Waves and Coasts in the Pacific

Cost analysis of wave energy in the Pacific

Cyprien Bosserelle, Sandeep Reddy, Jens Krüger

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Executive summary

Ocean waves are often cited as an appealing source of renewable energy in the Pacific but the cost-effectiveness of wave energy converters (WECs) is deemed unproven and the technology is rarely considered as a reliable renewable energy resource in Pacific Island countries. However, single/stand-alone WECs could be a competitive option against fossil fuel generators because of the high cost of imported fuel. This study analyses the wave energy resource in the Pacific and calculates the potential cost and power generation of a benchmark WEC in Pacific Island countries.

The type of WEC chosen depends largely on the environmental and geophysical characteristics of the wave energy site where it is to be deployed. The aim of this study was not to report on the best device for each site but rather to give advice about the islands that could benefit most from wave energy. Therefore, the cost analysis is based on a single WEC – the Pelamis device. The Pelamis device cost presented here serves as a benchmark for comparison with other WECs in different locations. Due to uncertainties and variations in potential costs across the region, the study evaluated the range of costs applicable to the whole region. The costs of the WEC, transport, installation, operation and management, refit and decommissioning are included. Site-specific potential power generation was calculated, based on a realistic power output dependent on the wave conditions.

The study found that Pacific islands south of latitude 20°S receive a substantial amount of wave energy with a mean available wave resource above 20 kilowatts per metre (kW/m) and that many other islands also have potential for wave energy extraction with a mean wave resource above 7 kW/m.

This study found that a Pelamis device in the Pacific could cost between USD 6,318,000 and USD 14,104,000 to install and can operate for 25 years. The energy produced by such a device could be up to 1200 megawatt hours (MWh) per year for sites exposed to large swells. Using these values, the range of the total lifetime cost of power generation was calculated to be between USD 200/MWh for exposed sites and USD 1800/MWh for more sheltered sites. The corresponding operation and maintenance generation cost are between USD 40/MWh and USD 900/MWh.

These costs are on a par with the cost of generation of other renewable energies, such as wind and solar, and, for exposed sites, on a par with the cost of diesel generation. These findings suggest that wave energy is a genuine contender for the development of renewable energy in the Pacific and should no longer be ignored when planning such development; a concerted effort from all stakeholders should be made in order to benefit from this technology.

Further deployment in wave technology will reduce the cost of single wave energy devices, and most small Pacific Islands would not need to deploy large-scale wave farms of ten or more devices, as power production would greatly exceed the demand. With expected rises in fuel prices in the next decades, it would be wise to investigate further the potential of wave energy technology. The deployment of WECs in the Pacific could provide an opportunity for the technology to prove itself in the region and attract the attention of investors, policy makers and decision makers to invest in wave energy development in the Pacific .

Other recommendations are listed below.

1. French Polynesia, the Austral Islands in particular, should investigate potential wave energy sites. On these islands, wave energy generation could become a major renewable energy resource with a relatively low cost that could even compete with fossil fuel.
2. Tonga, Cook Islands and New Caledonia should also investigate wave energy sites and suitable wave energy devices. Wave energy has a great potential for helping these countries reach their renewable energy targets and supply energy more cheaply than other renewable energy resources.
3. Countries with a mean wave energy flux above 7 kW/m should also investigate wave energy hotspots and wave energy device options, especially in exposed locations. There, wave energy may be able to supply a significant amount of renewable energy and help these countries meet their renewable energy targets. However, wave energy in these locations may be more expensive than other types of renewable energy.
4. Countries with a mean wave energy flux of less than 7 kW/m, such as Papua New Guinea and Solomon islands, are unlikely to benefit from wave energy unless a major technological breakthrough makes wave energy devices much more efficient. These countries should therefore not consider wave energy as a significant renewable energy resource.

The WACOP project has provided calculations similar to those presented in this study for more than 200 Pacific locations in wave climate reports that should be consulted as an initial assessment of the wave energy resource available.[1] The WACOP project also provides a detailed wave climate analysis for Samoa, Rarotonga in Cook Islands, Tongatapu and ‘Eua in Tonga, southern Viti Levu in Fiji, Efate in Vanuatu, and Funafuti in Tuvalu. These analyses include wave energy and cost calculations based on the calculations presented in this report.

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[1] http://gsd.spc.int/wacop/WaveclimateReports.html

1 Introduction

Ocean waves are often cited as an appealing source of renewable energy in the Pacific (Barstow and Falnes 1996) but the cost-effectiveness of wave energy converters (WECs) is often deemed unproven and the technology is rarely considered as a reliable renewable energy resource in these island countries. Indeed, the technology to harvest energy out of oceanic waves is still immature, with no WECs reaching the commercial stage and no wave energy device ever deployed in the tropical Pacific (Hourcourigaray et al. 2014). However, there are full-scale prototypes of wave energy converters deployed in every ocean and some of these grid-connected devices are proving reliable and efficient. These prototypes have been calculated to be commercially viable for large-scale commercial 'wave farms' where hundreds of devices are deployed. Such wave farms are being planned on the coastlines of Europe, America and Australia (CSIRO 2012; Pelamis 2014; SI OCEAN 2014).

For small islands, however, these large-scale wave farms may not be a realistic option due to the high capital cost of their deployment and because they would produce far more electricity than the island requires. On the other hand, single WECs could compete against fossil fuel generators typically used on the islands because of the high price of imported fuel. As yet, however, not enough is known about the regional wave energy resource and the potential cost of WECs for Pacific Island countries and territories (PICTs) to make an informed decision on whether to dismiss or embrace the technology today or wait until the converters become more efficient and/or cheaper. To help countries make this decision, this study has conducted a preliminary assessment of the wave energy resource in the Pacific and calculates the potential cost and power generation of a WEC in the region.

The commercial viability and feasibility of renewable energy converters can be obtained by comparing the overall cost of a project with the overall benefits. Section 2.5 of this report describes the details of a wave energy project and the steps necessary for a detailed feasibility study. This report focuses only on the regional scale and provides only a preliminary assessment of the wave energy. The method used in the analysis is described in Section 3.

For WECs, the overall cost includes all the physical cost of the converter throughout its lifetime, as well as the cost of operation, maintenance and decommission. The cost also has to include costs associated with potential negative effects of the device on the environment or on other industries. These costs are not included in this study as they can be difficult to evaluate and are often dependent on the selected sites. Section 4.1 of this report provides a preliminary, regional cost range that covers a lot of scenarios affecting the cost of a device in the region.

The overall benefit of the device is the energy it produces, which is dependent on the wave climate and the efficiency of the device. For some devices, a power output can be calculated, depending on the wave conditions. Section 4.2 uses a regional wave model to assess the wave climate at several sites in the region and calculates the power output that would be produced by a single WEC (Pelamis) at these sites.

The cost of energy produced is presented in section 4.3 and then discussed in Section 5. Recommendations are made in section 6.

2 Background

2.1 Wave energy converters

Wave energy converters (WECs) can be categorised by type and location, though designs may vary across locations with special consideration given to site-specific conditions to optimise power generation (Drew et al. 2009; Lopez et al. 2013). Iglesias et al. (2010) classified WECs according to their principle of operations. The three classes were: (i) overtopping devices; (ii) wave-activated bodies; and (iii) oscillating water columns.

(i) **Overtopping devices** – their principle of operation is based on waves overtopping a barrier and water being collected at a reservoir above mean sea level. The water flowing back to the ocean is then directed towards turbines, which produce electricity.

(ii) **Wave-activated bodies** – these devices capture wave energy through bodies that are made to oscillate at the passage of each wave.

(iii) **Oscillating water columns** – these are devices that convey the wave energy to a second fluid (air), which drives an air-turbine.

A similar definition was provided by Lopez et al. (2013) and Kempener and Neumann (2014) as part of the International Renewable Energy Agency's (IRENA) wave energy technology brief. Drew et al. (2009) in their review paper (See also Lopez et al. 2013), classed WECs into three predominant types:

(i) **Attenuators** – lie parallel to the predominant wave direction and extract energy as they 'ride' the waves. They are typically larger than a wave length and produce electricity by converting the movement of the waves.

(ii) **Point absorbers** –are small, relative to incident wavelength. They can be floating structures that move up and down on the surface, or they can be submerged, relying on the pressure differential. Wave direction is not important for these devices because of their small size. Only their vertical movement is used to generate electricity.

(iii) **Terminators** – have their principal axis parallel to the wave front and physically intercept waves, forcing them to dissipate. The devices often use the difference in water levels generated by the waves to run turbines or they use the air compressed by the waves for that purpose.

Classification of WECs can also be done based on the site they operate in – onshore, nearshore or offshore. Onshore devices are built and fixed on land. The location may be the length of the coastline or integrated into structures such as breakwaters. Adjacent depths are typically less than 15 m. Nearshore devices are predominantly fixed on the seabed. They capture wave energy nearshore and convert it to electricity in an onshore facility. Depths are typically less than 25 m. Offshore devices are moored to the seabed and transfer the generated electricity using sub-sea cables laid on the seabed. Table 2.1 lists some of the device classes, as well as their rated capacity and status in the marine energy industry.

Table 2.1 Classification of some wave energy converters

Device	**AquabuOY**	**Pelamis**	**Oceanlinx OWC**	**Oyster 800**	**Wave Dragon**	**CETO 5**
Parent Company	Aqua Energy Development UK Ltd	Pelamis Wave Power Ltd	Oceanlinx	Aquamarine Power Limited	Wave Dragon	Carnegie Wave Energy Ltd
Rating (kW)	250	750	500-2000	800	4000	240
Site	Offshore	Offshore	Offshore	Nearshore	Nearshore	Nearshore
Status	demonstration	commercial	commercial demonstrator	prototype	demonstration /prototype	Design (CETO 3 commercial)
Type	wave activated bodies/point absorber	attenuator	OWC	terminator	overtopping	point absorber

Various WECs have been deployed around the world (Figure 2.1) mainly for testing purposes as prototypes.

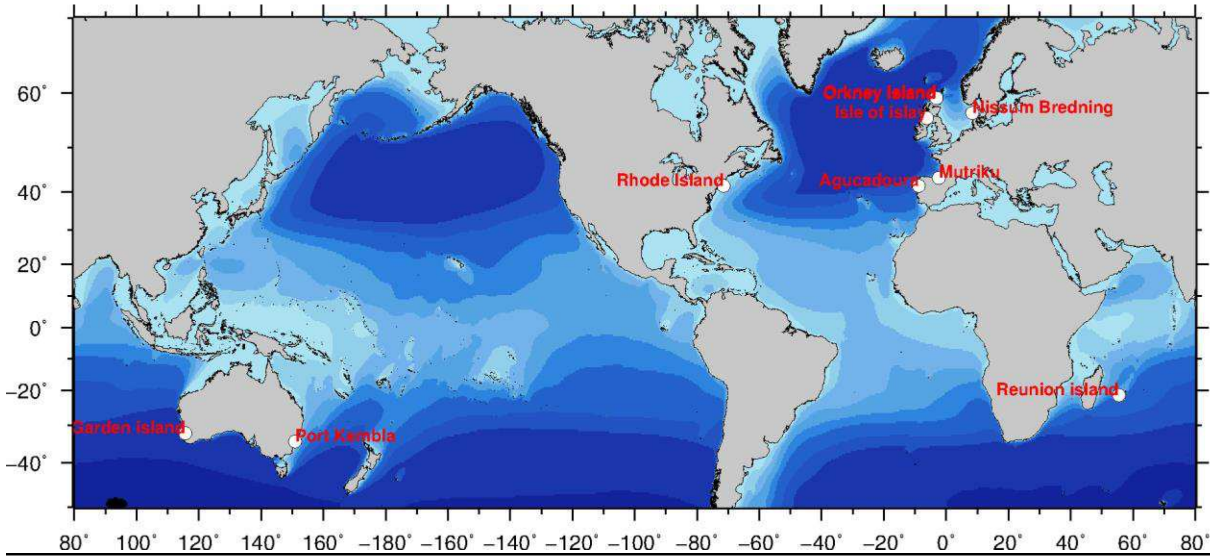

Figure 2.1 Mean available wave energy and the location of wave energy converters

Devices such as the Pelamis, Wave Dragon, Oyster, CETO, shoreline and nearshore oscillating water columns have made it past the design phase and have achieved grid-connected electricity production. Table 2.2 summarises some of these deployments.

Table 2.2 Global WEC deployments

Country	Portugal	Scotland	Denmark	USA
Site	Aguçadoura Wave Farm	Isle of Islay	Nissum Bredning	Rhode Island
Wave climate	32 kW/m	15–25 kW/m	24 kW/m	Average 20 kW/m
Year	2008	2000	2003-2005	2007
Device installed	3 Pelamis units	Limpet OWC	1:4.5 scale Wave Dragon	Energetech OWC
Device output	2.25MW	500kW	20kW	500 kW
Device characteristics	capacity to supply 1500 households	Onshore	Deployed, grid-connected & tested. Terminated	Enough to power 300 homes
Status	Deployed & removed (09/08–11/08)	Operational	tested	unknown

Table 2.2 (continued) Global WEC deployments

Country	Australia	European Marine Energy Centre (Scotland)	European Marine Energy Centre (Scotland)	Spain	Australia	Reunion Island
Site	Port Kembla	Orkney Islands, U.K.	Orkney Islands, U.K.	Mutriku	Garden Island, Perth	Off Saint Pierre city
Wave climate	Operational	Test phase	test phase	commercial	in construction	test phase
Year	Average 7.6 kW/m	40 kW/m	40 kW/m	26 kW/m	35 kW/m	17 kW/m at 40 m depth
Device installed	2006	2009	2010	06/2011	2014	2011
Device output	Energetech OWC	Oyster 1	Pelamis 2	Voith Hydro OWC	CETO 5	CETO 4
Device characteristics	500kW	31 kW	750 MW	300 kW	3 x 240 kW	180 kW
Status	Enough to power 500 homes and Capacity to produce 200 litres of desalinated water	Demo & grid-connected	Demo & grid-connected	electricity for 250 homes/ 25 years operational life	proposed grid-connected & desalination/ Expected to power 3500 homes	Development phase

2.1.1 The Pelamis wave energy converter

From the many wave energy devices developed globally, the Pelamis WEC is one of only two to have reached commercial readiness (Dalton et al. 2010a). Although Pelamis Wave Power Ltd, the firm behind the device, went into administration at the time of writing this report, the milestones reached and the research behind the Pelamis device are unprecedented and unmatched by any other device. Because of the large amount of literature on the Pelamis, it is still a benchmark and, although it is unlikely that more Pelamis devices will ever be built (at least under the same name), the device's physical characteristics and cost evaluation can be used to probe the economic feasibility of wave energy. It is also likely that the technological progress made with the Pelamis will not be lost and will be integrated into other technologies under another name.

The 750 kW Pelamis prototype was the first to be deployed in the United Kingdom, followed by three Pelamis prototypes deployed as part of a 2.25 MW wave farm in 2008 in Portugal (Kempener and Neumann 2014). The device was a product of the Pelamis Wave Power Limited (formerly Ocean Power Delivery). It uses the motion of the waves to generate electricity in an offshore environment, operating in water depths greater than 50 m and installed between two and ten kilometres from the shoreline. Rated at 750 kW, one machine should be capable of providing sufficient power to meet the annual electricity demand of approximately 500 homes on average (Pelamis 2014). Pelamis is made up of four tube-like sections linked by joints that allow two dimensional flexing (Figure 2.2). It is semi submerged and faces into the waves (Previsic 2004b). As waves pass down the length of the machine, the sections bend in the water and the movement is converted into electrical energy via hydraulic power take-off systems housed inside each joint of the machine tubes. The power is transmitted to shore using sub-sea cables and equipment.

The device needs to be adequately moored to withstand the conditions of an offshore environment. The manufacturer's mooring designs are based on site specifications. Factors such as survival conditions, maximum current velocities, water depth and sea-floor soil densities are crucial elements for consideration in the detailed design phase (Previsic 2004a). The mooring consists of a three-point mooring configuration. It allows the device to turn into the wave direction within its mooring constraints (Previsic 2004b). Table 2.3 lists the technical details of the Pelamis device.

Figure 2.2 Pelamis device deployed in Scotland

After various numerical modelling and scaled tests, a full-scale Pelamis prototype was tested at the European Marine Energy Centre in Scotland between 2004 and 2007. The manufacturers claimed that the prototype was the world's first commercial scale WEC to generate electricity to a national grid from offshore waves. Following successful tests, three machines with an installed capacity of 2.25 MW were deployed off the northwest coast of Portugal at Agucadoura (The Guardian 2004). It was commissioned in 2008, supplying power to the grid. Pelamis Wave Power Limited has since embarked on a series of design improvements and tests on their second generation Pelamis P2 machines (Yemm et al. 2012). The Pelamis P2 devices are 180 m long, four metres wide and weigh approximately 1350 tonnes. Bigger than the first design, the Pelamis P2 can capture more energy, which therefore reduces the cost of energy generation per unit (Pelamis 2014).

Table 2.3 Pelamis device specifications

Structure	
Overall length	150 m
Diameter	4.6 m
Displacement	700 T
Power take off	three independent power conversion modules
Total steel weight	380 T
Power	
Rated power	750 kW
Generator type	Asynchronous
System voltage	three-phase, 415/690 VAC 50/60 Hz
Transformer	950 kVA step-up to required voltage
Site mooring	
Anchor type	Stevpris type embedment anchors[13]
Total anchor weight	14.5 T [13]
Total mooring chain weight	100 T [13]
Additional mooring	20 T steel-wire rear yaw line and clump weight [13]
Water depth	>50 m
Current speed	<1 knot
Mooring type	Compliant slack moored (site-specific requirements). Combination of steel wire, chain, dead weights and embedment anchors. Catenary moored [13]
Subsea cable	Water-tight insulation and addition armour, insulated submersible cross-linked polyethylene cable
Installation	
Vessels	Anchor handler vessels, barges and heavy uplift cranes

The Pelamis Wave Power firm was involved in a number of ongoing and future projects to develop the technology into a fully commercial venture until the firm went into administration in December 2014. The Aguçadoura project (Portugal) is earmarked for a second phase installation of 26 Pelamis P2 machines with an installed capacity of 20 MW. The company was developing a 10 MW wave farm project off the west coast of Lewis in the Outer Hebrides (Scotland). A joint venture had been launched between Pelamis Wave Power and Vattenfall to develop a 10 MW Pelamis farm off the south-west coast of Shetland (Scotland). As part of the project, two wave buoys were deployed for wave measurements and public consultations were carried out to address issues. Furthermore, an environmental impact assessment is currently being carried out for the proposed site, and an initial coarse-resolution geophysical survey has been completed.

Testing of two Pelamis P2 machines is ongoing at the European Marine Energy Centre's Billia Croo test site, which was built for E.ON and Scottish Power Renewables (Kempener and Neumann 2014; IRENA 2012).

2.2 Cost of wave energy – previous studies

Most past case studies used the Pelamis device, focusing on the technical feasibility and economic viability of wave energy. A document sponsored by the Electric Power Research Institute Inc. examined a conceptual design, performance and cost study of a demonstration unit and a commercial-scale Pelamis wave plant in California (Previsic 2004a). The aim of the project was to examine the power generation cost of a single device at a water depth of 25–35 m off San Francisco and a commercial plant at 50 m water depth. The wave energy resource data for the proposed site were based on a 21-year wave record from an offshore buoy. The proposed site of the commercial plant was to be located closer to the shore, and an adjustment of 20% power loss to the shallow water site on the device output was assumed. The average wave power at the proposed site was 20 kW/m. The annual energy produced by the conceptual single plant was estimated at 668 MWh and the commercial farm design was estimated at 1407 MWh/year for each device. A total of 213 Pelamis devices would be required to achieve the commercial plant target of 300,000 MWh/year. The cost would be:

Total plant investment = USD 279 million

Annual operation and maintenance = USD 13.1 million

10-year refit = USD 28.3 million

Cost of energy = 13.4 cents/kWh (nominal), 11.4 cents/kWh (real)

The nominal levelised cost of energy (LCOE) is the cost of energy that takes into account the effects of inflation associated with operation and maintenance (O&M) and fuel costs, whilst the real LCOE takes into account only the inflation associated with the initial WEC cost. Both are acceptable for use in cost comparison (Black and Veatch 2010).

Dunnett and Wallace (2009), examined the economics of a proposed 25,000 MWh (27 Pelamis devices) wave power plant in Canada. The cost of electricity ranged from USD 0.236 to USD 0.381 per kWh in the five sites assessed, having electricity production ranging from 942.8 to 1724 MWh/year per device.

A report for the Marine Institute/Sustainable Energy Ireland (ESBI 2005) uses the Pelamis device in evaluating the technical energy resource. The average annual technical resource is expected to be 12.5 TWh, implying a conversion efficiency of 32.09% for a 40 GWh/km contour level. The cost of energy (COE) reported was USD 0.13/kWh to USD 0.15/kWh.[2]

Dalton et al. (2010a) investigated the performance and economic viability of the Pelamis over a twenty-year period in various global locations. In Ireland, the highest annual wave energy output was calculated, with the COE being USD 0.25/kWh for a single Pelamis device.

Previsic (2010) carried out an evaluation of the Pelamis device in Oahu, Hawaii and Humboldt County, California as part of a conceptual feasibility study. Wave data were acquired from buoy measurements at both deep-water locations. The average wave height recorded at the Hawaii site was 1.75 m, the dominant period was 8.5 s, the average wave power was 14 kW/m, and the annual output from Pelamis was calculated at 1290 MWh/year. The California site with wave power of 28.5 kW/m had an annual output of 1911 MWh/year for the same device.

Not all wave energy cost benefit analysis focussed on the Pelamis device. In the Pacific region, a study was undertaken on a shore-based oscillating water column device for the island of Tongatapu in Tonga (Argo Environmental 2011). The feasibility study looked at setting up a 3 MW wave power station for a 20–30 m shoreline collector width. The wave power characteristics were obtained from a 12-year hindcast dataset. The average wave height was found to be 1.62 m, peak period in the range of 10–14 s dominated by swells from the south-west. The study reported a mean wave power of 15 kW/m with 9 kW/m in summer and 17 kW/m in winter. The expected annual energy output of 11.9 GWh from six 500 kW turbines could account for 30% of Tongatapu's grid requirement. The capital cost of the project is estimated to be USD 17.2 million and, for the project to be operationally feasible, an indicative electricity sale price of USD 0.21 has to be achieved.

2.3 Global wave resource

Wave energy is held to be a reliable and consistent resource because waves travel long distances and so can accumulate energy from the wind that pushes them. They lose little of this energy while crossing the ocean (Arinaga and Cheung 2012; Cornett 2008; Joubert 2008). Furthermore, as waves interact with bathymetry, local winds and currents and become very variable nearshore, finding the best location nearshore for energy extraction can be difficult. In addition, because of seasonal and inter-annual variation in the climate, *in situ* wave measurements need to be obtained for several years before obtaining reliable statistics on wave height, period (time interval between consecutive waves) and direction. Fortunately, wave parameters can be obtained using numerical models but these require a detailed local bathymetry and *in situ* wave measurements to calibrate and verify the model. Often, energy resource is assessed by complementing *in situ* measurements, satellite derived measurements and numerical modelling. Hence, many analyses of global and regional wave energy resources use hindcast wind, bathymetry and numerical models. These models are often verified

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[2] converted from € to 2014 USD

with *in situ* wave measurements and satellite measurements (e.g. Dodet et al. 2010; Bosserelle et al. 2012; Arinaga and Cheung 2012).

Global analysis of the available wave power (Arinaga and Cheung 2012; Cornett 2008; Joubert 2008) shows that the high latitudes (40–60^{o}) receive the most wave energy because they are in the path of extra-tropical storms. The Southern Ocean is constantly rough and the North Atlantic and North Pacific Oceans alternate between calm and rough conditions with the seasons (Sterl and Caires 2005). Global wave climate analysis is often not suitable for wave energy resource evaluation because the hindcast models are too coarse to take into account the way waves change when they cross continental shelves and propagate nearshore. The coarse resolution of a global model also often misses small bathymetry features that greatly affect wave refraction and dissipation. For the same reason, coarse global wave analysis generally overestimates the wave energy resource in the tropical Pacific. This is because numerical models used to assess the global wave energy resource do not have a high enough resolution to take into account the small islands in the Pacific and therefore neglect the wave shadow in the lee of these islands. Hence the power estimates are either overestimated or underestimated, and often reduced to a single value for the whole region, ignoring the potential wave energy hotspots.

2.4 Wave energy project development strategy

As pointed out earlier; there has not been any commercial scale deployment of wave energy converters in the Tropical Pacific region so there are no guidelines or best practices for marine power project development in the Pacific. However, the European Marine Energy Centre has published a document entitled *Guidelines for project development in the marine energy industry* (Croll and Andina-Pendas 2009). Though based on current policies and legislation in the United Kingdom, some of the guidelines may be tailored to suit the Pacific region. We recommend the guidelines presented below when investigating the feasibility of WECs in a particular location.

2.5 Generic project development guidelines

These generic guidelines include pre-installation and decommissioning issues as part of project development strategy.

Project development strategy

- Outline project objectives, potential benefits and risks. Identify any current or planned legislation/policies in place regarding the marine renewable energy sector and support mechanisms.

Site screening (pre-feasibility assessment)

- Carry out desktop screening of the area, based on available data, and identify one or more potential sites within a wider area.
- If a device for a particular site is chosen beforehand, identify technical, physical and environmental constraints influencing site identification in relation to the device's performance characteristics.
- Introduce preliminary discussions with key consultants and stakeholders, initiating contacts.

- Include preliminary discussions with a utility company for suitability of grid connection and capacity to accommodate the WEC.
- Plan for initial site survey.

Project feasibility

- Identify the device that best suits the project objectives.
- Develop a conceptual design of the device: detailed drawings, layouts, site survey drawings, moorings and foundations layout, cable routes, onshore and offshore electrical design, onshore infrastructure.
- Prepare an initial financial assessment, indicating energy yield prediction and all costs related to the device from procurement to decommissioning. Identify funding options for the project. Include financial risks.
- For information dissemination, prepare a comprehensive list of stakeholders and people to be consulted: government departments and ministries, organisations holding site ownership over seabed and adjacent land, utility companies, and the local community.
- Confirm grid connection capacity and availability with a utility company and consult on power purchase agreement options.
- Explore tax issues and insurance options for the duration of the entire project.

Project design and development

- Carry out an environmental impact assessment (Inclusive of installation and decommissioning).
- Apply for consent of project with relevant authorities.
- Initiate project design: this is the basis for preparation of a suitable procurement and contract strategy. It should take into account but not include the criteria for conceptual design and relevant legislative requirements, international codes and standards.
- Procurement strategy: should meet project objectives and risks. Consider elements to be procured, current market-status, rules and procedures for procurement and a pricing strategy.

Project fabrication and installation

- Prepare a detailed design: electrical equipment and cable, communication and control equipment, onshore facilities and auxiliary equipment, safety features.
- Prepare a detailed review: WEC layout and mooring design, converter electrical design and protection, independent verification.
- Review and refine cost estimates.
- Project fabrication: manufacture project infrastructure based on standards and specifications, timescales and costs.
- Project installation: appoint project representatives and supervisors to oversee construction, method of installation, connection with grid, etc.
- Ensure that the equipment has been installed without damage and is functioning correctly according to specifications before it is accepted or ownership is taken by the operating organisation. Include full documentation required to operate and maintain the system.

Operation and maintenance

- Set up acceptable performance parameters to monitor operation of the project.
- Appoint a liaison officer for operation and maintenance activities.
- Prepare an operation and management plan, to include: management structure, emergency procedures, subcontracting of support services, corrective measures, logistics and associated contingencies, review, monitoring and audit of technical performance, planned and unplanned maintenance implementation, grid disconnection during maintenance, and availability of spare components. Prepare an operation and maintenance budget for the life of the project.

Decommissioning

- Prepare a decommissioning plan for effective and safe removal of project infrastructure, associated reinstatement work and disposal of removed equipment.
- Set aside a decommissioning fund for the above.
- Prepare a suitable procurement strategy for the elements of the decommissioning work to be outsourced.

2.6 Site selection

One critical issue in the project development phase involves site identification and screening. A successful site must be located in an area with the most advantages and the fewest disadvantages. Advantages include a good and consistent wave energy resource and proximity to technical facilities, whilst negative effects on the environment and lack of technical resources may be some of the disadvantages. Most importantly, an accurate assessment of the wave resource would enable developers to choose the most appropriate device for power calculation. Numerical models may provide accurate and up-to-date estimates of wave climate, but it still becomes necessary to carry out physical monitoring (e.g. wave measurement) at the site of interest. The major contributing factors in site selection when planning a wave energy project are shown in Figure 2.3 and discussed in more detail below.

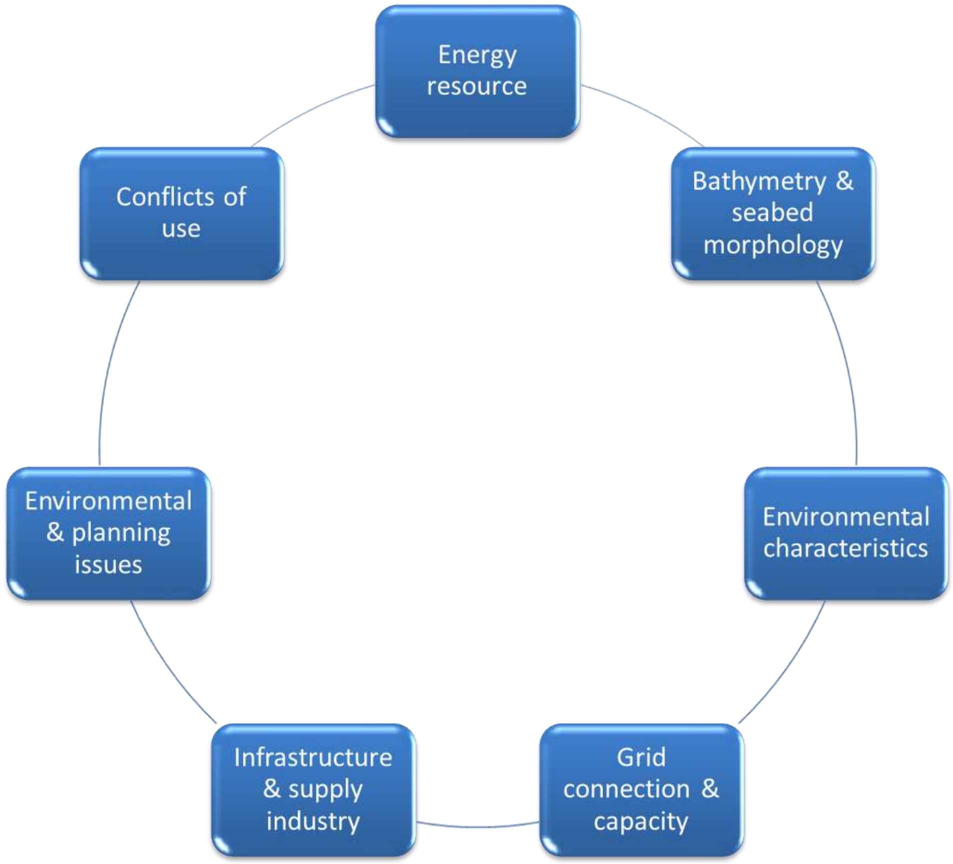

Figure 2.3 Diagram showing the major factors affecting wave energy conversion site selection (Waveplam 2009a)

Energy resource: It is essential to identify the wave climate on site in order to assess the available wave power resource. The wave climate can be inferred from statistical wave data. Although these data may be sourced from satellites (remotely sensed) or numerical models, *in situ* wave measurements become necessary in the early stages of the project, often as soon as the preferred site has been selected. Each source is not usually sufficient on its own, so a combination of sources can be used. For example, a numerical model has to be validated using *in situ* and remotely sensed data. Statistical analysis includes, but is not limited to, the average monthly wave height, the mean wave power, and the percentage of time the wave height exceeds a certain threshold.

Bathymetry and seabed morphology: This has a significant influence on the methods used for installation, which subsequently affect the cost of the project. The bathymetry will provide the depth information – the shallow and deep points (gradient) – which will dictate installation and mooring requirements. To study wave transformation, the characteristics of the seabed have to be well understood, including the proximity of isobaths and slopes; the presence of sandy flats, rocks and other seabed irregularities; and the capacity of the seabed for holding anchors. The seabed morphology is the first element that defines the environmental characteristics.

Environmental characteristics: In selecting a site for works and access and to ensure the viability of the engineering operations during installation, it is essential to know the geographical characteristics and the atmospheric conditions. For the WEC to withstand the environmental conditions for the duration of the project, extreme event records and the return period need to be well documented. Information on tides, tidal currents and seasonal patterns are relevant to the project as well.

Grid connection and capacity: The ultimate objective of the project is to supply power to the grid. Hence a site needs to take into account its proximity to grid connection and its capacity to accept power. The length of the underlying cable to supply the generated power to the grid will also add to the cost factor. Technical information on connection points, substations, distribution lines, supply capacity and voltage in the region have to be acquired. Moreover, the distance between the production point and the consumption point has to be convenient to reduce transport costs and to make the infrastructure more justifiable and viable.

Infrastructure and supply industry: A great deal of research and pre-planning are needed here to guarantee the longevity of the project. Specialised vessels and equipment are required to transport, assemble and install the device on site. These may not be available locally, as projects of such magnitude are infrequent, so infrastructure may be outsourced, thus adding to the cost of the project. There would also be a need for harbours for the vessels servicing the device and storage facilities to house any spare parts required during routine maintenance. Planned and unplanned maintenance may require backup support such as shipyards, remotely operated underwater vehicles, divers, monitoring equipment, and the availability of qualified staff. Considering all the above, it would be an advantage to choose a site in close proximity to services and infrastructure.

Environmental and planning issues: The effects of introducing an artificial structure (i.e. a wave energy converter) into the environment have to be considered as part of the planning. Some effects are described below.

- Interference with the habitat. This is a really critical issue for a coral reef environment. Coral reefs are a highly valuable environment and the extent of their destruction has to be evaluated carefully. For example, most nearshore devices are built on the seafloor. In a coral reef environment, this means complete destruction of the reef underneath the structure and along the path of the subsea power cable. In this case, the cost of the environmental loss would outweigh the benefits from the project.
- Changes in sediment supply and beach morphology. Waves play a significant role in transporting and mixing sediment on and off the beach. The installation of a WEC can, therefore, modify the sediment supply to the beach and indirectly cause erosion.
- Changes in wave and current pattern. Waves are a significant source of mixing and dispersal along the coast, and a WEC can block and disrupt the waves on the coast. This could lead to additional unwarranted outcomes and additional cost to the project.

Ensuring that the projected development will be compatible with local, national and regional land-use plans must be part of the planning and consultation process.

Conflict of use (interference with other users): Most Pacific populations are concentrated near coastal areas and they depend on the sea as a food source, and for income generation and transportation. There might, therefore, be constraints to the installation of WECs in **populated coastal areas**. For example, shoals are natural fish aggregators but are also known to concentrate wave energy and create wave energy hotspots. The installation of a WEC on such a bathymetric feature would cause considerable conflict with **local fisheries**. Bathymetric features that focus wave energy are also associated with world class surf breaks and diving spots, which are a source of high **tourism revenue**. A conflict might also arise in the rapidly expanding **aquaculture industry;** there may be competition for space between the aquaculture industry and renewable marine energy installations in shallow waters. Areas associated with **military activity** will also perhaps be out of bounds to any commercial operations. This would, however, depend on future negotiations with the relevant authorities. For example, in Western Australia, the CETO WEC was installed as a facility of the navy base off Garden Island (Perth Wave Energy Project 2014). **Navigational routes** should be clearly mapped and interference with them should be avoided to ensure that ports and commercial marine routes function normally. **Dredging, sand and gravel extraction** activities also need to be accounted for, and **communication cables and pipelines** should be mapped and, where necessary, avoided. Developments may also be taking place in **other forms of renewable energy** parallel to wave energy and they also need to be factored in.

3 Method

The overall aim of this project is to calculate the cost of energy of a single WEC in the Pacific region. The method is described below.

1. Calculate a cost range for a Pelamis wave device for the Pacific.
2. Calculate the wave energy resource for the region and the detailed wave climate for selected sites.
3. Calculate the cost of energy at the selected sites.

The choice of the Pelamis device for this study was made because there is extensive literature on it. However, it is unlikely that a Pelamis device can actually be purchased at this stage because the firm that developed it went into administration in 2014. The cost of energy is an indicator of the most suitable locations for wave energy conversion in the region and provides a benchmark for other potential WECs. Countries seeking a WEC (or approached by companies for a WEC) should obtain a cost of energy equal to or lower than the cost presented in Section 4, Results.

3.1 Pelamis cost review

The Pelamis device cost calculations were done by following the guidelines presented in section 2.5, where all the items implicated in cost were estimated for the region, based on the available literature on the Pelamis device. To account for cost improvement on the technology, the possibility of cost reduction by using local material, and also the increasing cost of transport to remote islands, the cost is given as a range – from an optimistic to a pessimistic expense.

Because this study focuses on the regional scale, it is impossible to evaluate the cost associated with environmental damage and conflicts with other industries. This, however, does not mean that these costs are negligible. Wave energy devices that are to be deployed in intermediate or shallow water may bear a significant cost associated with the destruction of coral reefs, and wave energy hotspots are often associated with surf breaks and dive sites, which, if affected by a wave device, would mean a significant cost to the tourism industry.

3.2 Regional wave energy: PACCSAP/CAWCR wave hindcast

There are insufficient *in situ* wave measurements in the Pacific to derive the wave climate for the whole region (Barstow and Falnes 1996) and, similarly, satellite-derived wave measurements are insufficient. Instead, this study uses a wave model. Typical global wave models are, however, unreliable in the Pacific region because they are too coarse to include the small islands and reefs that partially block the wave energy. To overcome the problem and calculate a reliable wave energy resource in the region, a specific wave hindcast (Durrant et al. 2014) was run with a high-resolution model grid over Australia and the Pacific Islands (Figure 3.1). A full description of the wave hindcast can be found in Durrant et al. (2014).

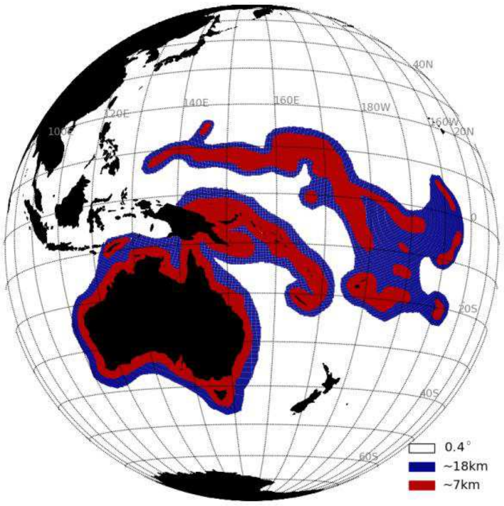

Figure 3.1 PACCSAP wave hindcast resolution (source: Durrant et al. 2014)

3.2.1 Validation

Numerical wave models are associated with a degree of uncertainty which needs to be quantified prior to any analysis of the results. The PACCSAP wave hindcast has been verified in the Pacific against wave measurements from Fugro/Oceanor (Barstow and Falnes 1996) made between 1989 and 1992. Table 3.1 presents a summary of the model skill (Equation 3.1) for all the measurements. The model skill for most of the locations is very good (above 0.85). The exception is Funafuti, where the model constantly underestimated the wave height. This is because the four arcminute resolution (~8 km) is still too coarse to properly resolve the shape of the island. The model compensates for this by automatically removing a predetermined fraction of the wave energy that would be blocked by the island on the entire model cell. This results in an underestimation of the wave height by the model at the particular model cell, but the amount of wave energy left in the ocean past the island is correct.

$$skill = 1 - \frac{\sum |X_{model} - X_{obs}|}{\sum (|X_{model} - \overline{X_{obs}}| + |X_{obs} - \overline{X_{obs}}|)^2}$$

Equation 3.1. where X_{model} is the simulated wave parameter and X_{obs} is the observed wave parameter.

The high skill indicates that the model outputs are reliable for calculating wave power statistics in the Pacific region, but care should be taken for wave statistics calculated close to small islands.

Table 3.1 Summary of model results

Island (Country)	Location Longitude	 Latitude	Depth (m)	RMS (m)	Skill	Bias (m)
Rarotonga (Cook Islands) 1	200.2717	21.2700	300	0.413	0.895	0.087
Rarotonga (Cook Islands) 2	200.2922	21.2560	675	0.433	0.885	0.099
Kadavu (Fiji)	177.9567	19.3067	356	0.355	0.910	–0.097
Eua (Tonga)	184.5850	21.8383	n/a	0.307	0.931	–0.080
Tongatapu (Tonga)	184.7300	21.2370	309	0.321	0.920	–0.039
Funafuti (Tuvalu)	179.2150	8.52500	585	0.559	0.544	0.504
Efate (Vanuatu)	168.5500	17.8750	285	0.419	0.905	0.309
Upolu (Samoa) 1	187.8000	13.8800	104	0.394	0.871	0.241
Upolu (Samoa) 2	187.7500	14.0583	1040	0.314	0.868	0.136
Upolu (Samoa) 3	188.7800	14.4150	850	0.347	0.883	0.146

3.2.2 Wave statistics

The mean wave energy in the region was calculated by averaging the wave energy flux (wave power) from 1979 to 2012. The mean annual wave energy is not sufficient to drive the choice of a site for wave energy conversion: it is important to also consider how consistent the resource is. For example, the North Pacific is known to be rough during the winter months but relatively calm during the summer months. By contrast, equatorial Pacific is constantly battered by waves generated from the trade winds – only the direction changes. The consequence for wave energy generation is that the low energy waves are consistently present in the tropical Pacific, whereas the high energy swell may only be present for half the year. A measure of the consistency of the wave energy resource is the mean annual variability of the wave power (Equation 4.1).

$$V = \frac{\overline{std(ECg)}}{\overline{ECg}} \times 100$$

Equation 4.1 V is the variability; std is the yearly standard deviation; ECg is the instantaneous wave power and the overbar represent the average over 34 years.

3.2.3 Site selection

The wave power and consistency of the wave climate is preliminary information needed to select sites. The minimum wave energy threshold chosen was the lowest mean annual wave energy where a WEC has been tested for commercial purposes. This threshold was 7 kW/m, which was the average energy in Port Kembla in Australia, the site of an Energetech oscillating water column device. The consistency of waves present year round at the site was also taken into account in making the selection. Locations with an average annual wave power of more than 7 kW/m often have a relatively consistent wave energy resource. For example, Kiritimati Island receives a lot of wave energy during the northern hemisphere winter, ranging between 10 and 12 kW/m. However, this is not maintained all year around and very little wave reaches the island during the summer months (2–3 kW/m). Hence the yearly wave energy average is less than 6 kW/m.

Once an area is chosen based on the above, the size of the population with access to grid-connected electricity is assessed. In some cases, the total population of an area is far too small to bear the cost of installing and maintaining a WEC. For example, in Cook Islands, two islands have a wave energy far above the 7 kW/m threshold – Rarotonga (population approx. 13,000) and Mangaia (population approx. 700). Though both locations are exposed to high wave activity, the small population in Mangaia would have to bear a much larger share of the cost of generating electricity per capita than Rarotonga, and likely much more energy would be generated by a single wave energy converter than would be used (a single converter is estimated to provide electricity to 500 households).

Islands with no installed electric grid, such as Kadavu in Fiji, are not presented here because the development of a WEC there would require an overall development and upgrade of the electric grid, which cannot be taken into account in this analysis. That does not mean that wave energy cannot be an option for these islands, but the calculation of the cost would require taking into account the installation of an electrical grid and such cost calculation is beyond the scope of this report. It can, however, be found in the wave climate report produced by the WACOP project.[3]

Although it is an important consideration, this calculation does not take into account what class of device would be most suitable for the selected locations. WECs can be classed as onshore, nearshore and offshore devices. Onshore devices are most suited to a rock platform on the sea edge, nearshore devices are best where the seabed is sub-horizontal at a depth of 15–30 m, and offshore devices are moored to the seabed in deep waters. The decision on which class to choose depends on the bathymetry of the location, the geomorphology of the environment and the habitat affected. For example, in Niue the narrow reef platform adjacent to the sea cliffs and the high wave activity close to the shore provide the ideal environment for an onshore device.

3.2.4 Detailed wave climate and power output for selected sites

The mean wave power and the consistency of the wave describe the resource but are often not used to calculate the potential power output of a device. Wave energy prototypes are tested in a controlled environment (usually a wave pool) in a range of wave heights and periods. For each height and period tested, the power output of the device is estimated, resulting in a power matrix that can be used to predict the power output of the device in a particular location (Figure 3.2). During sea trials, the device’s power output for each condition is measured again.

In order to calculate the power outputs of a given WEC, the occurrence and duration of each sea state is required. This is calculated using the time series of hourly sea states (wave height, wave period, and wave direction) extracted from the model for selected sites. The annual mean duration in hours is calculated for each combination of wave height and period, producing a sea state matrix.

The power matrix of the Pelamis device is presented in Figure 3.2. The first row of the table gives the range of energy period (Te) and the first column provides the range of significant wave height (Hs). The total energy output is calculated by multiplying each cell point of the power matrix with a sea state matrix, which is the number of hours per year when the combination of wave height and period occurred. The sum of all the resulting values gives the total energy generated by the device in kilowatt hours.

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[3] http://gsd.spc.int/wacop/WaveclimateReports.html

Hs, Te	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	12.5	13
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	22	29	34	37	38	38	37	35	32	29	26	23	21	0	0	0
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	0	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4	0	0	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	0	0	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5	0	0	0	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	0	0	0	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6	0	0	0	0	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	0	0	0	0	750	750	750	750	750	750	750	743	658	621	579	512	481
7	0	0	0	0	0	750	750	750	750	750	750	750	750	676	613	584	525
7.5	0	0	0	0	0	0	750	750	750	750	750	750	750	750	686	622	593
8	0	0	0	0	0	0	0	750	750	750	750	750	750	750	750	690	625

Figure 3.2 Pelamis power matrix in kW (Source : Silva, Rusa and Soares 2013)

3.3 Cost of energy generation

The cost of energy (CoE) is a measure of generating electricity considering all lifetime costs and energy production (Figure 3.3). The CoE is measured by equating the power production with estimated costs, which yields the cost of power in $/kWh (San Francisco Public Utilities Commission 2009).

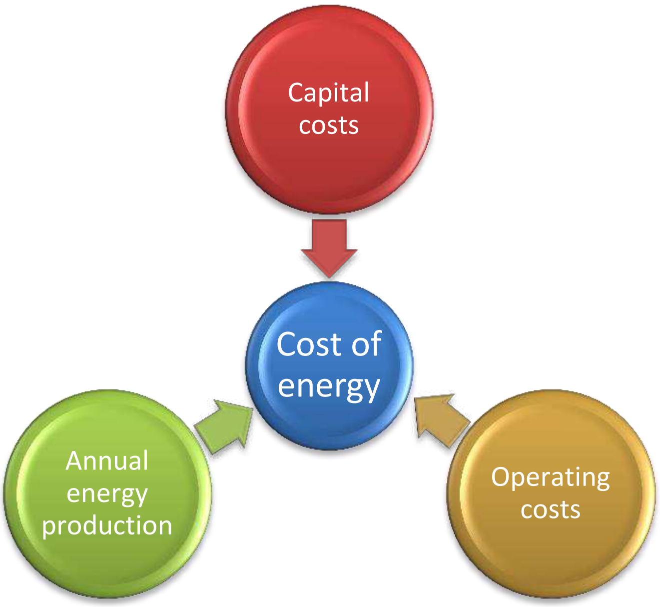

Figure 3.3 Factors affecting the cost of energy

The annual energy production (AEP) is a function of site resource, device energy capture and its availability. The yield of an energy extraction device is a key input, as the amount of electricity generated by the device will affect the cost per kilowatt hour. The SI OCEAN report (2013) defines the cost of energy as the sum of capital and lifetime operational and maintenance costs, divided by lifetime electricity generation to the grid on the assumption that the operation and maintenance

(O&M) cost and power generated is constant each year. Callaghan and Boud (2006) outlined the cost of energy as:

$$cost\ of\ energy = \frac{Capital\ cost + PV(O\&M\ costs)}{PV(Energy\ production)}$$

where PV indicates the present value over the service life. The capital costs, O&M costs and performance of a marine energy device are interrelated; an improvement in one may require a trade-off with another. The present report uses this methodology in the calculation of cost of energy. However, to compare the cost of existing installation, the cost of generation and maintenance is sometimes used:

$$cost\ of\ O\&M\ energy\ generation = \frac{PV(O\&M\ costs)}{PV(Energy\ production)}$$

The *Pacific Power Utilities Benchmarking Report 2012* (Todd and Simpson 2013) provides an assessment of Pacific electricity utility performance and compares the performance of the utility organisations over a defined period of time. The report defines generation operation and maintenance costs as the total cost for O&M of the utility, excluding independent power producer costs, labour costs and fuel and oil costs. The generation operation costs in the Pacific were provided in USD/MWh as follows:

- average generation O&M = USD 222/MWh;
- maximum generation O&M = USD 522/MWh.

4 Results

4.1 Cost of wave energy generation

The main objective of this section is to calculate the cost of a Pelamis device for the Pacific region. It is beyond the scope of this study to present an accurate cost for each location because many of the costs are sensitive to the site environment and isolation. Instead, the cost presented here is a range for the whole region that takes into account cost uncertainties and the variability of cost between islands. The cost range is presented for indicative purposes only, in order to promote thought and policy debate on wave energy opportunities. A full cost calculation will need to to be done for each site as part of a detailed feasibility study. Evaluating the cost of energy generation is the first step in assessing the efficiency of wave energy converters.

4.1.1 Cost of project

The cost associated with wave energy projects varies significantly with location, as the location defines the infrastructure and resource capacity. For the Pacific region, there are many cost uncertainties because no similar projects have been undertaken to date. In addition, information on resource and infrastructure for marine energy projects is too sparse in the region to undertake such assessments. However, many Pelamis projects and conceptual studies are under way globally (Dalton et al. 2010ab; Pelamis 2004; Previsic 2004a; Previsic 2004b; Waveplam 2009a) and for each project a cost analysis has been undertaken. Therefore, indicative cost estimates suited to the Pacific can be extrapolated from these reports.

The major costs associated with marine wave energy devices are referred to as cost centres (Carbon Trust 2006). These include:

- device
- shipping
- mooring/foundations
- installation
- operation & maintenance
- mid-life refit
- decommissioning.

The *Wave energy pre-feasibility studies* (Waveplam 2009b) provides an indicative measure of the capital cost derived as a percentage of the WEC's initial cost. The breakdown of capital cost for WECs is given in Table 4.1. Note that the cost of each item is reflected as a percentage of the initial cost of the wave device itself. The total capital cost would therefore correspond to 252% of the device cost.

Table 4.1 Capital cost breakdown as a percentage of initial device cost (souce: Waveplam 2009b)

Capital cost	Percentage of device cost
Replacement cost	100%
Installation of device and mooring	33%
Mooring	10%
Cabling	10%
Grid connection	5%
Siting and permits	2%
Spare parts	2%

Dalton et al. (2010a), provide a similar breakdown on the capital cost or capital expenditure (CAPEX) for WECs that was adopted for this study. The capital cost can be grouped in four categories: (Carbon Trust 2006; Callaghan and Boud 2006):

i. the cost of the device itself (materials, components and labour);
ii. the cost of keeping it in position (mooring and foundation);
iii. the cost associated with deployment and installation; and
iv. the cost of grid connection (electrical cable, etc.).

Figure 4.1 illustrates the capital cost breakdown of a wave energy converter. The larger share of the cost is taken up by the structure and mechanical/electrical components. These cost estimates are applicable to the many wave energy devices that exist in the marine energy industry and are discussed below in relation to the Pelamis concept.

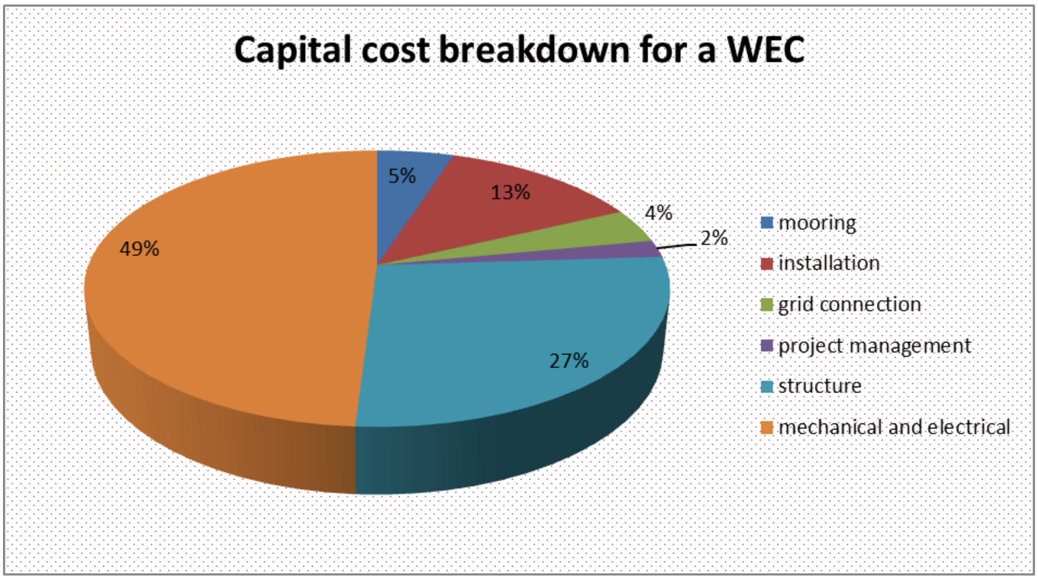

Figure 4.1 Capital cost breakdown of wave energy converters

4.1.2 Capital cost

The device, shipping, mooring/foundations and installation form the capital cost or the capital investment of the project.

4.1.2.1 Device

Based on existing applications, the device's structure forms the largest cost component, as it has to interact with waves and support power conversion equipment such as generators, hydraulics and gearboxes. Some WEC designs allow for structures to be built locally from off-the-shelf materials, whilst complex designs require the whole device to be manufactured overseas. In this case, the cost of shipping the device to the site must be included.

The Pelamis has four tubular steel sections that are the main structural elements of the device (Figure 2.2). Each steel section weighs approximately 70 tonnes and is 25 m long. The sections can be manufactured in a facility/warehouse using steel plates rolled into shape. Once formed, the sections are welded together to form segments (Previsic 2004a). The electrical and mechanical costs that form part of the device cost include all the components required to convert the motion of the device to electrical energy. The cables are all three-phase cables with a fibre core. They are used to establish reliable communication between the shore-based system and the device. The cost of the Pelamis device includes all the components related to the structure, power take-off and the many mechanical and electrical components fitted for device functionality. Previsic (2004b) gives the cost of a single Pelamis device in the range of USD 2.5–3.78 million. The same author in another conceptual design study on the Pelamis gives the cost of device as USD 3 million (Previsic 2004a). The present report uses the cost range of Pelamis as USD 3–4 million.

4.1.2.2 Shipping

The shipping of the structure, parts and components are cost factors that are dependent on the location of the project. If the technical expertise and process of manufacturing steel sections are too complex to be achieved locally, manufacturing can be done in more industrialised countries such as Australia, New Zealand or Indonesia, which are close to the region. This would be cheaper than transporting the complete device from Pelamis Wave Power Ltd. in Scotland (Previsic 2004a). However, the Pacific region lacks information on the cost of shipping marine energy devices for deployment purposes, so this warrants further investigation. A comprehensive study on shipping costs would entail identifying the nearest facility to fabricate the device and the most cost-effective route to ship the device to the site. A case study carried out by Woodruff (2007) on the Mangaia Wind Project calculated the freight cost as 4.5% of the total capital cost estimates (including spare parts, mooring, etc.). The shipping cost was for two 20 kW wind turbines shipped from the manufacturers to the site. The same percentage was used in the present study for shipping cost estimates of the Pelamis to the site. Although wind turbines weigh less and take up less space than the envisaged WEC, the Pelamis device is composed of four modules that are more easily stored than a wind turbine propeller or mast. The same percentage and a higher initial cost of Pelamis is estimated to be a reasonable cost estimate. Hence the shipping cost estimates range from USD 0.18–0.24 million.

4.1.2.3 Mooring/foundation

The mooring comprises all the parts necessary to hold the device in place. The mooring design must allow the device to move independently while preventing it from drifting from its station (Carbon Trust 2006). Furthermore, the design has to incorporate the extreme loads placed on it by hydrodynamic forces at sea.

Pelamis Wave Power Ltd designed the mooring arrangement based on site conditions. Factors considered were device survival conditions, maximum current velocity, seafloor soil density and water depth. Pelamis employed a catenary type mooring system using a combination of steel wire, chains, dead weights and embedment anchors (Previsic 2004a).

A specialised vessel with adequate lifting capacity in handling the mooring modules is required for transporting and installation work on site. Such vessels are often used in the region to install ship moorings and are available locally. The cost of mooring was assessed at 10% of the device cost (Waveplam 2009b; Dalton 2010a). In addition, a report published by Pelamis (2004) gives a detailed analysis of the performance and economics of the Pelamis device using 10% of the device cost as the mooring cost. Hence the mooring cost was calculated to be in the range of USD 0.3–0.4 million.

4.1.2.4 Installation

Installation methods are dependent on the nature of the device and are perhaps the most demanding part of the project. For WECs that can be towed to the site, suitable vessels include tugs, anchor-handling vessels, heavy-lift vessels and barges. The cost of deployment can be estimated using vessel charter rates and location.

Grid connection includes the cost of all electrical connections to shore. The length of the subsea cables from the point of power generation to the point of distribution depends on the proximity to shore and the seabed conditions, and these affect the cost of installation. There may be a need to upgrade the grid in locations where infrastructure is obsolete or not capable of absorbing the new generation.

Previsic (2010) reports on the pre-installation and installation activities specifically for the Pelamis device. The allocated resources and duration are listed in tables 4.2 and 4.3.

Table 4.2 Site pre-installation resource and duration (Previsic 2010)

Activity	Resources	Duration
Survey for mapping bathymetry and cable route at site	Survey vessel	Less than a week
Sub-bottom profiling to identify sedimentation layer thickness	Survey vessel	Less than a week
Cone penetration and vibrocore sampling	Barge and tugboat	Less than a week
Visual inspection of seabed	Survey vessel, ROV or diver	Less than a week
Wave resource characterisation using measurement buoy or ADCP	Survey vessel or RIB	1 year
Environmental baseline studies	Survey vessel, stand-alone instruments	1–2 years

Table 4.3 Pelamis installation, resource and duration (Previsic 2010)

Activity	Resources	Duration
Directional drilling to land power take-off cable on shore	Drill rig	Less than two months
Subsea cable installation	Cable installation vessel, supply boat	Less than two weeks
Moorings system installation	Derrick barge, two tugs and supply boat	One week
Electrical collector system installation	Derrick barge, two tugs and supply boat	One day
Device deployment and decommissioning	Custom vessel	One week

The availability of specialised vessels for specific tasks as listed in Tables 4.2 and 4.3 needs more research in the region. There would be cost savings if vessels were hired from within the region rather than looking abroad for alternatives. The California Pelamis Offshore Wave Power Plant project (Previsic 2004a) used three-phase cables with double armour and a fibre optic core for connecting the device to the shore. The core allowed data transmission between the device and the operator station located on shore. The cable is buried in soft sediments along a predetermined route to protect it. Using directional drilling, the cables were taken from the shoreline into the ocean.

The cost of installation of a WEC as shown in Table 4.1 is 33% of the initial device cost (Waveplam 2009b; Dalton et al. 2010a). However, because a coral environment is likely to be present in the vicinity of mooring or in the path of the undersea cable, more precautions may be needed during installation. Therefore, a more conservative approach has been adapted in this report whereby the cost has been rounded up to 40% of the initial device cost. This is to account for the hiring of specialised vessels for installation of moorings and deployment of the device. Moreover the cost of installation includes the installation of underwater cables from the device to the shore and related components. In total, the cost of installation amounts to USD 1.2 million –1.6 million.

4.1.2.5 Summary of capital cost

Table 4.4 Pelamis capital cost summary

Device	USD 3–4 million
Mooring	USD 0.3–0.4 million
Installation	USD 1.2–1.6 million
Shipping	USD 0.18–0.24 million
Total	**≈ USD 4.7–6.3 million**

4.1.2.6 Operation and maintenance

The operation and maintenance (O&M) aspect of the device includes costs related to planned and unplanned maintenance, overhaul or mid-life refit of the device during its service life, and monitoring throughout the operational life of the plant (Table 4.5). All elements, including underwater components, need to undergo thorough inspection to ensure the continued operation of the plant. To increase the duration of device operation while minimising downtime, proper planning is required on the availability of purpose-built vehicles, quick access to parts, quick connect and disconnect systems, and the availability of skilled labour. Major maintenance activities are carried out in the summer months during calm weather conditions for safety purposes (Previsic 2010). After storms or cyclones, some unplanned maintenance may need to be carried out on failures requiring immediate attention.

Planned maintenance includes:

- the cost of replacement parts and regular servicing components;
- the cost of the servicing vessel (charter rate) and the personnel required; and
- the cost of waiting on weather conditions to be right to allow for servicing.

Unplanned maintenance may include:

- the cost of replacement parts;
- the cost of stocking spares in case of failure;
- the cost of servicing and labour requirements; and
- the cost of having standby equipment and personnel in case of device failure.

The Pelamis incorporates a design for a quick connect/disconnect system, which allows for rapid deployment and recovery with a relatively small vessel. The subsystems and components are designed so that they can be lifted without the use of cranes and replaced with tested subsystems. The Pelamis device has remote monitoring capabilities to isolate the fault and determine the exact problem. In some cases, the fault may be rectified without physical intervention as the operator monitoring the device is able to identify the cause. In more sophisticated circumstances, major problems would require the Pelamis to be towed to a sheltered site for repair, thus adding to the cost. Removal of the device is required only to repair structural damage (Previsic 2004a). Pelamis Wave Power Ltd developed a system that can seal off a portion of the tubular section and provide dry access to the Pelamis machine below the waterline (Previsic 2010).

The WAVEPLAM study (2009b) reports on the cost of operation and maintenance and calculates it as 3% of the total project initial cost, i.e. the capital cost, while the *Wave power feasibility study report* (2009) undertaken for the city of San Francisco, USA, reports on the annualised operations and maintenance, ranging from 3% to 5% of total capital cost. Dalton et al. (2010b) assessed the O&M costs to be in the range 1% to 5% of capital cost. The present study considers two approaches for analysis of annual O&M. To calculate the minimum O&M cost, 1% of minimum capital expenditure (CAPEX) is taken and 4% of maximum CAPEX is considered. These yielded annual O&M costs of USD 49,000 and USD 272,000 respectively.

Table 4.5 Pelamis operation/maintenance activities

Activity	Resources	Frequency
Recovery and re-deployment	Custom vessel	Annual
Unplanned maintenance	Custom vessel	Every four years
Visual inspection of underwater elements	Research vessel, ROV	Every four to five years
Replacement/refurbishment of moorings and electrical collector system	Derrick barge, two tugs, supply boat	20–25years

4.1.2.7 Mid-life refit

During its lifetime the device may require an overhaul and refit of major components. This usually takes place mid-way in the plant’s operational lifetime to ensure that it is able to withstand the extreme marine environment.

The device has to be taken ashore for a complete overhaul and refit every ten years. As part of the refit, the power take-off systems and variable pitch mechanisms will need to be exchanged and the structure will undergo repainting. The final checks of the refit require inspection and approval by qualified and specialised personnel (Previsic 2004a). The cost of the refit depends on the severity of wear and tear that the device has undergone under operational conditions. Ten per cent of the capital expenditure (Dalton et al. 2010b) was accounted for in refit, which would result in an expenditure of USD 490,000–680,000 half-way through the operation lifetime.

4.1.2.8 Decommissioning

The device has to be removed from the site and disassembled towards the end of the project life (20–25 years). Similar equipment and procedures used in installation activities are used for decommissioning. It may not be practical to remove some elements, such as heavy anchors, so they can be left in place, as they may provide a habitat and shelter for marine life (Previsic 2010).

Decommissioning costs are difficult to predict, and at the end of the life of the moorings the device may be sunk or sold for scrap. In some cases, the cost of towing the device to a decommission site may be high (Table 4.6). The maximum cost of decommission of a Pelamis device should not exceed USD 1 million. That should cover retrieval of the device and mooring line, and disassembly of the structure for recycling, reconversion or disposal.

Table 4.6 Pelamis decommissioning resources

Activity	Resources	Duration
Recover device	Custom vessel	One day
Recover device moorings	Two tugs, derrick barge, supply boat	One week
Collector system removal	Cable handling vessel	One day
Subsea cable removal	Cable handling vessel	Two weeks

A summary of the operational expenditure expected for a Pelamis device is given in Table 4.7.

Table 4.7 Operational expenditure of Pelamis

Annual operation and maintenance costs per year	**USD 0.049–0.272 million**
Mid-life refit	USD 0.49–0.68 million
Decommissioning	USD 0–1.0 million

4.1.2.9 Total lifetime cost of the Pelamis

A cost range of the device was presented earlier for each cost centre. The same approach was adopted to calculate the total lifetime cost of one Pelamis device. The total costs shown in Table 4.8 were calculated considering a device life of 25 years.

Table 4.8 Total lifetime cost of one Pelamis device

Cost centre	Cost range
Device	USD 3,000,000–4,000,000
Mooring	USD 300,000–400,000
Installation	USD 1,200,000–1,600,000
Shipping	USD 180,000–240,000
Lifetime operation and maintenance for 25 years	USD 1,225,000–6,800,000
Mid-life refit	USD 490,000–680,000
Decommissioning	USD 0–1,000,000
Total	**USD 6,318,000–14,104,000**

4.2 Regional wave power

The characteristic of the wave climate was calculated from the wave hindcast output. Of particular interest for this report is the wave energy resource. The mean annual wave power (wave energy flux) in the Pacific ranges between 0 and 30 kW/m. Papua New Guinea and Solomon Islands are the countries that receive the least amount of wave energy; islands south of latitude –20° and north of latitude 10° receive more than 25 KW/m (Figure 4.2) .

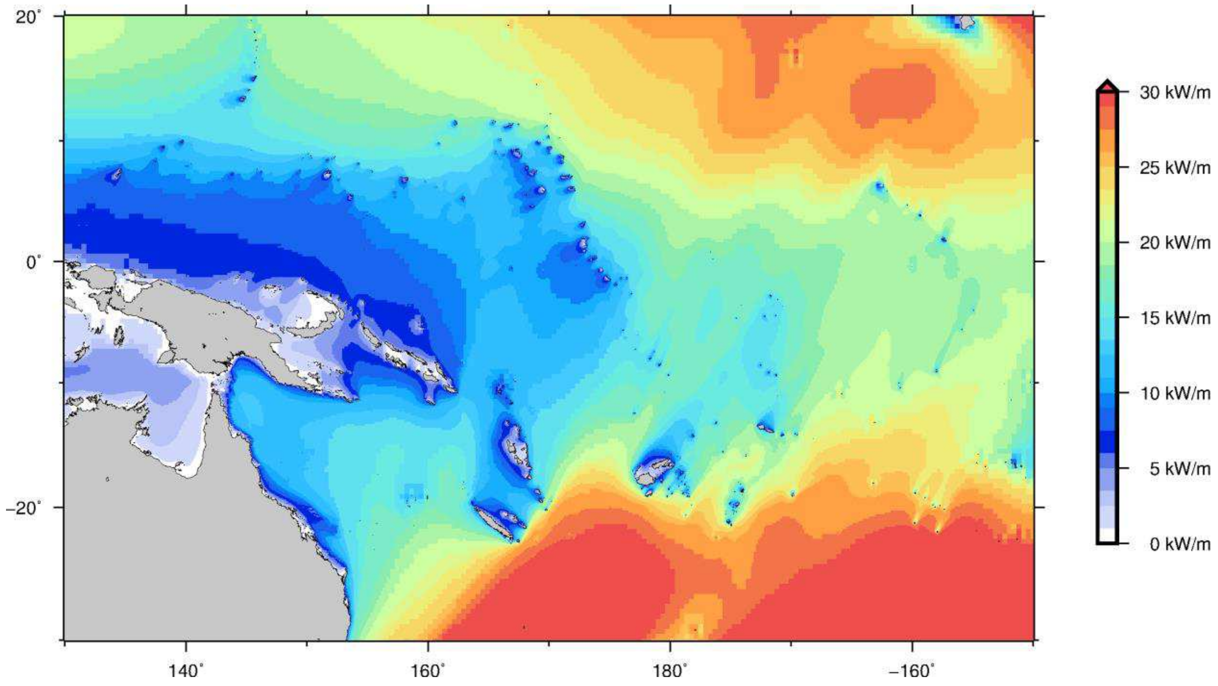

Figure 4.2 Average wave power in the Pacific (kW/m)

In the Pacific, the wave power variability (Figure 4.3) is between 30% and 120%. The areas with the highest variability are often locations with low wave power that can double if local winds become stronger. By combining the mean wave power and the variability, we can start identifying the most suitable sub-region of the Pacific for wave energy. The area between the southern tip of New Caledonia all the way to the Austral Islands (French Polynesia) has a high mean wave energy and relatively low variability, making this the most suitable region in the sub-tropical Pacific for wave energy conversion.

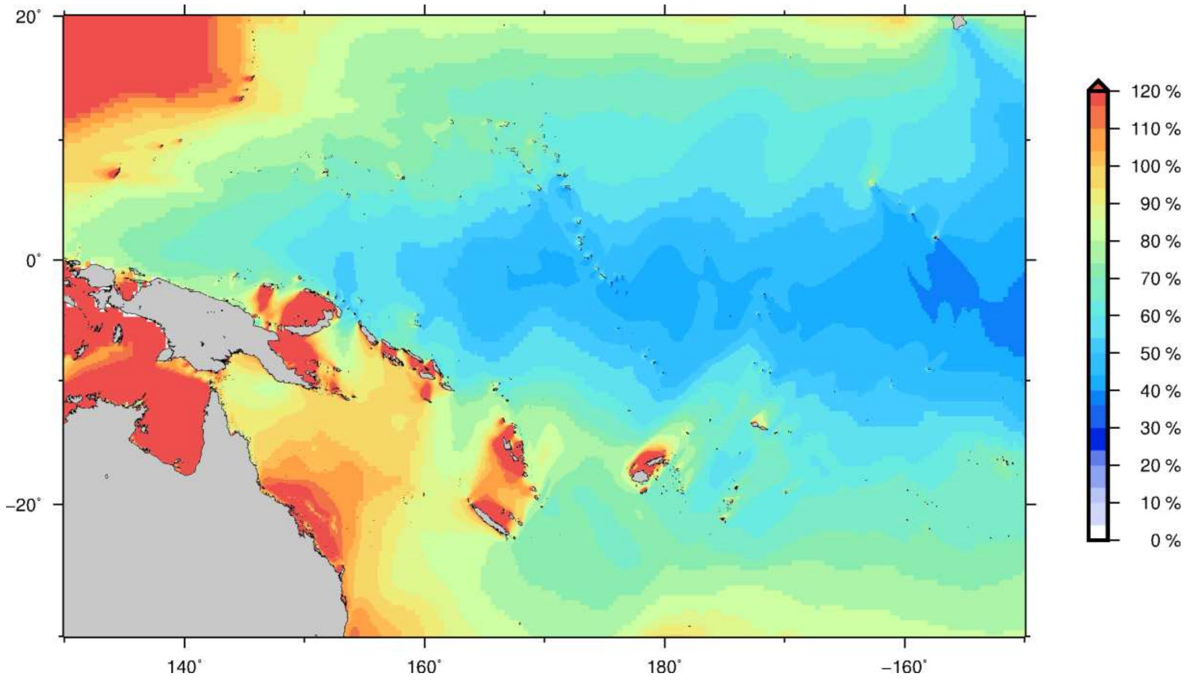

Figure 4.3 Mean annual variability of wave power in the Pacific as a percentage of the mean annual available wave power

The mean annual wave power and its variability are still an incomplete representation of the available wave power and are unpractical to use to predict the electricity generation of WECs.

4.2.1 Pacific regional sites

The regional wave climate does not provide a practical view of where to site WECs in the region. Some sites within the region were selected for further analysis of cost of energy. These sites derive from a relatively coarse analysis but represent the most promising sites for benefiting from a WEC. They should be subjected to further refining of the cost analysis for each island, following the guidelines in Section 2.5.

The sites were ranked to identify the best in the southern Pacific region for a wave energy pre-feasibility study. Areas were classified first on the existence of infrastructure for electric grid connection and then in descending order on their average wave power (Table 4.9).

Table 4.9 Classification of the most suitable Pacific locations for wave energy conversion

Rank	Country	Site	Coordinates		Mean wave energy flux (kW/m)	Grid connection Yes No
			longitude	latitude		
1	FP	Tubuai	210.520	23.307	32.98	Y
2	FP	Rurutu	208.643	22.481	31.43	Y
3	FP	Mangareva	225.137	23.308	27.17	Y
4	Tonga	Eua	184.585	21.838	24.84	Y
5	Fiji	South VitiLevu	177.367	18.153	24.00	Y
6	Cook Islands	South Rarotonga	200.271	21.270	21.93	Y
7	Cook Islands	North Rarotonga	200.216	21.202	17.84	Y
8	NC	Pine Island	167.434	22.714	17.78	Y
9	Niue	Niue	192.027	19.044	16.49	Y
10	Tonga	Tongatapu	184.730	21.237	16.39	Y
11	NC	Mare	168.129	21.577	16.15	Y
12	FP	Papeete	210.42	17.513	14.76	Y
13	NC	Noumea	166.241	22.374	14.30	Y
14	WF	Wallis South	183.780	13.395	13.12	Y
15	NC	Nepoui	164.922	21.416	12.40	Y
16	NC	Poum	163.830	20.259	11.71	Y
17	Samoa	Apolima strait	187.800	13.880	11.68	Y
18	Kiribati	Tarawa	173.296	1.441	11.46	Y
19	Vanuatu	Efate	168.550	17.875	10.98	Y
20	FP	NukuHiva	219.898	8.954	10.78	Y
21	FP	HivaOa	220.973	9.826	10.76	Y
22	RMI	Majuro	171.186	7.179	10.74	Y
23	FSM	Chuuk	151.980	7.514	10.52	Y
24	Vanuatu	Tanna	169.247	19.567	9.26	Y
25	FP	Bora Bora	208.220	16.494	8.81	Y
26	FSM	Kosrae	162.931	5.369	8.81	Y
27	Am. Samoa	Pago Pago	189.334	14.296	7.94	Y
28	Nauru	Nauru	166.904	0.530	7.68	Y
29	Tuvalu	Funafuti	179.192	8.503	7.53	Y
30	FP	Rangiroa	212.363	14.841	7.47	Y
31	Tonga	Nuku'alofa	184.815	21.009	7.33	Y
32	FSM	Pohnpei	158.184	7.027	7.13	Y
33	Samoa	Apia	188.235	13.820	7.12	Y
34	Fiji	Kadavu	178.321	19.223	22.51	N
35	Cook Islands	Penrhyn	201.926	8.960	13.27	N
36	Tokelau	Nukunonu	188.119	9.235	11.17	N
37	Cook Islands	Arutanga, Mangari	200.187	18.850	9.26	N
38	Fiji	Taveuni	179.874	17.059	7.75	N

The classification of the most important locations found 33 sites in 12 countries that correspond to the criteria (population above 1,000 inhabitants, mean wave power above 7 kW/m and electrical grid connection). Most of these sites are in the southern hemisphere and nine of the top ten locations are below latitude 20^{o} S. This shows that the swells from the southern ocean are a great energy resource.

4.2.2 Power generation for selected sites

The mean annual wave power and consistency are not sufficient to predict the power output of a device because the device performance varies with wave height and period. The sea state matrix is necessary. This was calculated for each selected site (e.g. Figure 4.4) and multiplied by the Pelamis power matrix (Figure 3.2) to calculate the device power output. Results from the 33 sites are presented in Table 4.10.

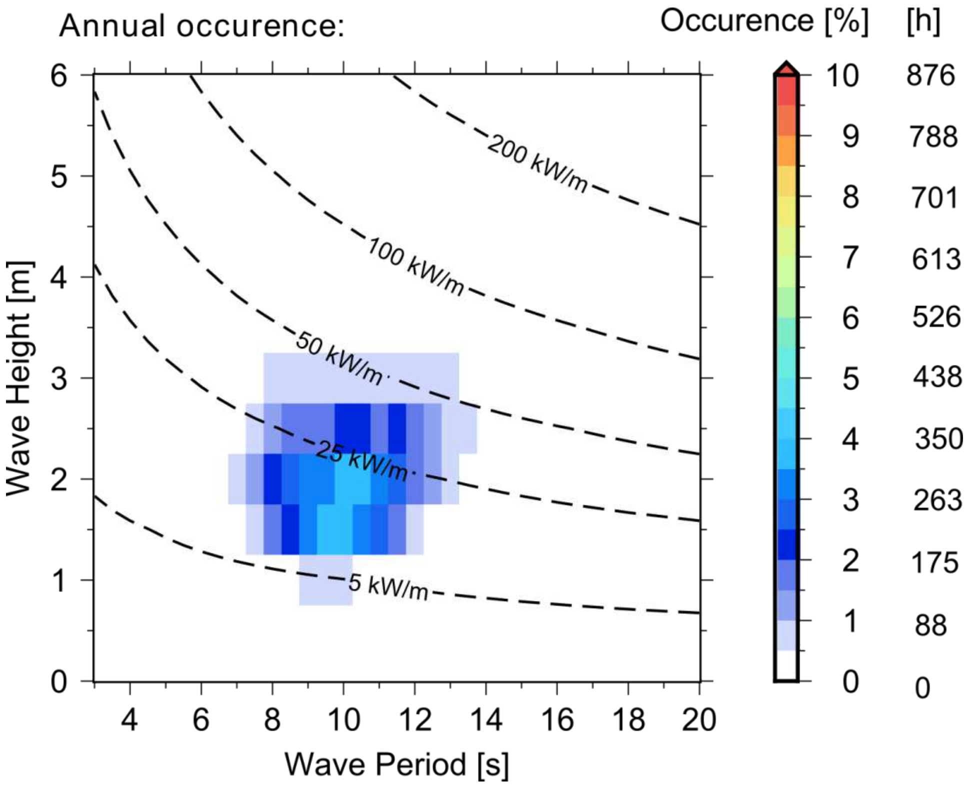

Figure 4.4 Example of occurrence matrix for Tubuai in French Polynesia

The 33 selected sites were assessed and their cost range of generating electricity from one Pelamis device rated at 750 kW was compared. The Pelamis power output presented ranges between 310 and 1210 MWh for one device per year. Interestingly, the ranking based on the mean wave energy does not correspond with the ranking based on the Pelamis annual power output. This is because the Pelamis device is more efficient at extracting wave power for a particular wave period. As a result, a device located in ‘Eua would produce more electricity than the same device in Tubuai, even if the mean wave energy resource is higher at Tubuai.

The wave climate for each island was not selected as the most suitable for wave energy location on the island. For example, locations in the Apolima strait in Samoa receive more energetic waves than the Apia region but could not be included in this analysis due to lack of resolution in the wave model used to extract the wave climate.

4.3 Cost of energy generation

The cost range of the Pelamis device was calculated, using both the total energy generation cost and the O&M generation cost. This facilitates the cost comparison with existing regional infrastructures and other renewable energy technology. The generation cost range (Table 4.10) was calculated using the cost range summarised in Table 4.8.

Table 4.10 Cost of generation for the best wave energy sites in the region

Rank	Site name	Mean wave energy flux (kW/m)	Pelamis annual energy output (MWh)	O&M generation cost range (USD/MWh)		Total generation cost range (USD/MWh)	
				(USD)Min	(USD)Max	(USD)Min	(USD)Max
1	Tubuai	32.98	1192.06	41	228	212	473
2	Rurutu	31.43	1157.37	42	235	218	487
3	Mangareva	27.17	979.63	50	278	258	576
4	Eua	24.84	1208.09	41	225	209	467
5	South Viti Levu	24.00	1017.00	48	267	248	555
6	South Rarotonga	21.93	896.50	55	303	282	629
7	North Rarotonga	17.84	731.20	67	372	346	772
8	Pine Island	17.78	715.69	68	380	353	788
9	Niue	16.49	551.44	89	493	458	1023
10	Tongatapu	16.39	649.12	75	419	389	869
11	Mare	16.15	888.70	55	306	284	635
12	Pape’ete	14.76	458.50	107	593	551	1230
13	Noumea	14.30	519.82	94	523	486	1085
14	Wallis South	13.12	659.54	74	412	383	855
15	Nepoui	12.40	435.20	113	625	581	1296
16	Poum	11.71	448.16	109	607	564	1259
17	Apolima strait	11.68	404.89	121	672	624	1393
18	Tarawa	11.46	633.17	77	430	399	891
19	Efate	10.98	676.36	72	402	374	834
20	Nuku Hiva	10.78	560.03	87	486	451	1007
21	Hiva Oa	10.76	571.41	86	476	442	987
22	Majuro	10.74	631.68	78	431	400	893
23	Chuuk	10.52	618.28	79	440	409	912
24	Tanna	9.26	322.72	152	843	783	1748
25	Bora Bora	8.81	368.18	133	739	686	1532
26	Kosrae	8.81	459.99	107	591	549	1226
27	Pago Pago	7.94	312.12	157	871	810	1808
28	Nauru	7.68	374.40	131	726	675	1507
29	Funafuti	7.53	353.82	138	769	714	1594
30	Rangiroa	7.47	335.95	146	810	752	1679
31	Nuku’alofa	7.33	382.29	128	712	661	1476
32	Pohnpei	7.13	314.48	156	865	804	1794
33	Apia	7.12	310.37	158	876	814	1818

The total cost of generation ranges from USD 209–467/MWh in Eua in Tonga to USD 814–1818 /MWh for Apia in Samoa. The O&M generation cost ranges from USD 41–225/MWh for Eua to USD 158–876/MWh for Apia.

5 Discussion

Diesel generation is the conventional form of electricity production for many PICTs, whilst solar PV systems and large scale wind farms are fast becoming an alternative electricity generation option for clean renewable energy (IRENA 2013). The generation cost for these sources (Syngellakis 2011; IRENA 2012) and the Pelamis generation cost for some selected locations are comparable, being in the same range (Figure 5.1). This is despite the fact that wave energy converters have not had the technological maturity of solar PV or wind turbines. For example, the generation cost for the islands of Tubuai and ‘Eua are within the range of urban diesel generation. If the generation cost from the Pelamis device can be maintained to a minimum in southern Viti Levu, Mare and Efate, wave energy costs might be as competitive as solar PV and urban diesel costs in these locations.

In addition, all the locations considered in this assessment have a minimum O&M generation cost below the Pacific average (Figure 5.2). Eighteen out of the thirty-three sites evaluated here have a maximum O&M generation cost which is well within the Pacific O&M generation cost range. These findings contrast with the fact that wave energy is often ignored as a source of renewable energy but are consistent with reports on suitability of the wave climate in the region (Argo Environmental Ltd 2011; Barstow & Falnes 1996). The cost presented here remains, however, a coarse analysis of the true cost of a wave energy device. For example, these costs do not account for the cost of environmental impact, and the estimation of transport costs, O&M and decommissioning may be further refined (and reduced) using salary estimates and management plans adapted to the site. The wave energy estimation is also the result of a relatively coarse spatial analysis and does not account for the local bathymetry that may focus the wave energy in hotspots that could double the energy output from a device.

The study findings show that in French Polynesia (in particular the Austral Islands), Tonga (‘Eua and Tongatapu) and Cook Islands (Rarotonga), wave energy is a genuine contender for the development of renewable energy. We recommend that potential wave energy sites be investigated further with a detailed cost and benefit analysis adapted for each location.

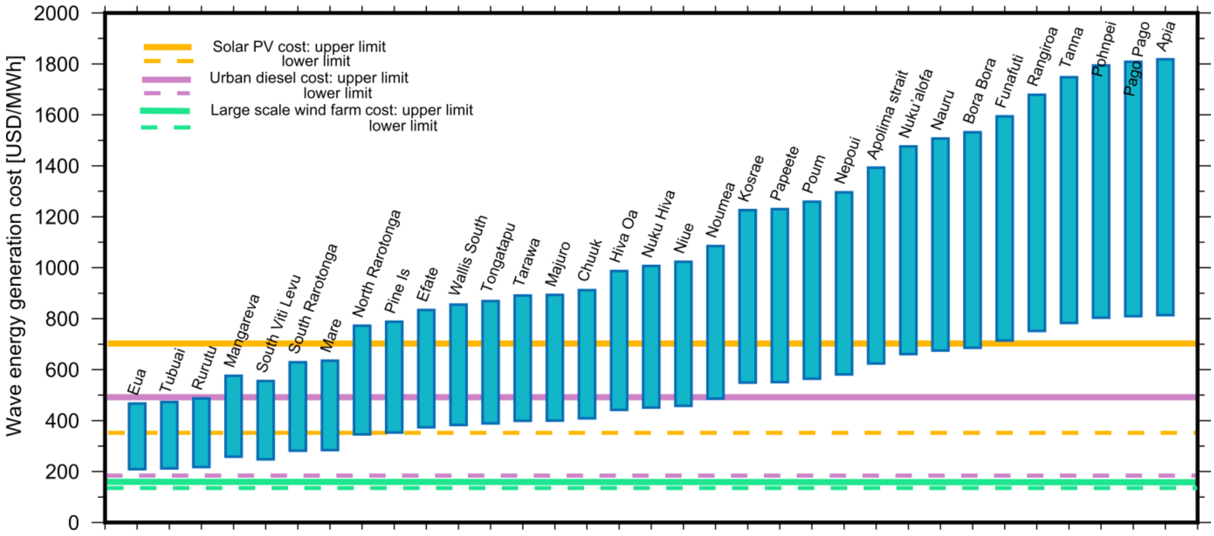

Figure 5.1 Generation cost comparison for selected sites and other sources of energy (source: Syngellakis 2011).

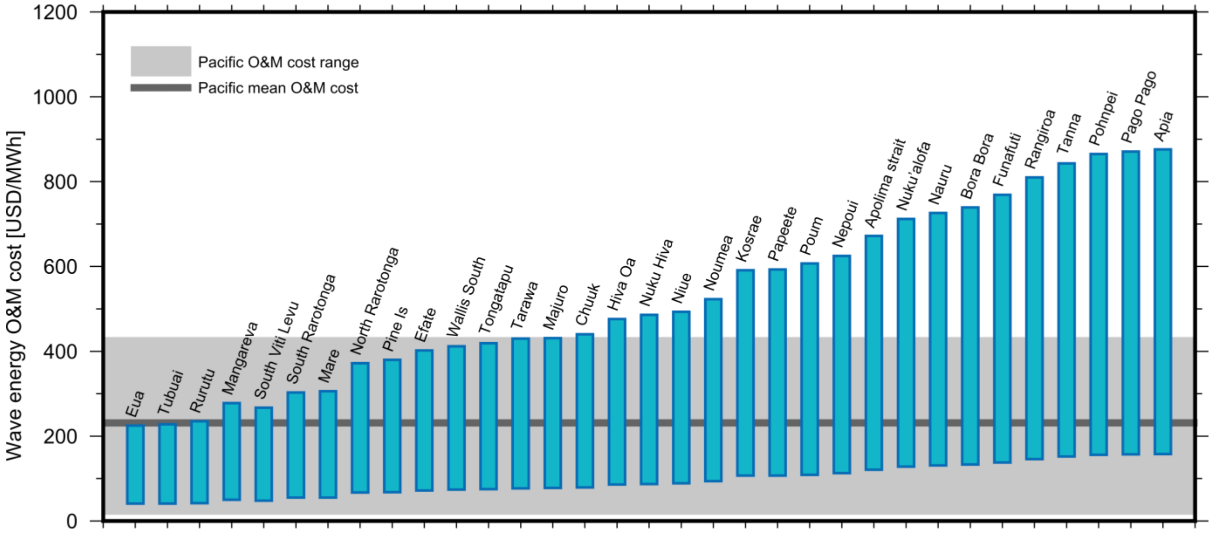

Figure 5.2 O&M generation cost comparison of sites against the Pacific range (source: Todd & Simpson 2013)

The O&M and total generation cost take into account costs associated with producing electricity from wave power without any financial gains. The cost of energy (COE) detailed in Section 2.2 from global studies on the Pelamis device account for the system lifetime costs (construction, financing, taxes, insurance and incentives) and are adjusted for inflation and discounted for time-value of money (Renewable Energy Advisors 2014). However, both approaches rely on the same concept of measuring costs over power output. Previsic (2004a) reported a COE of USD 134/MWh, Dalton et al. (2010b) presented a cost range of USD 200/MWh–778/MWh, and the ESBI 2005 report provided a COE of USD 130/MWh–150MWh.

In comparison, the best performing wave power output site calculated for the Pacific has a cost range of USD 209–467/MWh and the least favourable site has a cost range of USD 814–1818/MWh. As expected, the regional costs are higher than on the coast of Europe or the USA due to the technology's lack of footprint in the region and higher transport costs. Further initiatives in developing the technology in the region would likely bring down some of the costs presented here. In particular, the bulk of the device could be manufactured in one of the major ports in the region, drastically reducing the capital cost. The costs presented in this report are all based on a single Pelamis device and, as other studies suggest (Dalton et al. 2010a; Previsic 2004a; SI OCEAN 2013), the generation cost can be brought down further by using multiple devices. Other WEC devices could have a strong competitive edge if they are constructed locally and perform reasonably well compared with the Pelamis.

The energy output for a single device would correspond to a large proportion of the energy demand of the small islands listed above. Considering the best three sites as examples, the Pelamis would be able to supply electricity more than two times the current demand (464 MWh) for 'Eua Island (Tonga/Powerplants 2011). The energy output from the device could account for 42% of the total demand (2800 MWh) for Tubuai Island (Pacific Economic Cooperation Council 2012) and 87% of the current demand (1320 MWh) for Rurutu Island (The Global Development Research Center 2000). Therefore, for most of these small Pacific islands it would not be necessary to employ a large-scale wave farm that consists of ten or more devices. This relatively low demand and the high cost of imported fuel for conventional energy generation on small islands makes the Pacific region one of the few locations worldwide where a single wave energy device might be economically viable.

Although Pelamis devices have been the WEC device that received a lot of attention from cost and benefit analyses, it is now unlikely to be selected for any given site because of the economic situation of the company behind the device. Nevertheless, the Pelamis device serves as a cost-effective benchmark for other WECs in development. Devices in development can be quickly compared with the Pelamis device in terms of generation efficiency and cost, and will be considered for commercial scale deployment only by either being cheaper to build and deploy or by being more efficient at converting wave energy. In other words, the cost of energy generation of future devices should be cheaper than the Pelamis in the region.

Oscillating water columns (OWCs) have been one of the earliest and more established WECs that fall in the categories of onshore and nearshore devices that could provide a good alternative to the more expensive offshore devices and limit the cost to the environment. OWCs are comprised of chambers in which air is compressed and decompressed by wave action. The passing air rotates a turbine connected to a generator.

In the past 30 years several prototype scale OWCs have been constructed and tested. The major ones include the Pico OWC in the Azores, Portugal; the Energetech OWC in Port Kembla, Australia; the Vizhinjam OWC in India (Carbon Trust 2005); and the LIMPET OWC on the isle of Islay, Scotland, which took two years to complete and was built into a rock cliff with 2 x 250 kW turbines installed for energy extraction. The LIMPET OWC is the only success story for the OWC industry and is a benchmark for further research and development on this technology. Based on the Carbon Trust (2005) report, the Scotland and India OWC plants have a measured overall efficiency of 8% and 6.8% respectively.

The major costs incurred over the lifetime of a shore-based OWC device are during its construction and installation phase. O&M costs are incurred in the servicing of the turbines and related electrical/mechanical components. The O&M costs are also affected by whether there is ease of access during construction and servicing, since the device is located onshore. The projected cost estimates in the *Tongatapu wave power feasibility study* (Argo Environmental 2011) show almost 50% of the total being spent on civil works. Most of this is on-site excavation, preparation and device construction. On the downside, the efficiency of OWCs (as highlighted in the case of the LIMPET device) is very low compared to that of the Pelamis, which achieved efficiencies of around 70% during field tests (Pelamis 2014).

As a result of the low efficiency, the generation cost from an OWC is much higher in the Tongan study. The proposed three-megawatt Tongatapu OWC plant would provide an annual energy output of 11.9G Wh in a 15 kW/m wave climate, which equates to a generation cost of USD 1445/MWh. In contrast, the present study shows that from a 16 kW/m wave climate, the maximum generation cost from a Pelamis would be USD 869/MWh. Furthermore, deep water sites have the potential advantage of having a higher average incident wave power than a nearshore or shoreline site along the same stretch of coastline (Folley et al. 2005).

The cost calculations presented in this study are coarse and do not include the environmental cost of the device; nor do they include the cost associated with preventing other industries from operating where the device will be located, as such a cost is obviously variable, depending on the environment of the deployment site, but it can be substantial.

Nearshore WECs are also more problematic than offshore and onshore devices when they are deployed in steep slopes, which are common around Pacific islands. This suggests that nearshore wave devices in the Pacific are suitable in only a limited number of cases. Communication with companies designing and building wave energy devices is critical to obtain realistic costs and benefits.

For PICTs that have pledged to phase out plants powered by diesel or fossil fuel (Majuro Declaration), the goal may be difficult to attain, due to the increasing electricity demand and inconsistencies in the power output from solar PV and wind. But by complementing renewable energy resources with each other and with adequate power storage facilities, the use of fossil fuel power plants may be reduced to only backup systems, thus reducing fuel import bills as well as reducing green-house gas emissions.

The results of this study show that, for some locations, wave energy can be part of this renewable energy mix in terms of the annualised energy output and generation cost. In addition, there are some distinct advantages that wave energy systems have over their competitors. Grid-connected solar PV systems occupy a large land footprint, which is not at the disposal of some small island nations, and the technology is also very vulnerable to coastal inundation in low lying islands. With the current technology, a 1 MW solar PV system would require a land area in the range of 24000 m^2 to 36000 m^2 (Jayakumar 2009) whereas one Pelamis device rated at 750 kW situated out in the ocean would take up an area of only 750 m^2 on land, with sufficient room for further expansion. In addition, solar generation is limited to the sun hours and the issues of the high cost of battery storage and the capacity needed for storing solar energy for night time, when usage is normally high, remain.

Similarly, large-scale wind farms occupy significant land mass and their siting is dependent on the wind regime of the area. For example, the Butoni Wind Farm situated in the narrow ridge behind Sigatoka Town in Fiji operates in wind speeds of up to 4 to 20 m/s (Prasad and Anand nd). In Butoni, three 55-m high wind turbines (275 kW each) would be required to match the capacity of one Pelamis device. The IRENA report (IRENA 2013) attributes the limitation of wind energy in the region to the lack of technical expertise for wind resource assessment, the increasing trend of turbine manufactures to focus on larger wind turbines and hence fewer production models suited for island wind climate, and the requirement for wind turbines to withstand tropical storms in excess of 200 km/hr. The highly seasonal nature of wind in many Pacific Island countries adds to the complication.

Although many of the issues discussed above apply to wave energy, they are somewhat less marked. The wave energy resource does not vary between day and night (less than 0.3% of daily variability), whereas the wind speed can vary by 7%.[4] In the most exposed locations, wave energy is a resource available to supply power at a similar cost to solar, wind and even fossil fuel generation in the Pacific and with clear advantages over counterpart renewable resources. While the technology has not been tested in the Pacific yet and there are uncertainties about device reliability and overall cost,

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[4] Calculated from the CFSR wind hindcast in Funafuti, Tuvalu.

some of these uncertainties will be lifted only when actual wave energy conversion devices are deployed and used in the region.

6 Conclusion

This study presents the cost of generating energy from a benchmark wave energy device. The findings presented here are based on the wave climate of assessed locations, the energy output from the most developed wave device, and the estimated cost range for power generation. The findings suggest that wave energy conversion could potentially be a cost-effective option, in at least some Pacific Island countries. However, this analysis is not sufficient to warrant the deployment of a wave energy device at any of the locations cited above; a detailed study of the site(s) is needed. This report can be used as the foundation for a complete, detailed cost-benefit analysis. These site analyses are important because a site's geological and environmental features may dictate the best device to employ for optimum energy extraction with minimal environmental impact and cost. For example, sites with a rocky platform near the sea edge should be investigated for deploying an onshore device that is embedded in a modified rock platform, thus concentrating the waves for maximum energy extraction. A nearshore device could be used for sites that have a relatively flat seabed at a depth of 15–30 m. Offshore devices such as the Pelamis are best utilised where deep-water waves are available close to the shore for maximum energy extraction. The factors to consider for site assessment are listed in Sub-section 4.2 of this report and the generation cost of the Pelamis device should be used as a benchmarking tool to determine the most economical option for harnessing wave energy. A detailed site analysis should determine the constraints, if any, that would hinder wave energy project development, as well as assist in identifying tailor-made solutions for optimum wave energy extraction.

6.1 Recommendation

Preliminary assessment of the potential efficiency of wave energy in the Pacific region suggests the following:

1. There is value in French Polynesia, the Austral Islands in particular, to further investigate potential wave energy sites and feasibility. On these islands, wave energy generation might have the potential to become a renewable energy resource option for a relatively low cost that could even compete with fossil fuel energy generation.
2. Tonga, Cook Islands and New Caledonia may also benefit from further investigating wave energy sites and suitable wave energy devices to help reach their renewable energy targets and supply energy at a competitive cost compared to other renewable energy resources.
3. Countries with a mean wave energy flux above 7 kW/m could carry out further investigation into wave energy hotspots and wave energy device options, especially in exposed locations. In these exposed sites, wave energy may have the potential to supply a significant amount of renewable energy and help these countries meet their renewable energy targets. However, wave energy at these locations may be more expensive than other type of renewable energies.
4. At first glance, countries with a mean wave energy flux of less than 7 kW/m, such as Papua New Guinea and Solomon islands, are unlikely to benefit from wave energy unless a major technological breakthrough makes wave energy devices much more efficient. These countries should therefore not regard wave energy as a significant renewable energy resource.

5. The Changing WAves and COasts in the Pacific project (WACOP) has provided the calculations presented in this study for more than 80 locations in the Pacific in wave climate reports that should be consulted as an initial assessment of the wave energy resource available (http://gsd.spc.int/wacop/WaveclimateReports.html). The WACOP project also provides a detailed wave climate analysis for Samoa, Rarotonga, Tongatapu and ‘Eua, southern Viti Levu, Efate and Funafuti., The analysis includes wave energy and cost calculations based on the calculations presented in this report.

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