 2010.
[73] National Topographic Office. NZ Coastlines and Islands Polygons (topo 1:50k), LINZ Data Service, v38. 2018. https://data.linz.govt.nz/layer/51153-nz-coastlines-and-islands-polygons-topo-150k/.
[74] New Zealand Hydrographic Authority. 200 Mile Exclusive Economic Zone Outer Limits, LINZ Data Service, v5. 2015. https://data.linz.govt.nz/layer/50842-200-mile-exclusive-economic-zone-outer-limits/.
[75] Ministry for Primary Industries Geospatial Management. Taiapure, ArcGIS REST Services; 2017. https://maps.mpi.govt.nz/wss/service/ags-relay/arcgis1/guest/arcgis/rest/services/MARINE/MARINE_RestrictionsCustomary/MapServer/10.
[76] Ministry for Primary Industries Geospatial Management. Current marine farms. ArcGIS REST Services; 2017. https://maps.mpi.govt.nz/wss/service/ags-relay/arcgis1/guest/arcgis/rest/services/MARINE/MARINE_Aquaculture/MapServer/1.
[77] Ministry for Primary Industries Geospatial Management. Settlement areas, ArcGIS REST Services; 2017. https://maps.mpi.govt.nz/wss/service/ags-relay/arcgis1/guest/arcgis/rest/services/MARINE/MARINE_Aquaculture/MapServer/6.
[78] New Zealand Hydrographic Authority. Offshore Platform Points (Hydro, 1:90k - 1:350k), LINZ Data Service, v18. 2018. https://data.linz.govt.nz/layer/50480-offshore-platform-points-hydro-190k-1350k/.
[79] New Zealand Petroleum and Minerals. Petroleum wells. Permit Maps - Petroleum; 2019. http://data.nzpam.govt.nz/permitwebmaps?commodity=petroleum.
[80] New Zealand Petroleum and Minerals. Mineral active permits, Permit Maps - Minerals; 2018. http://data.nzpam.govt.nz/permitwebmaps?commodity=minerals.
[81] Ministry for the Environment (MfE). Benthic Protection Areas (2016 Report), MfE Data Service, v8. 2016. https://data.mfe.govt.nz/layer/53494-benthic-protection-areas-2016-report/.
[82] Ministry for the Environment (MfE). DoC Marine Mammal Sanctuaries (2016 Report), MfE Data Service, v6. 2016. https://data.mfe.govt.nz/layer/53495-doc-marine-mammal-sanctuaries-2016-report/history/.
[83] Kaikōura (Te Tai o Marokura) Marine management act 2014 (NZ).
[84] Ministry for the Environment (MfE). Type 2 Marine Protected Areas, MfE Data Service, v7. 2016. https://data.mfe.govt.nz/layer/52762-type2-marine-protected-areas/.
[85] Ministry for the Environment (MfE). Marine Reserves, MfE Data Service, v9. 2016. https://data.mfe.govt.nz/layer/52760-marine-reserves/.
[86] Ministry for the Environment (MfE). Seamount Closures (2016 Report), MfE Data Service, v6. 2016. https://data.mfe.govt.nz/layer/53496-seamount-closures-2016-report/.
[87] National Topographic Office. NZ Chatham Island Wreck Points (Topo, 1:50k), LINZ Data Service, v10. 2018. https://data.linz.govt.nz/layer/50118-nz-chatham-island-wreck-points-topo-150k/.
[88] National Topographic Office. NZ Wreck Points (Topo, 1:50k), LINZ Data Service, v40. 2018. https://data.linz.govt.nz/layer/50379-nz-wreck-points-topo-150k/.
[89] New Zealand Hydrographic Authority. Wreck Points (Hydro, 1:4k - 1:22k), LINZ Data Service, v20. 2019. https://data.linz.govt.nz/layer/50763-wreck-points-hydro-14k-122k/.
[90] New Zealand Hydrographic Authority. Wreck Points (Hydro, 1:22k - 1:90k), LINZ Data Service, v22. 2019. https://data.linz.govt.nz/layer/50633-wreck-points-hydro-122k-190k/.
[91] National Institue of Water and Air (NIWA). New Zealand regional bathymetry. NIWA; 2016. 2016, https://www.niwa.co.nz/our-science/oceans/bathymetry.
[92] New Zealand Hydrographic Authority. Dredged Area Polygon (Hydro, 1:90k - 1:350k), LINZ Data Service, v20. 2018. https://data.linz.govt.nz/layer/50450-dredged-area-polygon-hydro-190k-1350k/.
[93] New Zealand Hydrographic Authority. Dredged Area Polygon (Hydro, 1:22k - 1:90k), LINZ Data Service, v21. 2018. https://data.linz.govt.nz/layer/50557-dredged-area-polygon-hydro-122k-190k/.
[94] New Zealand Hydrographic Authority. Dumping Ground Polygons (Hydro, 1:4k - 1:22k), LINZ Data Service, v18. 2018. https://data.linz.govt.nz/layer/50449-dumping-ground-polygon-hydro-190k-1350k/.
[95] New Zealand Hydrographic Authority. Dumping Ground Polygon (Hydro, 1:90k - 1:350k), LINZ Data Service, v18. 2018. https://data.linz.govt.nz/layer/50449-dumping-ground-polygon-hydro-190k-1350k/.
[96] New Zealand Hydrographic Authority. Dumping Ground Polygon (Hydro, 1:22k - 1:90k), LINZ Data Service, v18. 2018. https://data.linz.govt.nz/layer/50555-dumping-ground-polygon-hydro-122k-190k/.
[97] Land Information New Zealand (LINZ). 5 firing practice, exercise and submarine safe bottoming areas. In: New Zealand Nautical Almanac 2018/19; 2018. p. 222–8. Wellington.
[98] Pilois J. NZ commercial ports. ArcGIS REST Services; 2018. https://services.arcgis.com/hLRlshaEMEYQG5A8/arcgis/rest/services/NZ_Commercial_Ports_(View_Layer)/FeatureServer.
[99] New Zealand Hydrographic Authority. Cable, submarine polyline (hydro, 1:350k - 1:1,500k), v13. LINZ Data Service; 2017. https://data.linz.govt.nz/layer/51091-cable-submarine-polyline-hydro-1350k-11500k/.
[100] Submarine cables and pipelines protection (Tui Area development) order 2007 (NZ).
[101] Submarine cables and pipelines protection (Kupe gas project) order 2008 (NZ).
[102] Submarine cables and pipelines protection (Maari development) order 2008 (NZ).
[103] Submarine cables and pipelines protection order 2009 (NZ).
[104] Land Information New Zealand. New Zealand Continental Shelf Lambert Conformal 2000 (NZCS2000), https://www.linz.govt.nz/data/geodetic-system/datums-projections-heights/projections/new-zealand-continental-shelf-lambert; [accessed 30 January 2020].
[105] Submarine cables and pipelines protection act 1996 (NZ).
[106] Land Information New Zealand (LINZ). 13 submarine cables and pipelines. In: New Zealand Nautical Almanac 2018/19; 2018. p. 255–8. Wellington.
[107] McSaveney E. Landscapes – overview – offshore islands. In: Te Ara - the encyclopedia of New Zealand [internet]; 2007. Available from: http://www.TeAra.govt.nz/en/landscapes-overview/page-10.
[108] Environmental Systems Reseach Institute (ESRI). Data classification methods, https://pro.arcgis.com/en/pro-app/help/mapping/layer-properties/data-classification-methods.htm; [accessed 30 January 2020].
[109] Smith HCM, Haverson D, Smith GH. A wave energy resource assessment case study: review, analysis and lessons learnt. Renew Energy 2013;60:510–21.
[110] Albuquerque J, Antolínez JAA, Gorman R, Méndez FJ, Coco G. A high resolution 20-year partitioned hindcast for the New Zealand area. Coast and Ocean Collective; 2019. https://uoa-eresearch.github.io/waves/#NZ-HIST-000-HSIGN-Hsig@1993-01-01%2000:00.