Ocean Energy in the Caribbean: Technology Review, Potential Resource and Project Locational Guidance

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Energy Division

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TECHNOLOGY REVIEW, POTENTIAL RESOURCE AND PROJECT LOCATIONAL GUIDANCE

OCEAN ENERGY IN THE CARIBBEAN

TECHNICAL NOTE: MARINE RENEWABLE ENERGY

Inter American Development Bank
and Caribbean Development Bank

November 2021

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Photograph source: Grenada

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Photograph source: Trinidad and Tobago

/ EXECUTIVE SUMMARY

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This Technical Note is a standalone piece of work commissioned by the Inter-American Development Bank (IDB) in partnership with the Caribbean Development Bank (CDB). It draws on and presents outcomes from work undertaken in 2019 as part of a Technical Cooperation Agreement between the IDB and CDB under the *Support for Sustainable and Resilient Projects in the Caribbean* programme.

This Technical Note fulfils three key aims;

1. Present a technology review covering the operating principles, development status, and suitability of Marine Renewable Energy (MRE) technologies relevant to the Caribbean region.
2. Present the outputs of analysis on the potential resource levels in selected countries of interest (COI's), namely; Antigua & Barbuda, The Bahamas, Barbados, Grenada, Jamaica, Saint Kitts & Nevis, Saint Lucia, St Vincent & the Grenadines, and Trinidad & Tobago
3. Present outputs from Locational Guidance work identifying preferred areas for installation of selected technologies in the COI's.

The key outputs from each aim are discussed in turn.

1. / TECHNOLOGY REVIEW

This Technical Note presents information on the operating principles and current development status of selected MRE technologies whilst also commenting at high level on the suitability of each technology for deployment in the Caribbean. Much of this section is an update of prior work undertaken by the same authors in IDB (2020) but which has been rigorously refreshed with new information where appropriate. It is presented to provide a solid foundation from which to understand the subsequent sections of this Technical Note which in turn present entirely new analysis not previously published. The broad findings for each technology considered are;

Fixed Offshore Wind

Fixed Offshore Wind (OSW) is well established as a commercial technology suitable for waters of less than about 60m depth. Compelling levelized cost of energy (LCOE) is being achieved in many developments in Europe and Asia, largely driven by economies of scale with notable increases in turbine size and project installed capacity – a trend that is set to continue. The industry has developed over a ten-year period from a series of disparate demonstration projects to more than 37GW installed globally at present, and is expected to reach around 120GW in the next five years.

The overall wind resource in the region is not uniform but largely considered to be good, with some areas very good to excellent. Areas of suitably shallow sea are limited and uneven in distribution through the region, although overall initial analysis suggests that there are large areas of sea with suitable depths at a suitable distance from shore and close to centres of demand, albeit with some nations and islands better suited and endowed than others.

Floating Offshore Wind

Floating OSW is a rapidly maturing technology with very high global market potential due to the range of water depths it can be installed in (usually under 200m, but with installations planned at up to 1000m). At present there is less than 100MW installed globally in demonstration and early array projects, but the pipeline and rate of deployment of new projects is remarkable with 400MW expected by 2023, and 3.2GW by 2025. As with fixed OSW the trend for larger turbines and larger projects is projected to continue as the industry matures. The LCOE for floating OSW projects is generally viewed as being higher than fixed OSW due to increased installation complexity, however for smaller and more remote projects with limited access to large ports and specialised vessels, the economics of floating technologies could surpass that of fixed. In mature markets the technology is expected to reach commercial competitiveness within a few years.

Similar to fixed OSW, the wind resource is mixed but generally good. Given the wide range of potential installation depths for this technology there are expansive areas of suitable depth for installation, albeit many areas would be beyond conventional installation depths.

Ocean Thermal Energy Conversion (OTEC)

OTEC has been identified for many years as a promising technology concept due to its potential to deliver baseload consistent renewable energy. There are also potential ancillary benefits from OTEC such as production of desalinated water or cool water agriculture. The review undertaken however shows that the technology options favoured by most technology developers (i.e. closed cycle, offshore plants) makes these ancillary benefits impractical or unlikely to be achieved. The technology itself is expensive and has not yet been proven at MW scale. The first demonstrations at this scale will come with high cost and considerable technology risk, which is perhaps the reason that numerous proposed projects have stalled. The technology is anticipated to require substantially more than five years to reach commercial readiness.

The thermal difference between surface and deep waters in most of the region is found to be suitable for OTEC plant and there are plenty of areas with suitable sea depth in proximity to land to host an OTEC plant. From a resource perspective the region is very well suited to hosting OTEC projects.

Sea Water Air Conditioning (SWAC)

SWAC is a promising but highly site-specific technology. In the Caribbean it requires access to deep cool water in close proximity to shore and also in close proximity to a high cooling load. There are longstanding successful applications of SWAC technology over many years in temperate regions using sea surface water or fresh water, with installations of SWAC for cooling using deep sea water more limited. That said, deep sea water SWAC may be commercially viable at some locations at present however more commercial examples are required before it could be said to have reached a state of general commercial readiness at a broader range of sites.

The Caribbean is assessed as a promising location for SWAC projects given the generally high cost of energy and substantial, year-round cooling requirement. Further in-depth work is required to identify suitable projects with best access to deep water and highest cooling demand and assess overall feasibility.

Wave Energy

Wave Energy is a nascent technology with only a few MW installed globally to date. There are estimated to be more than 200 wave energy devices under development using a wide variety of concepts. This lack of technological convergence demonstrates the early-stage nature of the industry. Whilst the potential market for wave energy is large, commercialisation of the industry from its current high-cost base will require external support mechanisms and is expected to take between five and ten years to reach commercial readiness.

In terms of resource the Caribbean has a relatively consistent wave regime which may be suitable for some technology types, but overall wave energy levels are not considered high on a global scale.

Tidal and Ocean Current Energy

Several demonstration tidal stream projects are operational globally, with installed capacity of more than 10MW. There is a general convergence on technology type, with horizontal axis turbines generally used and attached to either a seabed mounted or floating foundation. Whilst still pre-commercial, the technology is clearly at a more advanced stage of development than wave or OTEC and may be commercial within five years. The technology is however incredibly site specific, requiring to be installed in fast flowing streams of water. Due to the open coastal geography of the region, generally lacking major inlets, it is considered highly unlikely that suitable sites of any scale exist for tidal projects. For ocean currents it is understood that flow rates are too low for a viable project given the current state of technological development. Tidal and ocean current energy can therefore be considered to have very low potential in the region.

2. / POTENTIAL RESOURCE

The second element of this technical note is the publication of entirely new analysis which investigates the potential for deployment of Fixed OSW, Floating OSW (split into 'conventional' and 'deep'), and OTEC in selected countries of interest (COI's) of the Caribbean region. The results of this analysis are presented below alongside the average electrical demand of each COI. Notably the overall electrical demand of the nine countries is around 2GW, whereas the technically exploitable resource across the technologies is around 138GW, indicating that there is potential to supply all the region's energy requirements many times over from marine renewable energy.

Technically Exploitable Resource for each technology and each COI

	Maximum Technically Exploitable Resource (MW)					
Country	Fixed OSW	Floating OSW - Conventional	Floating OSW - Deep	OTEC	Total	Average electrical demand (MW)
Antigua & Barbuda	4,935	1,477	11,718	100	18,230	38
The Bahamas	10,955	6,321	16,723	220	34,219	220
Barbados*	0	112	7,063	140	7,315	104
Grenada	2,618	476	7,196	110	10,400	25
Jamaica	1,211	1,848	9,709	180	12,948	498
Saint Kitts & Nevis	399	196	9,135	40	9,770	24
Saint Lucia	105	224	4,025	90	4,444	46
Saint Vincent & the Grenadines	3,227	385	3,017	70	6,699	17
Trinidad & Tobago	16,597	12,460	4,963	50	34,070	1,064
Total	**40,047**	**23,499**	**73,549**	**1,000**	**138,095**	**2,036**

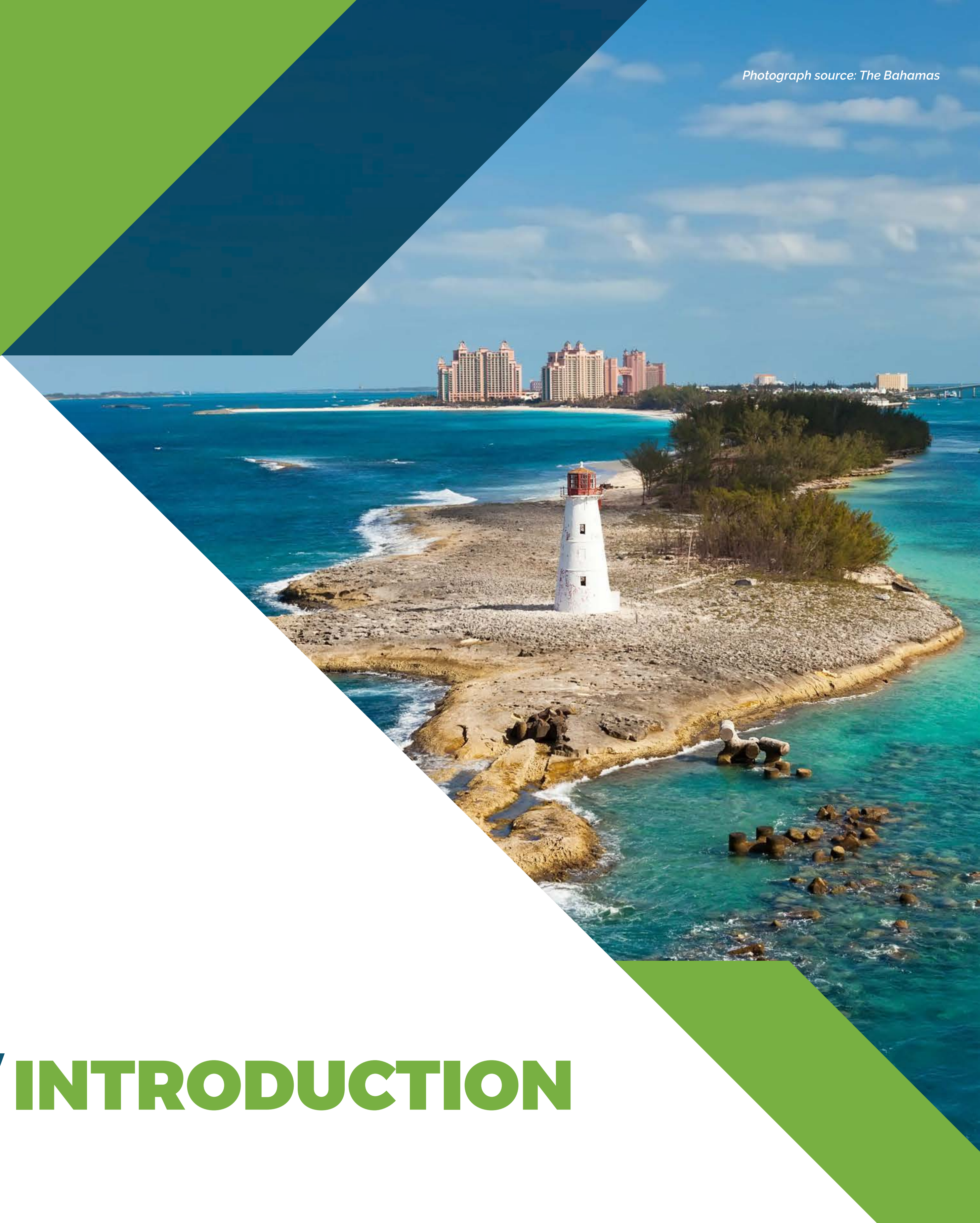
*Recent work using higher resolution country specific data has shown that there is in fact some limited potential for fixed wind in Barbados (Barbados Government, 2021).

3. / LOCATIONAL GUIDANCE

New analysis emanating from a detailed Geographic Information Systems (GIS) based 'Locational Guidance' exercise which uses layering and scoring of numerous data sets to identify the relative suitability of potential development areas for each technology is presented in Section 9 of this technical note. The analysis compares technologies across the COI's and also compares technology options for each COI, resulting in the production of detailed mapping imagery which visualises which technologies could be suitable for each country and which areas of ocean are most likely to be suitable installation locations

4. / SUMMARY

Overall, this Technical Note aims to engender a much-improved understanding of the potential for MRE deployment in the Caribbean by matching resource potential with technical and commercial readiness, and by utilising available data to provide 'Locational Guidance' at a country-by-country level. This work demonstrates – particularly in the case of fixed and floating OSW – that there is a strong match in terms of technological readiness, resource quality and LCOE potential which shows just cause for adoption of an aggressive approach in encouraging and promoting the deployment of this technology in the region.



Photograph source: The Bahamas

/ INTRODUCTION

/ INTRODUCTION

1.1 / INTRODUCTION TO MARINE RENEWABLE ENERGY AND ITS POTENTIAL FOR APPLICATION IN SMALL ISLAND DEVELOPING STATES IN THE CARIBBEAN REGION

The term 'Marine Renewable Energy' (MRE), also referred to as 'Ocean Energy' or 'Offshore Renewable Energy', describes a suite of related renewable energy technologies which are deployed in the offshore marine environment. These technologies operate by gathering energy and converting this to electricity. MRE technologies offer the potential for a secure, reliable and renewable supply of indigenous clean energy – this makes the sector particularly attractive and worthy of investigation for the Small Island Developing States (SIDS) of the Caribbean region.

There is a particularly strong rationale for exploration of the potential for MRE technologies in SIDS given the following:

- Onshore wind and solar energy deployed at large-scale require a significant amount of space and availability of suitable land is highly limited in most SIDS. The sea-space of SIDS is typically many times that of the land area and is much less constrained.
- As will be shown in this report, MRE technologies have the potential to meet the current and projected future electricity demand of the countries of interest many times over.
- MRE Technologies enjoy greater predictability and consistency than onshore technologies and can complement any onshore development.
- Leading MRE technologies are fast approaching technical and commercial maturity or have already reached this stage of development.
- There is significant long-term local job-creation potential associated with deployment of MRE technologies.

MRE technologies have largely been developed and are being proven in the industrialised nations of the northern hemisphere such as the UK, Germany, China and the USA, but have global deployment potential. The technologies are also of particular relevance in the Caribbean where they may offer potential to address critical issues related to security of supply, carbon emissions and cost of energy.

The technologies which make up this emerging sector are at different stages of commercial readiness. Fixed offshore wind (OSW) has now become cost-competitive with conventional forms of electricity generation in many settings and is being deployed in arrays at GW-scale. Floating OSW, which is another technology of enormous promise, has made rapid technical progress in recent years to the point where it is now on the cusp of being widely commercially available. Of the other technologies in the sector, Sea Water Air Conditioning (SWAC) offers the ability to utilise deep water close to shore to provide cost competitive cooling load to medium to large-scale industrial users. Related to this, although technically not as mature, Ocean Thermal Energy Conversion (OTEC), appears to offer a highly appealing combination of resource availability, scale and ancillary benefits. The other MRE technologies of tidal energy, ocean current energy and wave energy are also discussed in this technical note in the context of their suitability for deployment in the region in the near to medium term.

All of the above MRE technologies, once deployed, would contribute to the regional diversification of the energy mix, reduce reliance upon fossil-fuel imports, and by replacing demand with a local indigenous resource, have an overall positive impact on the resiliency of the energy system and economy.

1.2 / BACKGROUND TO THIS TECHNICAL NOTE

This Technical Note is a standalone piece of work that has been commissioned by the Inter-American Development Bank (IDB) in partnership with the Caribbean Development Bank (CDB). It draws on and presents outcomes from work undertaken as part of a Technical Cooperation Agreement between the IDB and CDB to provide technical consultancy services under the *Support for Sustainable and Resilient Projects in the Caribbean* programme.

This Technical Note has two key elements. Firstly, it presents information on the operating principles and development status of the following selected MRE technologies

- Fixed offshore wind (Fixed OSW)
- Floating offshore wind (Floating OSW)
- Ocean Thermal Energy Conversion (OTEC)
- Sea Water Air Conditioning (SWAC)
- Wave energy conversion
- Tidal and ocean current energy conversion

This element of the technical note is an update and extension of similar work previously undertaken by the same sector experts for the IDB, the main findings of which were subsequently published in March 2020 as;

> *IDB (2020), Ocean Energy in Barbados – A review of clean technology options, available resource and locational guidance for potential areas of interest for commercial development. S. Johnston, J McGlynn and V. Prado. March 2020*

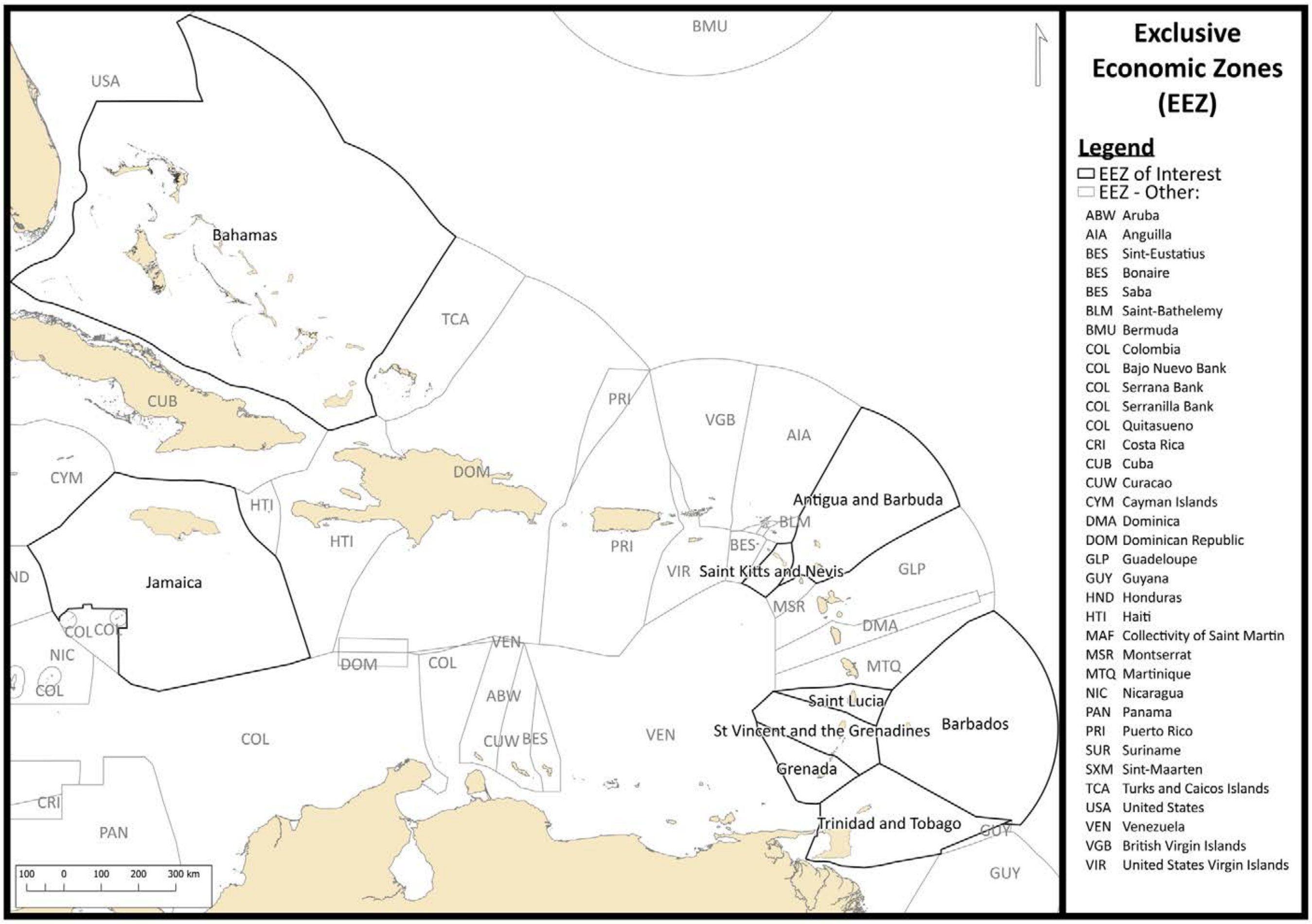
The content of this technical note with regard to technology 'operating principles' is necessarily largely similar to that report, whilst the 'development status' has been significantly updated to reflect the latest industry intelligence backed up by information provided by leading technology developers themselves.

The second element of this technical note is the publication of entirely new analysis which investigates the potential for deployment of selected marine renewable energy technologies in the following countries of interest (hereafter referred to as COI's);

- Jamaica
- The Bahamas
- Barbados
- Antigua and Barbuda
- Grenada
- St Kitts and Nevis
- St Lucia
- St Vincent and the Grenadines
- Trinidad and Tobago

The Exclusive Economic Zones for each of the COI's is illustrated in Figure 1.1.

Figure 1.1 Exclusive Economic Zones of the Countries of Interest



The overall potential is investigated from two perspectives. Firstly, the theoretical and technically exploitable resource is calculated and considered against the overall electrical demand of the COI's. Secondly the results of a Geographic Information Systems (GIS) based 'Locational Guidance' exercise to identify the relative suitability of potential development sites is presented. It should be noted at the outset that, while the GIS exercise conducted is comprehensive and detailed, it is also limited by the data available and should be viewed as an initial 'first step' exercise at a regional level. Further investigation and development, with suitable consultation, will be required and is recommended, particularly at a country specific level where it is likely that 'local' data could enhance the analysis.

The technology scope for the GIS analysis comprises all technologies covered by the technology review, with the following exclusions:

- SWAC, which was excluded due to the site-specific nature of this technology and the complexity and detailed data requirement to enable analysis of suitable sites.
- Wave energy conversion, which was excluded due to lack of available data of suitable quality and detail.
- Tidal and ocean current conversion, which was excluded due to a lack of available data which in turn is a result of the very low potential in the region.

1.3 / STRUCTURE OF TECHNICAL NOTE

This Technical Note is split into four main sections:

- Technology Review
- Potential resource
- Locational Guidance
- Overview and recommendations

The content of each section is elaborated on below.

Technology review

Each technology is considered in turn using the following structure;

1. Operating principles:
   - This section provides the layperson with an understanding of the basic principles by which the various ocean energy technologies operate. It is therefore intentionally broad in scope and general in nature.
2. Development status:
   - This section describes the current status of technology and project development for the selected technologies. The current global status and major industry-leading projects in each technology sector are presented and summarised.
3. Operational requirements and resource:
   - Broad consideration is given to operational requirements for each MRE technology, such as water depth and distance from shore, and a broad look at available resource in the region is considered.
4. Technical conclusion:
   - Technology readiness is considered against available resource in order to enable a brief general assessment of the likely applicability of each of the selected technologies in the context of the Caribbean region.

Much of this section is an update of prior work undertaken by the same authors in IDB (2020) but which has been rigorously refreshed with new information where appropriate. It is presented to provide a solid foundation from which to understand the subsequent sections of this Technical Note which in turn present entirely new analysis not previously published.

Potential Resource

The theoretical resource and technically exploitable resource are calculated following a scoping exercise to identify islands within COI's which have a suitable level of electrical demand to host an MRE project.

Locational Guidance

The results of Locational Guidance work are presented which, recognising limitations in availability of data, indicate the areas in the COI's likely to be most suitable for development of the selected technologies. The results are presented technology by technology, and then country by country, with discussion provided on the findings.

Overview Discussion, and Recommendations

The merits of each technology option are considered against each other alongside a discussion of the findings and general recommendations. Links to relevant industry reports are also provided.

Photograph source: St Kitts and Nevis

/ TECHNOLOGY REVIEW

/ FIXED OFFSHORE WIND (OSW)

2.1 / FIXED OSW - OPERATING PRINCIPLE

Air movements and currents in the form of wind are created due to ever changing locational variances in atmospheric pressure driven by the difference in heating from the sun between the equator and the poles. Wind energy is therefore a form of solar energy and is entirely renewable. Winds are also influenced by the rotation of the earth and are further altered by the Earth's topography. Wind energy devices harness these flows of air by converting them into mechanical rotational movement to drive an electric generator. Onshore wind generation is a well-developed industry and offshore wind essentially uses the same proven generation technology and pairs it with alternative foundation technology to secure the generator to the seabed and enable an electrical and communications connection to shore. The rationale for locating wind turbines offshore is to access a stronger and more consistent wind resource whilst also lessening the potential for visual impact and concerns relating to competition for land use. As a result, developers of offshore wind projects are typically less constrained in terms of the size of the individual turbine units themselves and the overall array or project size when compared with onshore projects.

Numerous concepts exist for physically connecting offshore wind turbines to the seabed. In shallow water (under a threshold of 60m) this is often achieved using proven technology from other industries such as piling, jacket foundation or suction techniques. Examples of foundation systems used are outlined in Figure 2.1.

Figure 2.1 Example foundation systems for fixed OSW

Source: Adapted from NREL (2015). Left to right: monopile, four-legged jacket, twisted jacket.

2.2 / FIXED OSW - DEVELOPMENT STATUS

Fixed OSW is a mature and well-understood technology with many GW of capacity now installed. The first fixed OSW project was installed off the coast of Denmark in 1991, and commercial-scale installations have been in operation ever since. Offshore array deployment has historically been spurred by a variety of mostly revenue-based subsidy regimes – with activity almost entirely concentrated in Europe until more recent years. Subsidy regimes have been effective in stimulating industry development and are in the process of being phased out in many leading markets. This reflects the technical and commercial maturity of the technology and major achievements in terms of cost reduction which, in turn, has led to increasing involvement of commercial lenders in the sector. The sector has and continues to grow rapidly. Offshore wind accounted for 1% of global wind installations by capacity in 2009 and this figure has now grown to over 10% with further exponential growth expected (Global Wind Energy Council 2020).

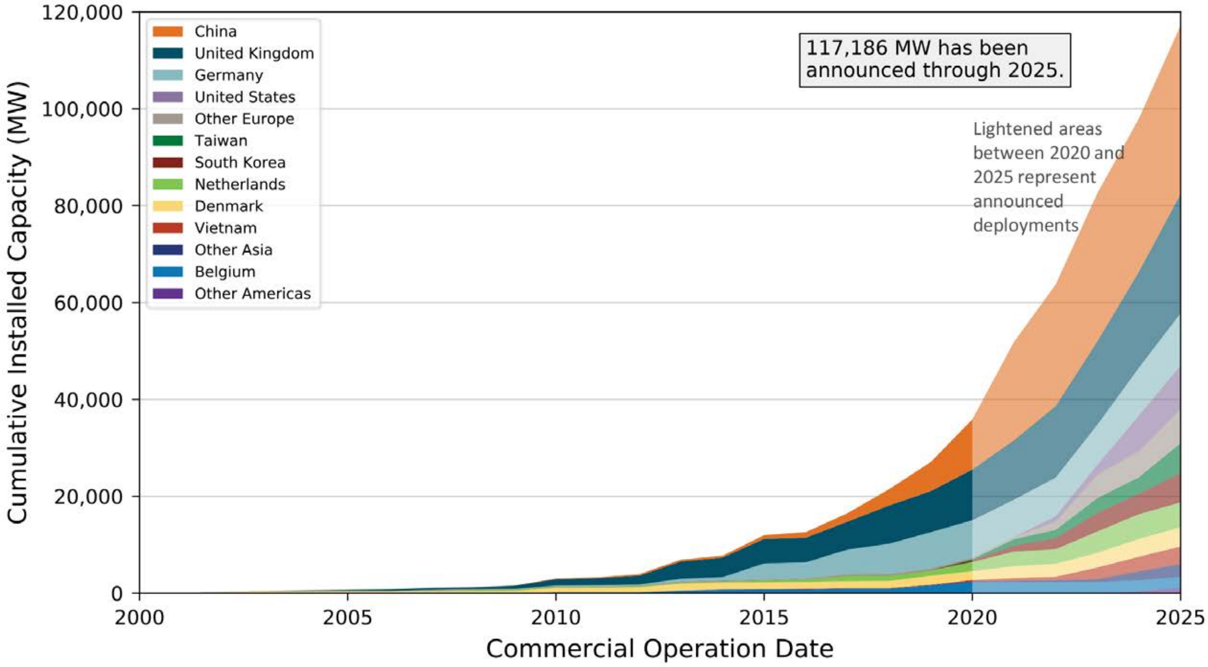
2.2.1 Global installed capacity & leading markets

Europe has to date been the most active region for OSW and remains the largest market for offshore wind. Europe accounts for 75% of total global installed capacity concentrated in the five key countries of the UK, Germany, Denmark, Belgium and Portugal (Global Wind Energy Council 2020). Installed capacity in Europe stood at 25GW at the end of 2020, with a total of 5,402 individual turbine units in operation across 12 countries. The UK has the largest amount of offshore wind capacity in Europe, accounting for 42% of all installations. Second is Germany with 31%, followed by Netherlands (10%), Belgium (9%) and Denmark (7%) (WindEurope, 2021).

Europe and China account for almost the entire global operational market at present, although activity is well underway in a number of other countries. In the Asian market 2.4GW was installed in China during 2019, more than anywhere else in the world. Other active markets include Taiwan, Vietnam, Japan and South Korea. Installed capacity in the USA at the end of 2019 stood at 30MW, with the entirety of this capacity accounted for by a single project located at Block Island, in the state of Rhode Island, however installed capacity in the USA is expected to accelerate significantly in the coming years.

The sector and projected growth scenarios do not appear to have been substantially impacted by the Covid-19 pandemic beyond the immediate term. Indeed, as Figure 2.2 shows, the market looks set to more than triple in size over the next five years, adding more than 80GW to installed capacity globally (US DOE, 2020).

Figure 2.2 Current and projected future levels of OSW capacity by region



Source: US DOE (2020)

Looking longer term, new installations are expected to continue on a steady and rapid trajectory towards around 200GW installed capacity by 2030 (GWEC, 2020, NREL, 2020). This can be attributed to continued growth in Europe and China with significant additional contributions from elsewhere in Asia in markets such as Taiwan, South Korea, Japan and Vietnam and the eastern seaboard of the United States.

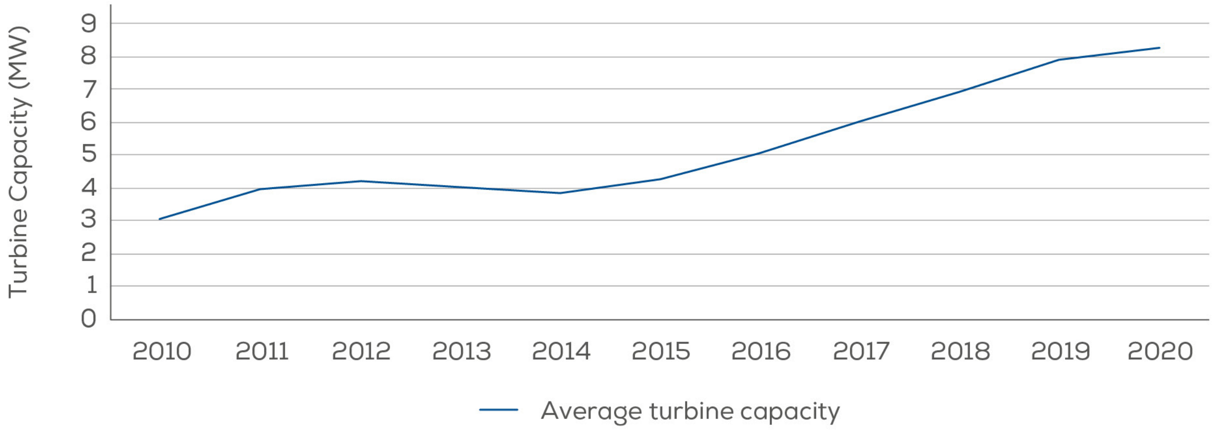
2.2.2 Turbine sizing trends

Fixed OSW turbines have to date shown a clear and continued trajectory of increasing in size and rated output. This trend can be expected to be sustained as developers continue to compete and innovate in search of performance and cost improvements which can be achieved by increasing turbine size and capacity.

The largest currently operational offshore wind turbine in the world, the V164-9.5MW developed by MHI Vestas, was installed in December 2019 at the Northwester 2 wind farm in Belgium. The average size of newly-installed offshore wind turbines in Europe in 2020 was 8.2MW, a 0.4MW increase on 2019. From 2014 – 2019 the average rated capacity of newly installed wind turbines grew at an annual rate of 16%. This is illustrated in Figure 2.3 below. Most fixed OSW farms under construction are now using turbines which are rated at 8MW or above. A number of leading developers (including Vestas, GE and Siemens Gamesa) have announced the launch of models with capacities in the range of 13MW to 15MW. The first of these to be deployed will be the Vestas V-236 15MW in 2022.

In China it is anticipated that turbine size will remain around 8MW for the near to medium term (GWEC 2020). This is presumably to stay aligned to the capabilities of the existing installation vessel fleet in the region as a 'next generation' of installation vessels will be required to enable deployment of ever-larger machines.

Figure 2.3 Average offshore wind turbine capacity by year



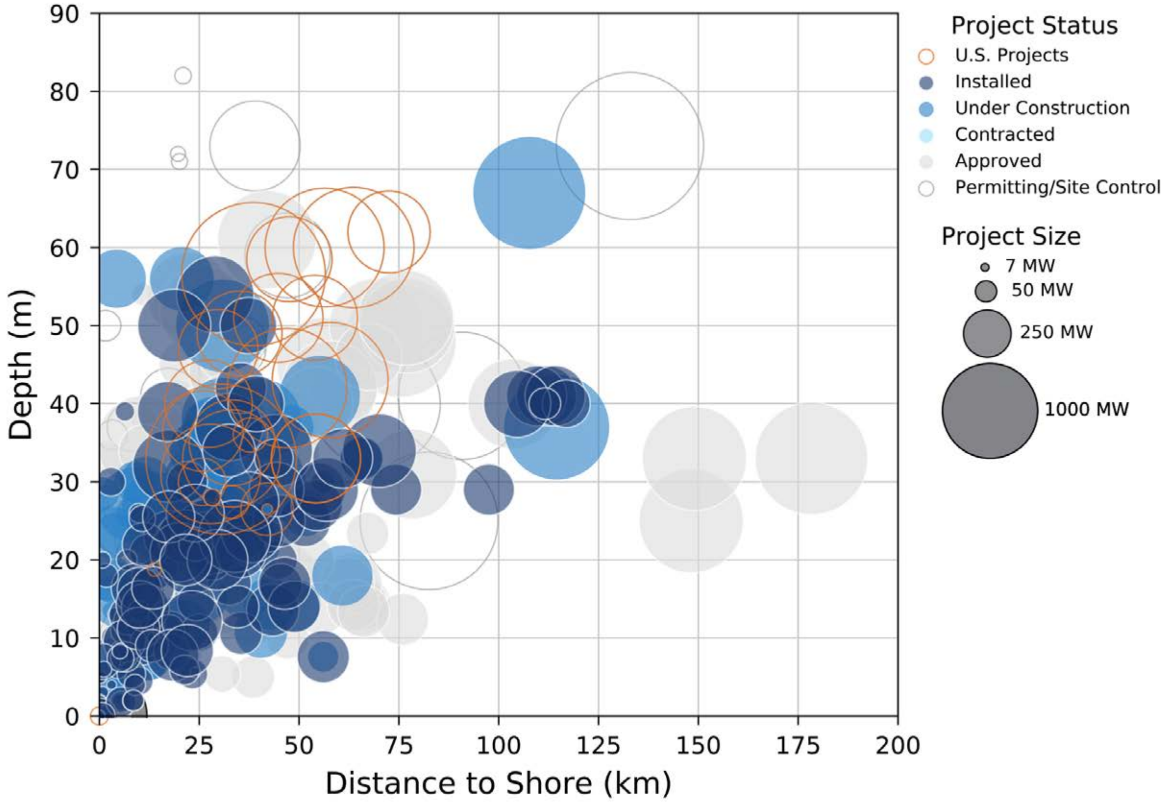
Source: WindEurope (2021)

2.2.3 Depth, distance to shore and project size

As the Fixed OSW industry has developed there has been a reasonably pronounced trend in sites moving into deeper waters further from shore. There is however a relatively firm technical limit for installing fixed structures of around 60m water depth. Figure 2.4 below illustrates project size and distance from shore globally. The data shows that the tendency for fixed offshore wind projects to be installed in depths of 60m or less is set to continue, which is again due to practical limitations in installing in deeper waters.

Figure 2.4 also demonstrates that projects have tended to be sited within around 50km from shore. This limitation is economic rather than technical and some large projects are proposed at distances of over 100km from shore, taking advantage of developments in high-voltage DC technology which reduces electrical loss on long connections.

Figure 2.4 Illustration of fixed OSW project depth, distance to shore and size

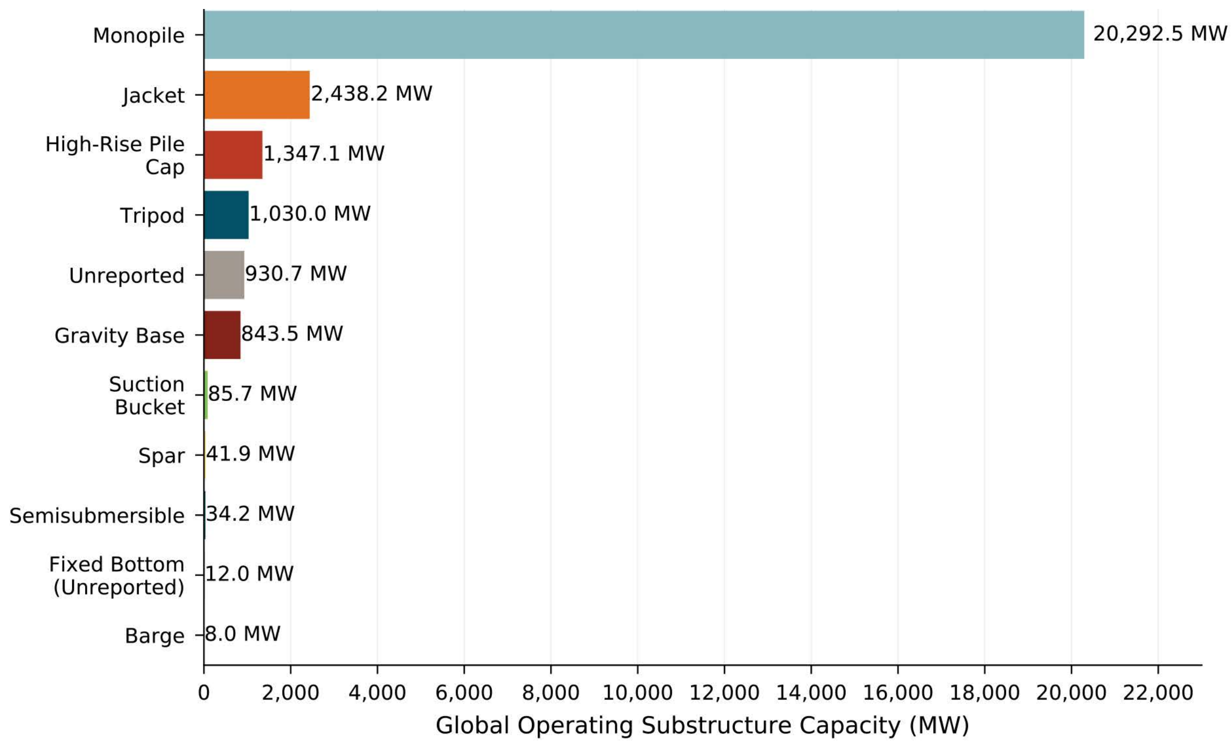


Source: US DOE (2020)

2.2.4 Foundation types

Figure 2.5 below shows the types of foundation utilised in the industry to date. Monopile foundations account for over 75% of turbines installed globally. However other foundation types, in particular jacket solutions, are predicted to increase market share in the near future (NREL, 2020). The predicted shift away from monopile foundations can be attributed to the increasing technical maturity and reducing cost of alternative foundation types relative to monopile solutions.

Figure 2.5 Current share of foundation types utilised in the OSW industry



Source: US DOE (2020)

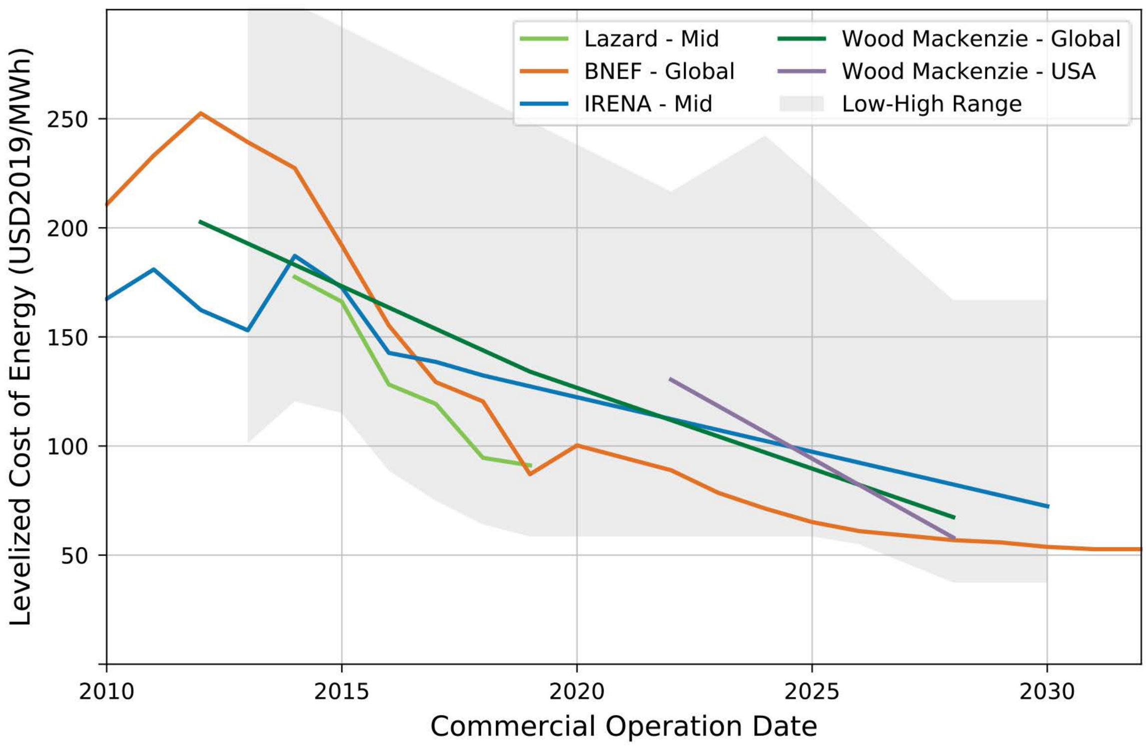
2.2.5 Cost trends

In 2020, the average capital expenditure for fixed OSW projects globally was estimated at less than $4 million USD per MW installed. The turbine element makes up about a quarter of this, with costs estimated at between $0.8-1.2 million USD per MW installed. Other capital-intensive elements are turbine foundation and 'Balance of Plant' which essentially comprises the additional system elements required to connect the turbine to the electrical grid.

In terms of levelised cost of energy (LCOE), fixed OSW has seen dramatic reductions and recent auctions in Europe have delivered costs as low as $0.06/kWh. In China, which adopts a system of annual incremental subsidy reductions, the subsidy for fixed OSW projects has dropped from $0.12 in 2019 to $0.11 in 2020. These costs are significantly below what was thought to be achievable until recently, however, it should be noted that to give context to the figures stated above, both in Europe and China developers can bid in auctions before their projects are operational, and therefore many of the projects bidding into these auctions have yet to be built. Ever improving capacity factors also play an important role in reducing LCOE. Additionally, in recognition of the consistency of the OSW resource, the IEA has also moved to reclassify OSW as a 'variable baseload' rather than 'intermittent' renewable energy technology. It has stated that „Offshore wind's high capacity factors and lower variability make its system value comparable to baseload technologies, placing it in a category of its own – a variable baseload technology" (IEA 2019).

Figure 2.6 shows the overall industry trend and predicted trajectory in terms of LCOE using data compiled from numerous sources (as detailed below the table). The graph shows that from 2012 to end-2020 costs have fallen by around two thirds and sees costs reducing to $0.05/kWh by 2030. Much of this reduction will relate to the development of ever-larger projects of GW-plus scale demonstrating significant economies of scale.

Figure 2.6 Fixed OSW LCOE estimates and forecasts



Source: US DOE (2020)

2.3 / FIXED OSW – OPERATIONAL REQUIREMENTS AND RESOURCE IN REGION

2.3.1 Operational requirements

The following criteria can broadly be assumed to be minimum requirements for a viable fixed OSW project:

- **Wind speed:** A minimum mean wind speed of 5m/s (at hub height) is typically required for a project to be deemed to deliver an acceptable commercial return. By way of validation of this assumption, a global geospatial analysis of OSW potential released by the International Energy Agency (IEA) in October 2019 excluded offshore areas with a mean wind speed below this threshold.
- **Depth:** Fixed OSW projects installed to date have been installed within a depth range of 10m – 60m with the majority of projects installed in depths of around 30m. Above 60m depth the additional cost and complexity of fixing the structure to the seabed means that floating structures become more technically and economically attractive.
- **Distance from shore:** Cabling costs increase as projects are located farther from shore. The cost of

operating and maintaining arrays also increases in line with the distance to a suitable shore base. Larger projects which can bear these increased costs can be located further offshore than smaller projects but the cost implications in general remain. As a result of these factors, projects installed to date have tended to be relatively near-shore (average of 31km in Europe in 2018). Again, IEA geospatial analysis (IEA, 2019) has applied a 60km limit for what it deems to be the 'nearshore' rather than the 'far offshore' extending to 300km.

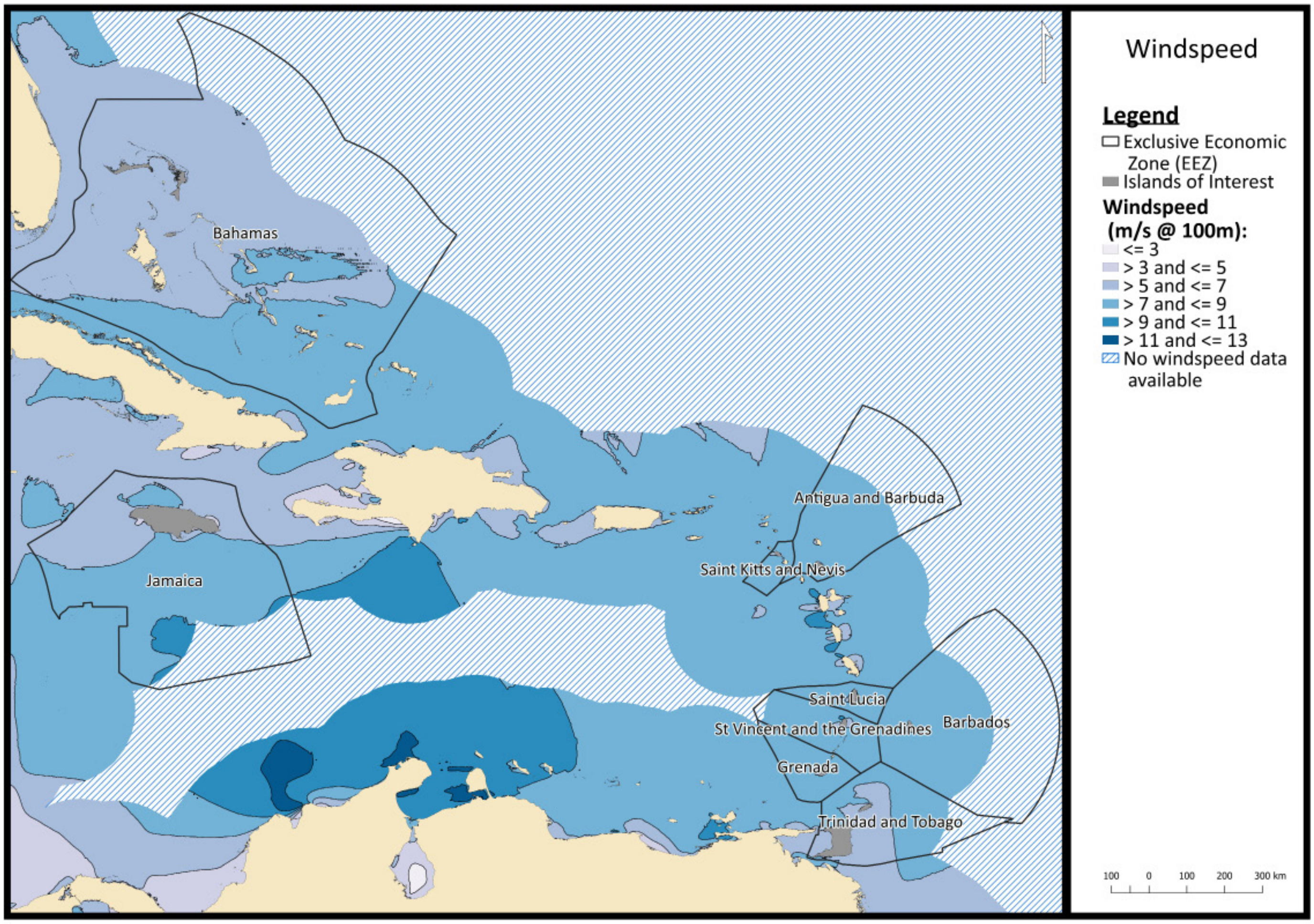
- **Survivability / Design Suitability:** Onshore and offshore wind turbine technology developers offer a range of 'classes' of turbine to suit different deployment environments. It is critical that turbines are appropriately suited to the environments in which they will operate – in terms of available wind speed, severity and frequency of extreme wind events and other factors. One concern that exists regarding OSW deployment in the Caribbean (and also sub-tropical Asia) is the more regular occurrence of extreme weather events such as earthquakes and hurricanes compared with the parts of the world in which the industry has been concentrated to date. Hurricanes present challenges which differ from the regularly extremely windy conditions found in environments such as the North Sea, due to the severity of extreme winds, erratic and gusty conditions and associated storm surges. In recent years turbine manufacturers have innovated in order to respond to these challenges. Successful development of 'typhoon class' or 'hurricane class' machines is vital to meeting the demand in much of Asia and parts of the USA. The size and increasing importance of these markets has acted as a strong incentive for companies to invest in technology development to arrive at appropriately robust solutions. For example in Q2 2020 MHI Vestas placed an order with its parent company Vestas for the supply of 33 x 4.2MW rated typhoon variant V117 turbines for the 139MW Akita Noshiro Offshore Wind Farm Project off Japan. Delivery is scheduled in the second half of 2021 and installation is expected to commence in 2022. Vestas has also launched a 9.5MW ‚Typhoon Class' turbine. According to its developer the turbine can withstand wind speeds of up to 57m/s – equivalent to 205km/h. A category 3 hurricane exhibits sustained windspeeds in the range of 178km/h - 208km/h. In Q2 2021 GE's Haliade-X 12MW and 13MW offshore wind turbines were awarded typhoon certification by independent certification body DNV. The Haliade-X 13MW offshore wind turbine will be used in the first two phases of UK's Dogger Bank offshore wind farm, with a total of 190 units to be installed starting in 2023. Whilst hurricanes of category 3 and above are relatively rare for parts of the Caribbean region this will remain a critical consideration in identifying suitable sites for OSW projects. This is especially important given the link between climate change and potential increases in the severity and frequency of tropical storms and hurricanes in the region combined with potential changes in predominant hurricane trajectories.
- **Geotechnical Considerations:** Large OSW turbines, including tower, blades and nacelle, can weigh in excess of 1000 metric tons. The localized seabed geology must be capable of supporting the weight and associated loadings of such a structure, although the choice of type of foundation can be tailored to suit the conditions to an extent.
- **Supply Chain and Maintenance Considerations:** Specialist heavy lift and 'jack up' vessels are required to install fixed OSW turbines. A cable laying vessel will also be required. These vessels are expensive and are generally in high demand and will continue to be in high demand as industry activity gathers pace globally. Suitable port and hardstanding facilities are also of importance during the construction phase. A fleet of smaller and less specialized vessels, with suitably qualified personnel, will be required to operate and maintain an array.
- **Suitable Cable Landfall and Grid Connection:** A viable project must be located within reasonable proximity

to a suitable onshore location where the project can be grid connected. Natural barriers such as reefs and coastal geographical features can present significant challenges in electrical connection of a project.

2.3.2 Fixed OSW Resource in region

A broad assessment of the offshore wind resource in the Caribbean can be made using modelled data, see Figure 2.7. This shows average wind speeds at 100m hub height (a standard assessment metric for the wind energy industry) ranging between 5m/s and 10 m/s. There is therefore a great deal of variation in wind resource across the region. Most of the region does however appear to have an acceptable or good level of resource, with perhaps the exception of the northern area of The Bahamas. Many areas, particularly those shaded in darkest blue below, could be considered to possess an excellent resource on a par or exceeding that of areas in Europe where projects have already been developed.

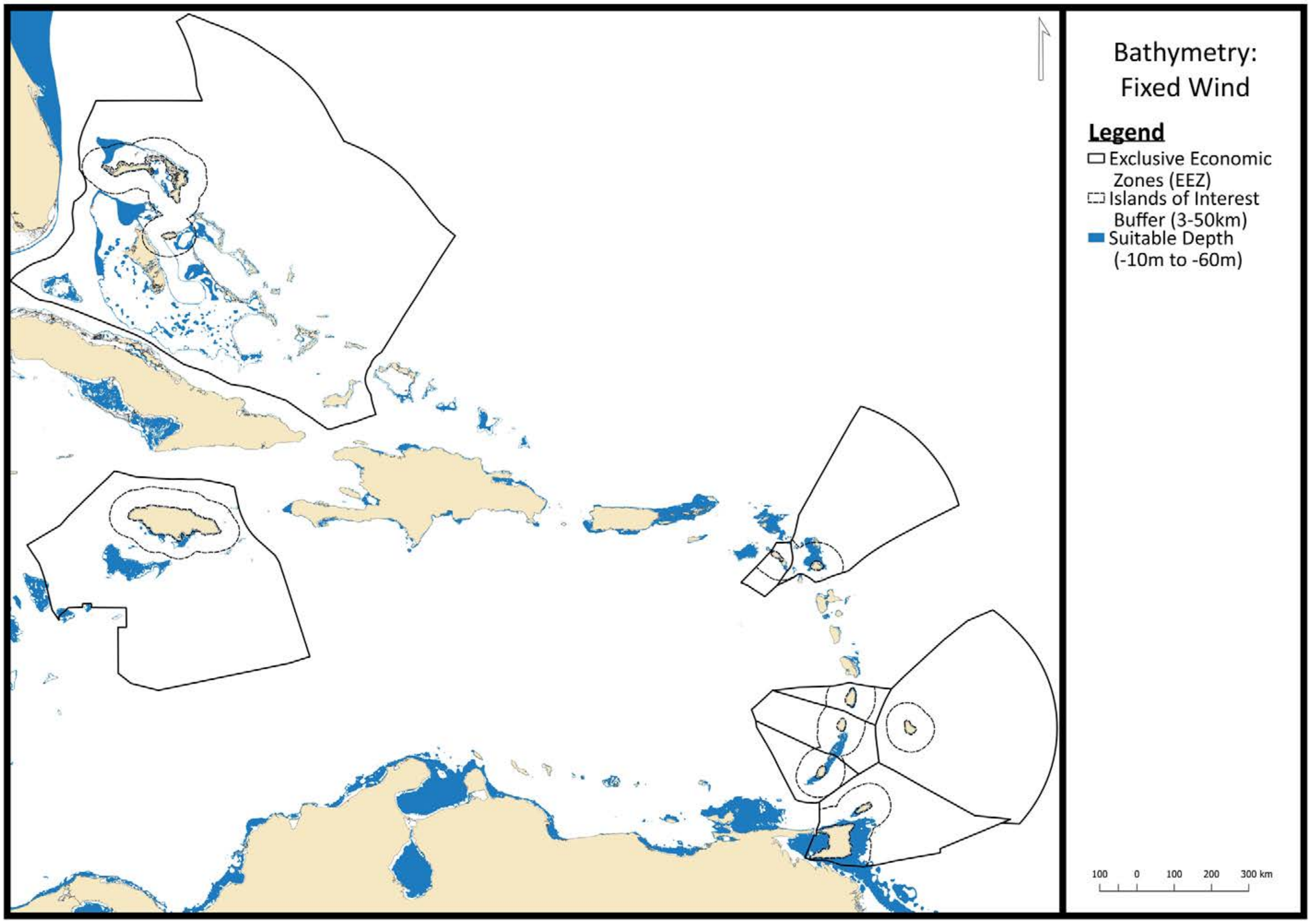
Figure 2.7 Average wind speeds within 200km of land at 100m height



Source: Adapted from Global Wind Atlas (2021)

Looking at suitable sea depths for fixed OSW in the region (Figure 2.8) it can be seen that most countries have a reasonable amount of suitable depth waters in proximity to land. A number of countries however appear to have very limited potential due to steep bathymetry down to deep waters very close to shore. The relative suitability of OSW projects in each COI is discussed in detail in Section 9.

Figure 2.8 Caribbean Sea: areas with suitable sea depth for fixed OSW



2.4 / FIXED OSW – TECHNICAL CONCLUSION

In terms of commercial readiness, the technology for fixed offshore wind turbines is proven and has been rolled out on a commercial basis at a significant scale in Europe and Asia for a number of years and the industry continues to expand rapidly, including a significant pipeline of projects in the US. Despite the definite coexistence of the suitable resource and market conditions in a number of locations throughout Latin America and the Caribbean, there is a notable absence of a near-term pipeline of projects. Fitch Solutions (2021) notes that it expects Latin America will remain an underdeveloped global region for offshore wind through 2030 due to the sector's complexity and infrastructure requirements. This is despite early stage work known to have been undertaken in a number of countries including Brazil, Chile, Trinidad & Tobago, and Jamaica.

Preliminary assessment suggests that the quality of the wind resource in the Caribbean region varies substantially however there are large areas which offer the conditions required for basic project viability. There are additional areas which offer conditions that would be likely to be deemed by developers to be highly attractive in terms of achievable capacity factors.

The availability of suitable sea depth close to land is also highly variable but again there are large areas which look to be well suited to deployment of fixed OSW turbines. It should be noted that investigation of additional geotechnical factors such as substrate type is beyond the scope of this technical note and these factors will further restrict suitability within the broader area of interest. Siting of potential projects to minimise conflict with other users of the sea is an additional key consideration which will affect overall 'extractable' potential.

Clearly a large amount of further work is required in identifying the most appropriate scale and location of fixed OSW projects. Nonetheless considering the readiness and competitiveness of the technology and the quality of resource in the region, fixed OSW is an established technology which is considered to offer significant potential throughout the region. Fixed OSW and other technologies are considered and discussed in greater detail in section 10.3 of this technical note.

/ FLOATING OFFSHORE WIND (OSW)

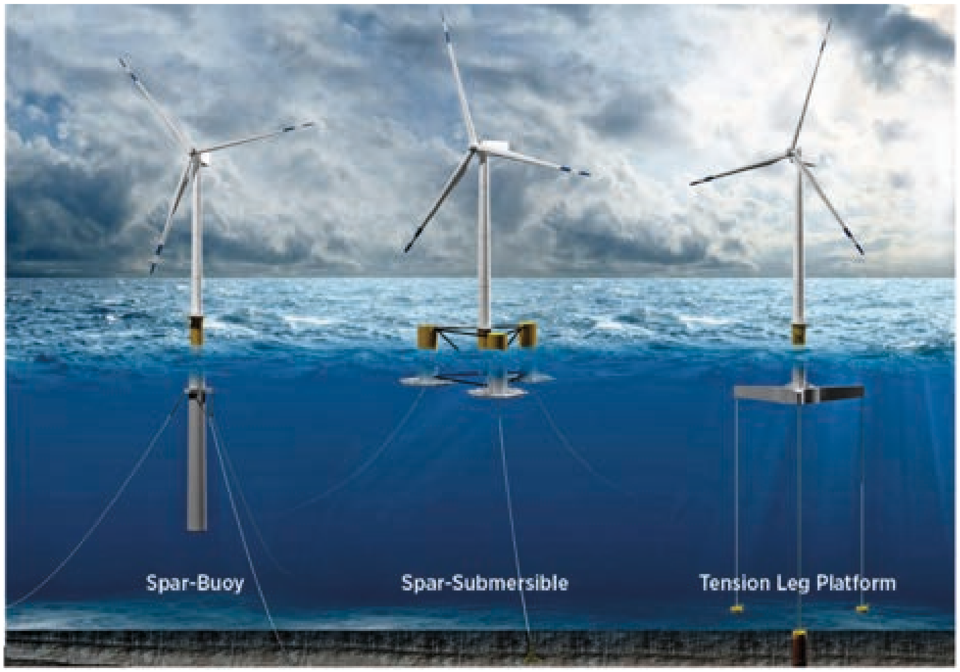
3.1 / FLOATING OSW - OPERATING PRINCIPLE

The operating principle for floating OSW is the same as for fixed OSW (outlined in Section 2.1) except that rather than having a direct weight bearing connection to the seabed, the turbine is installed on a floating structure, which in turn is attached to the seabed via mooring lines. This arrangement facilitates installation in much greater depths of water where, in theory, only additional mooring chain and electrical cable are required to achieve this.

The turbine technology is therefore the same as fixed OSW and indeed all floating turbines installed to date were first designed for fixed projects. Beyond the turbine element, some consideration is required for floating turbines to take account of how the movement of the platform (which is only moored rather than solidly fixed to the seabed) can create additional forces or loads on the equipment and anchoring system. Numerous concepts exist and have been tested for the floating platform and mooring elements of the technology. These tend to utilise well understood technologies and methodologies adapted from the offshore oil and gas industry. According to the Global Wind Energy Council there are approximately 40 concepts actively under development (GWEC 2020).

Examples of some platform and mooring systems are outlined in Figure 3.1. Because floating OSW can be installed in deeper waters and is less site specific than fixed OSW the technology opens up new markets for development, can aid in accessing better wind resource, can further lessen the potential for visual impact, and further mitigate concerns relating to competition for land use.

Figure 3.1 Example foundation systems used for Floating OSW



Source: Adapted from IRENA (2016).

3.2 / FLOATING OSW - DEVELOPMENT STATUS

The floating OSW sector is at a somewhat earlier stage of development than the fixed OSW sector, but the overall market potential is in all likelihood much greater because floating OSW offers the potential to open up new markets and sites in deeper water with less favourable geotechnical conditions which cannot readily be accessed using fixed wind technology.

Research into floating OSW technologies for deeper water sites began in the mid-1990's. Floating OSW technologies are approaching commercial readiness and could be considered to be now emerging from a pre-commercial demonstration stage ready for large scale deployment. A number of individual full-scale prototypes have been successfully installed and demonstrated individually and also as part of the first array projects in a small number of countries.

A significant number of floating OSW projects are being progressed around the globe and are expected to be operational by 2025.

Due to the ongoing success and commercial maturity of fixed OSW, it can reasonably be assumed that the floating OSW sector will continue to experience rapid technical development. Progress to date has reinforced this assertion. Key elements related to the development status are discussed below.

3.2.1 Global installed capacity & leading markets

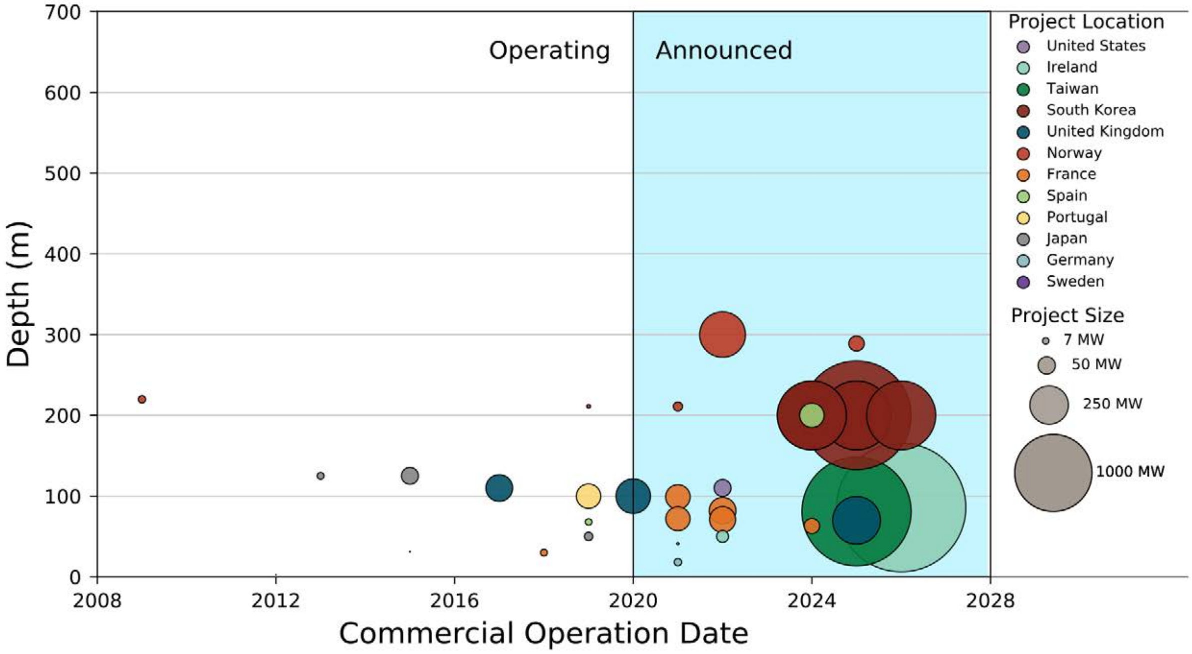
The floating OSW industry has been in steady development over the last five years or more, such that as of Q3 2020 there were 15 floating wind projects installed globally with 65.7MW of total capacity fully commissioned and in operation; when projects under construction are added this figure rises to 135MW. Ten projects (116.8MW) are in Europe and five (19MW) are in Japan. The 50MW Kincardine Offshore Wind Farm, partially still under construction at the time of writing, is currently the largest project in the world surpassing the 30MW Hywind project – both in Scotland. In addition, as can be seen in Table 3.1 below, there are 15 floating projects totalling about 1,100GW that are under development around the globe and are scheduled to be constructed by end 2025.

Table 3.1 Global Floating OSW project pipeline

Project name	Location	Capacity (MW)	Installed
Operational Projects as of end 2020			
Hywind Demo	Norway	2.3	2009
WindFloat 1 Prototype	Portugal	2	2011
Kabashima Floating	Japan	2	2013
Fukushima FORWARD	Japan	2	2013
Fukushima FORWARD	Japan	7	2016
Hywind Scotland	UK	30	2017
Floatgen	France	2	2017
Fukushima FORWARD	Japan	5	2017
Kincardine	UK	2 (testing)	2018
Hibikinada KitaKyushu Demo	Japan	3	2019
PLOCAN Test Site	Spain	0.2	2019
WindFloat Atlantic	Portugal	25.2	2020
Nezzy2 Floating	Germany	1.5 (testing)	2020
Kincardine	UK	48	2020
TetraSpar Demo	Norway	3.6	2020
Projects Under Planning or Construction by 2025			
EolMed project	France	24.8	2021
Provence Grand Large floating	France	25.2	2021
DemoSATH	Spain	2	2021
Hywind Tampen	Norway	88	2022
Atlantic Marine Energy Test Site	Ireland	30	2022
CTG first floating tender	China	10	2022
Les Éoliennes Flottantes du Golfe du	France	30	2023
Groix Belle Ile wind farm	France	28.5	2023
Aqua Ventus	USA	12	2023
Goto (GCS) Floating	Japan	21	2023
Celtic Sea Floating	UK	32	2024
Donghae 1	South Korea	200	2024
Equinor floating Canary Islands	Spain	200	2025
Sicilian Channel TetraSpar floating	Italy	250	2025
Redwood Coast offshore wind project	USA	150	2025
Projects Aiming to be Operational by 2030			
JERA, Ademe and Ideol	Japan	2000	
Equinor & KNOC floating projects	South Korea	800	
Ulsan 1GW floating	South Korea	1000	
Equinor floating project	Greece	300	
FLAGSHIP Iberdrola	Norway	10	
Erebus demonstration (TOTAL) project	UK	96	
Parque Eólico Gofio	Spain	50	
Industry proposed floating projects	Norway	1000	
Celtic Sea Floating	UK	1000	
French floating auctions	France	750	

Looking beyond 2025, the precise project outlook is less defined but there is a marked tendency towards much larger projects approaching the GW scale. This trend is clearly depicted in Figure 3.2 which shows Installations to date and global pipeline for floating OSW to 2030.

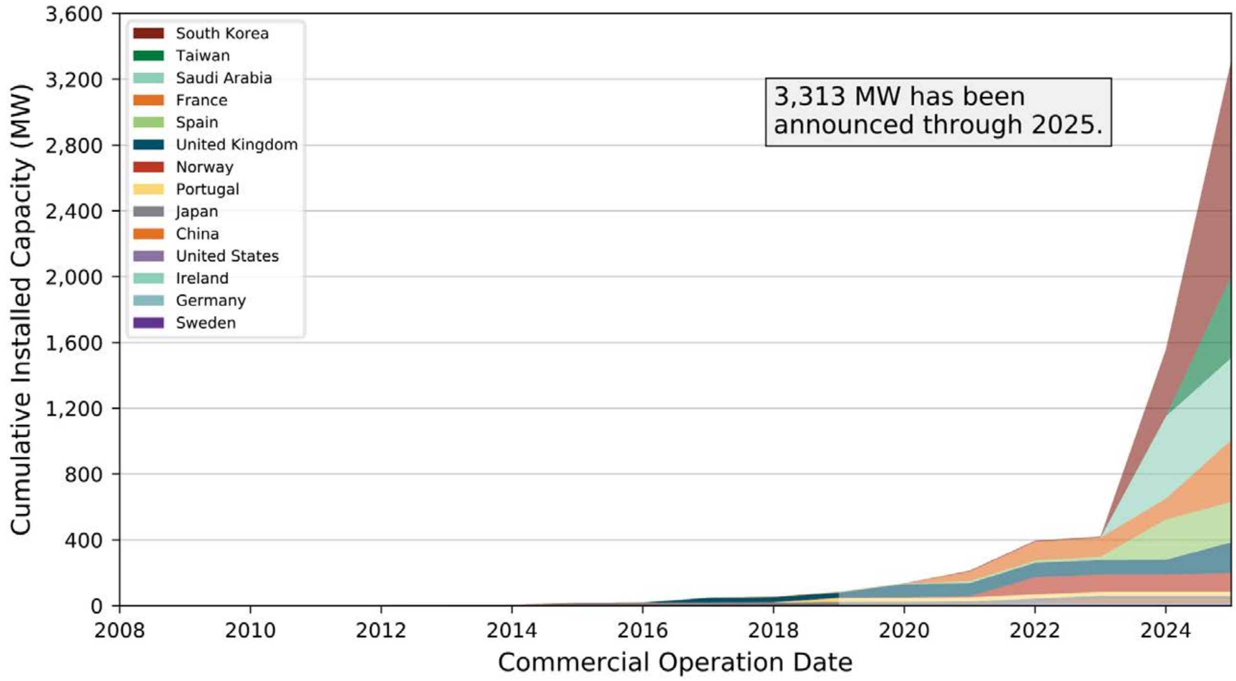
Figure 3.2 Global Floating OSW installations and pipeline (as of 2020)



Source: US DOE (2020)

The pace at which the global floating OSW pipeline has expanded in recent years is remarkable with a pipeline comprising 7,663 MW of capacity in 2020, growing by nearly 3,000 MW relative to the pipeline as calculated in 2019 (US DOE, 2020). Figure 3.3 below provides an interesting comparison of activity in the sector to date versus projected upcoming installations. This graphic also gives a breakdown of which regions and countries are expected to play the biggest roles to 2030 in terms of hosting large scale projects. Spain, Japan and South Korea in particular are projected to account for the largest projects by the end of the current decade.

Figure 3.3 Cumulative annual floating OSW capacity by country 2019 to 2025



Source: US DOE (2020)

Interestingly, floating OSW developments are not solely focussed on supplying electricity to the grid. 'Power-to-X' whereby surplus large scale renewable generation is applied direct to an existing industrial application is increasingly being seen as an important future driver. In the case of floating OSW enabling access to deeper sites further offshore means that, for example, floating wind is gaining interest from oil and gas companies looking to plug into renewables to reduce costs and carbon footprint from offshore production facilities. The 88MW Hywind Tampen project 140km offshore from Norway in 300m of water is an example of such a project. This project is scheduled for completion in 2022.

3.2.2 Turbine sizing trends

To date, is it understood that all turbines used in floating OSW projects have been designed for fixed OSW as the market size has not been sufficient to stimulate development of specific, fully optimised floating models. That said, there is now a significant pipeline, and manufacturers are understood to be undertaking advanced development work towards commercially ready floating models, with a reduction in overall system weight likely to be desirable. There is not enough market information to assess turbine size trends in any detail; however, the same imperative to increase the number of MWs on each foundation exists and it can be expected that the market will drive for ever larger turbines. The Hywind Scotland and Kincardine array projects use 6MW and 9.5MW turbines respectively which is largely in line with the industry standard range seen in the fixed OSW market

3.2.3 Depth and distance from shore

Figure 3.12 in Section 3.2.1 shows that the vast majority of floating OSW projects are proposed at depths of less than 200m, although some large projects are proposed at up to 300m depth. The technological feasibility of installing in deep waters is largely not in question as the oil and gas industry has been installing structures such as Floating Production, Storage and Offloading (FPSO) platforms in very deep water in for many years. However, installing in such depths, whilst opening up new markets, will have an associated cost penalty. Interestingly, sites which are overly shallow can also be problematic for large floating structures as these are generally 'slack' or catenary moored in order to provide passive load dampening. Taut moored systems, using shorter mooring lines, do not tend to be favoured for mooring of large floating structures in energetic environments.

No complete data was available as regards the distance from shore at which developers intend to locate proposed floating OSW projects; however, it is likely that similar economic and practical constraints to fixed OSW projects will exist. This means that whilst there are no insurmountable technical barriers to going farther offshore, doing so will come at a financial cost as installation, interconnection and operations will be more challenging and time consuming. Analysis of the fixed OSW industry showed that most projects stayed within 60km of shore. Significant economies of scale (i.e. very large projects) are likely to be required for an OSW project, either fixed or floating, to make sense at greater distances, unless purposed to supply power to offshore oil and gas assets. The increasing trend for ever larger projects of GW-plus scale does make the prospect of projects far-offshore seem more feasible in the medium to long term.

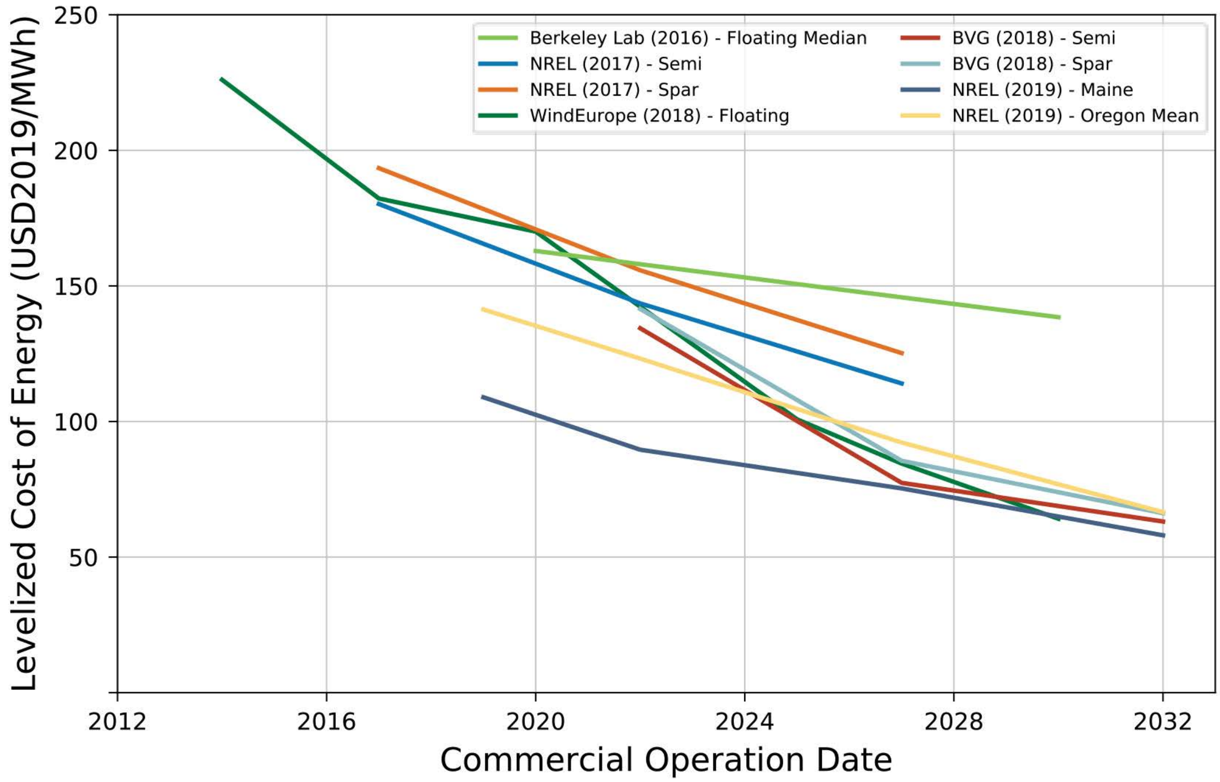
3.2.4 Foundation trends

Of the various platform types for floating OSW around 90% of projects in the pipeline propose using semisubmersible technology (US DOE, 2020). This technology appears to be favoured due to its familiarity and the benefit that turbines can be installed on the substructure close to shore in relatively shallow water, before being towed out to shore. This technology has the added advantage of avoiding the need for heavy lift offshore construction vessels or deep-water ports and suitably large onshore facilities. This is more challenging for other platform types, such as spars, which require a much greater depth of water to float. That said, the second largest existing project (the 30MW Hywind project in Scotland) does use spar platforms, and spar technology is projected to continue to be used in selected instances in the future. Platforms are generally fabricated from steel although concrete structures have also been used and are touted by some technology developers as offering cost reduction potential in serial production.

3.2.5 Cost trends

As shown in Figure 3.4, floating OSW LCOE over a range of studies was estimated at between \$0.11 and \$0.17/kWh in 2019 and across all estimates is predicted to reduce to around \$0.06/kWh by 2032 (US DOE, 2020). This level of strong cost reduction will make floating OSW highly cost competitive with other forms of renewable energy in many locations. Due to the relatively nascent nature of the industry no further breakdown of CAPEX or operational costs is available.

Figure 3.4 Floating OSW LCOE estimates and forecasts



Source: US DOE (2020)

3.3 / FLOATING OSW – OPERATIONAL REQUIREMENTS AND RESOURCE IN REGION

3.3.1 Operational requirements

The following criteria can broadly be assumed to be minimum requirements for a viable floating OSW project. These are largely similar to fixed OSW with some important exceptions.

- **Wind speed:** As with fixed OSW, a minimum mean wind speed of 5m/s (at hub height) is typically required for a project to be deemed to deliver an acceptable commercial return. Floating OSW projects are installed in deeper waters than fixed projects (so generally further offshore where the wind resource will usually be stronger).
- **Depth:** Floating OSW can be deployed in depths of 60m or greater where fixed OSW is no longer technically feasible. For the purposes of this study projects can be notionally split into 'conventional' installed in depths of up to 200m and 'deep water' installed in depths of 200m – 1000m. Most developers are focusing on conventional projects to prove their technology; however, a handful are directly targeting deep water markets – such as Japan and island groups including Hawaii – in an effort to gain first-mover advantage over competitors.

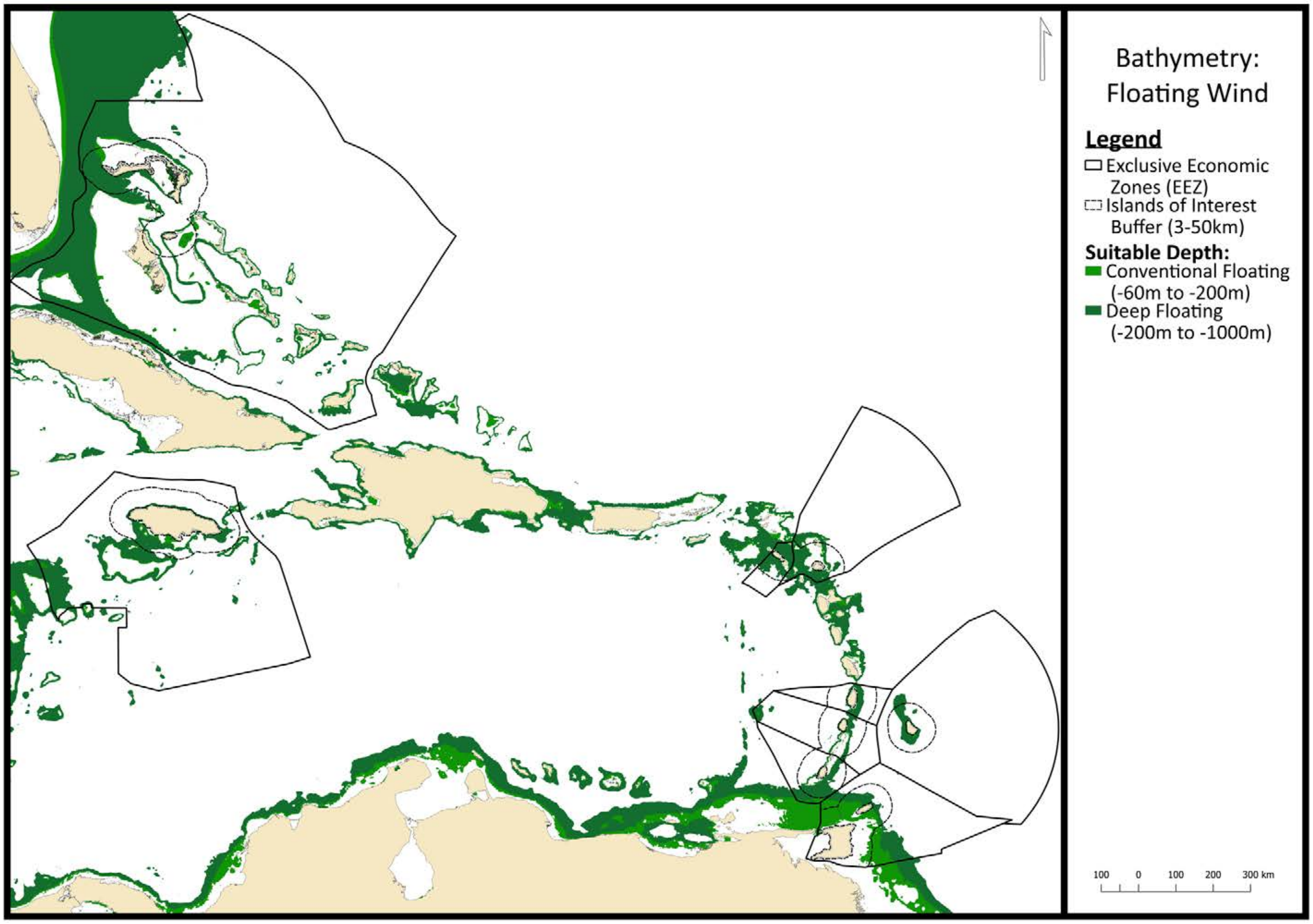
- **Distance from shore:** Cabling costs for fixed and floating OSW projects are much the same. Most projects, with the exception of the very largest which will utilise HVDC technology, will be classified as 'nearshore' in that they will be situated within a reasonable distance from shore of 60km or less.
- **Survivability / Design Suitability:** Extreme winds and storm surges present additional challenges for anchored floating structures offshore which have yet to be fully resolved. These issues generally vary by site and will be addressed by the project developer. The first mitigating action will always be to carefully site projects to minimize exposure. This issue is one that the industry is tackling 'head on'. As discussed in Section 2 leading offshore wind turbine developers have developed innovative models which can withstand extreme wind events. These turbines will be installed in upcoming projects (pre-2025) in Asia where the occurrence and risks posed by typhoons will be a critical consideration. Later projects will have the benefit of learning gained as part of these efforts.
- **Geotechnical Considerations:** Large floating OSW turbines plus foundations can exceed the weight of fixed OSW variants which in themselves can weigh in excess of 1000 metric tons. Although floating turbines are not directly in contact with the seabed, local conditions must be conducive to reliable anchoring of such structures.
- **Supply Chain Considerations:** Whereas specialist, in demand heavy lift and 'jack up' vessels are required to install fixed OSW turbines, this is not necessarily likely to be the case for floating OSW. Floating structures can potentially be assembled either on land or just offshore and be towed to site using a suitable, albeit still specialist, vessel – this is likely to provide some cost savings when compared with fixed OSW. Also this is likely to impact positively in that less extensive onshore port facilities are likely to be required than is the case with fixed OSW. As with fixed OSW, a fleet of smaller and less specialized vessels, with suitably qualified personnel, will be required to operate and maintain an array.

3.3.2 Floating OSW Resource in region

The wind resource for floating OSW largely matches that for fixed OSW (as discussed in Section 2). The resource across the majority of the region is therefore assessed as varied but generally acceptable or good for most locations. As with Fixed OSW some of the windiest locations could be considered to be excellent in global terms but it should be noted that some level of variation can be expected on a more site-specific level. Projects utilising floating technology in deeper water are likely to benefit from a minor increase in mean wind speed compared with fixed turbines if located further from shore.

Looking at suitable sea depths for floating OSW in the region (Figure 3.5) it can be seen that the available area for conventional floating (60-200m depth) is less than for deep floating (200-1000m). This is intuitive due to the wider depth range for deep floating OSW. There is a high degree of variability in water depth throughout the region, but most countries have some water depths suitable for conventional fixed floating wind technology at reasonable proximity to land although the scale of projects that can potentially be hosted within this depth range varies by country to country. Indeed, the naturally steep bathymetry down to deep waters close to shore makes the Caribbean generally very attractive for floating OSW deployment in terms of proximity to shore. As a result, projects utilising floating rather than fixed wind technology will be much less constrained in terms of where they can be deployed and overall scale of project. The relative suitability of floating OSW projects in each COI is discussed in detail in Section 9.

Figure 3.5 Caribbean Sea: areas with suitable sea depth for floating OSW



3.4 / FLOATING OSW – TECHNICAL CONCLUSION

In terms of commercial readiness, there are now several operational floating wind demonstration projects globally in Europe and Asia. Research carried out in the production of this technical note and prior industry consultation suggests that these projects have delivered upon expectations and the core technology has fared extremely well. However, the number of floating OSW concepts under development is evidence of a lack of commercial and technical maturity and there is still some way to go until full industrialisation and standardisation across the industry. Therefore, this technology still falls short of convergence on an industry agreed optimum approach and does present more of a technical and commercial risk than fixed OSW.

As with fixed OSW, preliminary assessment suggests that the quality of the wind resource in the region varies substantially but is in the main 'attractive' and in some areas could be considered to be excellent. The availability of suitable sea depth for conventional and deep floating OSW relatively close to land is generally more favourable for floating rather than fixed wind technology. It should be noted that investigation of additional geotechnical factors such as ruggedness and substrate type is beyond the scope of this technical note and these factors will restrict suitability within the broader area of interest – although floating OSW is less sensitive in this regard than fixed OSW. As with fixed OSW, siting of potential projects to minimise conflict with other users of the sea is an additional key consideration which will affect overall 'extractable' potential – again this tends to become less of an issue as projects are installed further from shore.

Floating OSW appears to be a suitable technology option and a highly attractive proposition in the Caribbean from both a wind resource and depth perspective. There are additional attractions with the technology in that vessel and onshore port requirements are less exacting than for fixed OSW and it is not excessively constrained by sea depth, meaning that projects can potentially be located further from shore thus reducing visual impact. These factors and others will be discussed in greater detail in section 10.3 of this technical note.

/ OCEAN THERMAL ENERGY CONVERSION (OTEC)

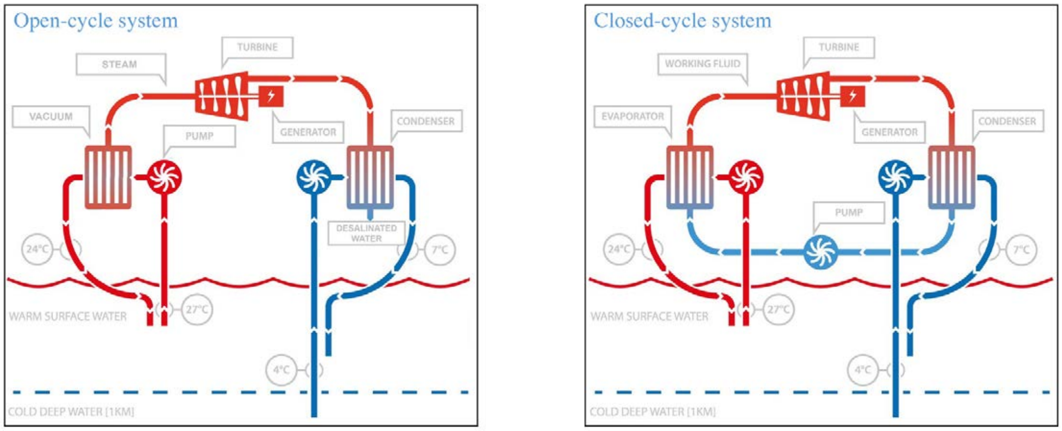
4.1 / OTEC - OPERATING PRINCIPLE

OTEC is a form of large-scale heat pump technology which utilises the difference in temperature between surface and deep-water layers of the ocean. This difference in temperature is created by solar energy stored as heat in the upper layers of the ocean and is therefore generally greatest in warmer tropical regions. OTEC technologies pump warm water from the surface layer and cold water from the deep ocean (generally around 1000m deep) to a generation plant which can be located either onshore or on an offshore platform. Electricity generation is achieved via an open-cycle system, a closed-cycle system or a hybrid system. The operating principles of each are;

- In an open-cycle system warm seawater is vaporised in a vacuum (to create steam) which drives a turbine and is condensed on the other side of the turbine using cold seawater. A useful by-product of this system is that the water exiting the turbine is desalinated.
- A closed-cycle system operates in a similar manner except that instead of seawater flowing through the system, a working fluid with a low boiling point (such as ammonia) is used with hot and cold seawater used to evaporate and condense the working fluid which is recycled in the closed-cycle.
- In a hybrid system warm seawater is turned into steam in a vacuum chamber (just as in an open-cycle system), but the resulting steam is used to vaporise a working fluid in a closed-cycle system which drives a turbine. The rational for the hybrid system is that the perceived technical benefits of the closed-cycle system can be had whilst at the same time also generating desalinated water as a useful by-product.

A schematic diagram of an open-cycle and closed-cycle system are provided in Figure 4.1.

Figure 4.1 Open-cycle and closed-cycle OTEC systems



Source: Adapted from Bluerise (2016).

Figure 4.2 shows what an OTEC project may look like in practice. It illustrates a 10MW offshore closed-loop project with a barge moored in deep water hosting heat exchangers, pumps and a generator, pipes suspended underneath down to 1000m, and a subsea cable transmitting the electricity generated back to shore.

Figure 4.2 Illustration of a 10MW floating closed-loop OTEC project

Source: Naval Group (2014)

OTEC technology, in contrast to intermittent or variable renewable energy technologies, has the potential to produce baseload (steady) electricity generation at a high-capacity factor (up to 90% or higher). The system can also theoretically be configured to derive added value from ancillary activities such as:

- Potential production of fresh water (in open loop or hybrid systems)
- Use of waste cold sea water to run sea water air conditioning (SWAC) plant (see Section 5)
- Use of waste cold sea water to run underground pipes in soil for chilled-soil agriculture
- Use of waste cold sea water (which is nutrient rich) for aquaculture

4.2 / OTEC - DEVELOPMENT STATUS

The OTEC sector can be described as being in an early pre-commercial phase where some technology R&D activity is underway at present. The technology itself is not new and a small number of individual single scale prototypes have been installed over several decades and operated over a limited time. Single scale prototypes have often doubled as Seawater Air Conditioning (SWAC) prototypes. Developmental work is thought to be underway on a handful of industry-leading commercial projects however, only a very small number of these are expected to be operational by 2025 and there appears to be a trend of proposed projects stalling.

In terms of the historical development of the sector, the very first project is thought to date to 1930 in Cuba. The first operational OTEC projects in the modern era were installed in the 1970s with a resurgence in technology and project development since the beginning of the 2000s. Projects have tended to focus on attempting to address power generation, cooling and seawater desalination issues for islands in tropical regions. Selected projects installed to date include:

- **Japan, Imari** - 30kW multi-use plant operational from 2003.
- **Japan, Okinawa** - 50kW plant completed in 2013.
- **United States, Hawaii** - 103kW closed cycle system at the Natural Energy Laboratory in Hawaii in 1979.
- **United States, Hawaii** - 1MW open cycle plant operated in Hawaii between 1993 and 1998.
- **South Korea, Busan** - 1MW capacity floating barge unit installed and tested by the Korea Research Institute of Ships and Ocean Engineering (KRISO) for a few days in September 2019 with 370kW gross power achieved before conclusion. The system will next be transported to Kiribati for installation. This was originally slated for late 2020 and is now expected to take place during 2021.

A small number of commercial projects are now in development. As well as the KRISO project mentioned above the National Institute of Ocean Technology (NIOT) in India is known to be developing an OTEC power desalination plant at Lakshadweep Island capable of desalinating 100m3 of seawater per day. These 'pathfinder' projects, if successful, will be absolutely critical in demonstrating that OTEC technology can deliver on its technical promise and pave the way for large scale project replication.

Due to the nascent nature of the OTEC industry there are no suitable industry reports or market analysis data sets available for analysis. As such the IDB previously commissioned industry engagement via questionnaire to gain a complete picture of the industry. This work has been more recently complemented by further industry engagement and desk-based research to garner the latest information. Responses to industry consultation were provided in confidence and as such cannot be published however some interesting, more generic points arising from the exercise are outlined below:

- The information gathering exercise revealed the various OTEC developers active in the sector at the time, in general, in a positive light.
- Comparing the analysis carried out in 2017 with the more recent update work there does however appear to be a trend of proposed projects stalling. No significant progression can be seen on many of the projects in development. Notably, some of the leading companies consulted with have since ceased their projects or have exited the sector entirely.
- The largest capacity project built to date is the 1MW open cycle plant operated in Hawaii from 1993 to 1998. The largest currently operational plant is also in Hawaii and is rated at 103kW. The relatively recent short test of a 1MW floating barge OTEC plant in South Korea by KRISO is however notable and the success or otherwise of its proposed installation in Kiribati could be a critical determinant in how the industry progresses.

- Despite challenges in getting large scale projects financed, an early-stage global project pipeline does exist with feasibility assessments having been conducted for a number of tropical island locations.
- All projects built to date have been onshore except for the recent test in Korea.
- All technology developers which responded to the consultation are focused on closed-loop OTEC technology due to the increased efficiencies that this variant offers. A pure closed-loop system limits the potential for production of fresh water as a by-product of the process to running desalinisation plant with the electricity generated. Plants located offshore, whilst looked upon favourably on in terms of reducing the LCOE, create logistical limitations in terms of delivering ancillary benefits such as production of fresh water and SWAC potential.
- Some technical effort is still being directed towards development of open and hybrid systems, but this is largely at an early conceptual stage. For example, Japanese and Malaysian engineers are known to be currently collaborating on design and demonstration of a 3kW hybrid system for installation in Malaysia (OTECnews, 2021).
- Technology developers seem to have largely converged on offshore OTEC plants for future commercial projects due to cost savings achievable although this does limit the availability of hot or cold water for secondary use (such as SWAC) onshore. However, a trend can be seen whereby developers are now expressing an openness to onshore projects where added value from ancillary benefits can be more readily achieved.
- All technology developers have indicated an intention to focus on developing projects ranging from 0.5-10MW net power. It seems that this level of output needs to be proved before moving to larger projects.
- Technology development focus in general seems to have been concentrated on heat exchanger and large-scale pumping plant. Less attention seems to have been paid by many of the developers to the installation, anchoring and operation and maintenance of the piping infrastructure although some companies do specialise in this aspect. There seems to be a general stance within the industry, which is reasonable, that if the engineering challenges around the core technology can be resolved then the other enabling technology pieces can be drawn from other sectors such as offshore oil and gas.
- OTEC plants use electricity to run the pumps that drive the process. This leads to a parasitic load of about one third of the electricity generated. Some developers referred to nameplate capacity of projects based on gross rather than net generation. The quoted achievable capacity factor of 90% or more used in this technical note refers to the net generation figure.

Looking in more detail at the economics of OTEC technology, there is a predictable paucity of information due to the low number of projects constructed and their proprietary nature. The limited studies which have been undertaken also show wide ranges in terms of cost estimates. IRENA (2014) compiles available information to show that estimated capital costs for existing projects and planned projects under 10MW range between about $16 and $32 million USD per MW.

With scale, increased global installed capacity, and a sharp learning curve, it is predicted that costs could however come down to as low as $2.5 million USD per MW by the time 100MW is installed globally. There is therefore a route to delivery of acceptable LCOE from this technology, but it is highly likely that the next phase of projects, if and when built, will have LCOE figures well in excess of current market levels in the region. Therefore, a combination of risk-accepting capital and innovative funding mechanisms applied at scale will be required to fund any first pathfinder projects.

4.3 / OTEC – OPERATIONAL REQUIREMENTS

4.3.1 Operational requirements

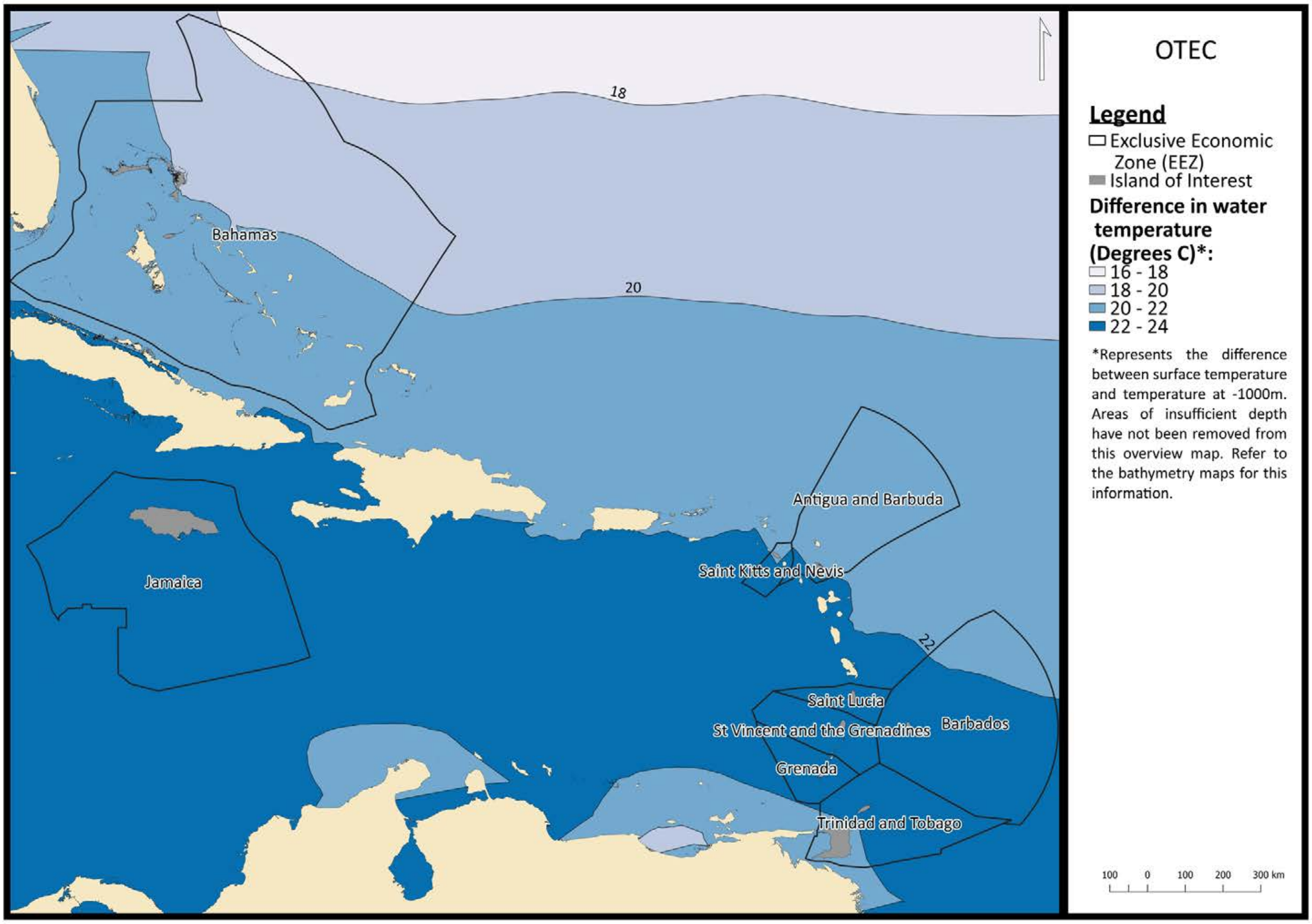
Industry experts contacted during the consultation exercise advised that a temperature differential between sea surface and deep-sea water of 20 degrees centigrade would be required for an OTEC project, with greater temperature differentials likely to yield additional efficiencies. This translates to a basic requirement for sea surface temperatures of around 25 degrees and water depth of 1000m (where water temperature will generally be around 5 degrees) so in practical terms OTEC is only suited to tropical regions.

Bathymetry is also a key factor for OTEC projects with the need to access deep cold water as close to shore as possible. Industry consultation suggests that reaching 1000m depth within 10km of shore is desirable for project economics, although there is no technical reason why it wouldn't be possible to operate an OTEC plant at much greater distances from shore.

4.3.2 Resource in region

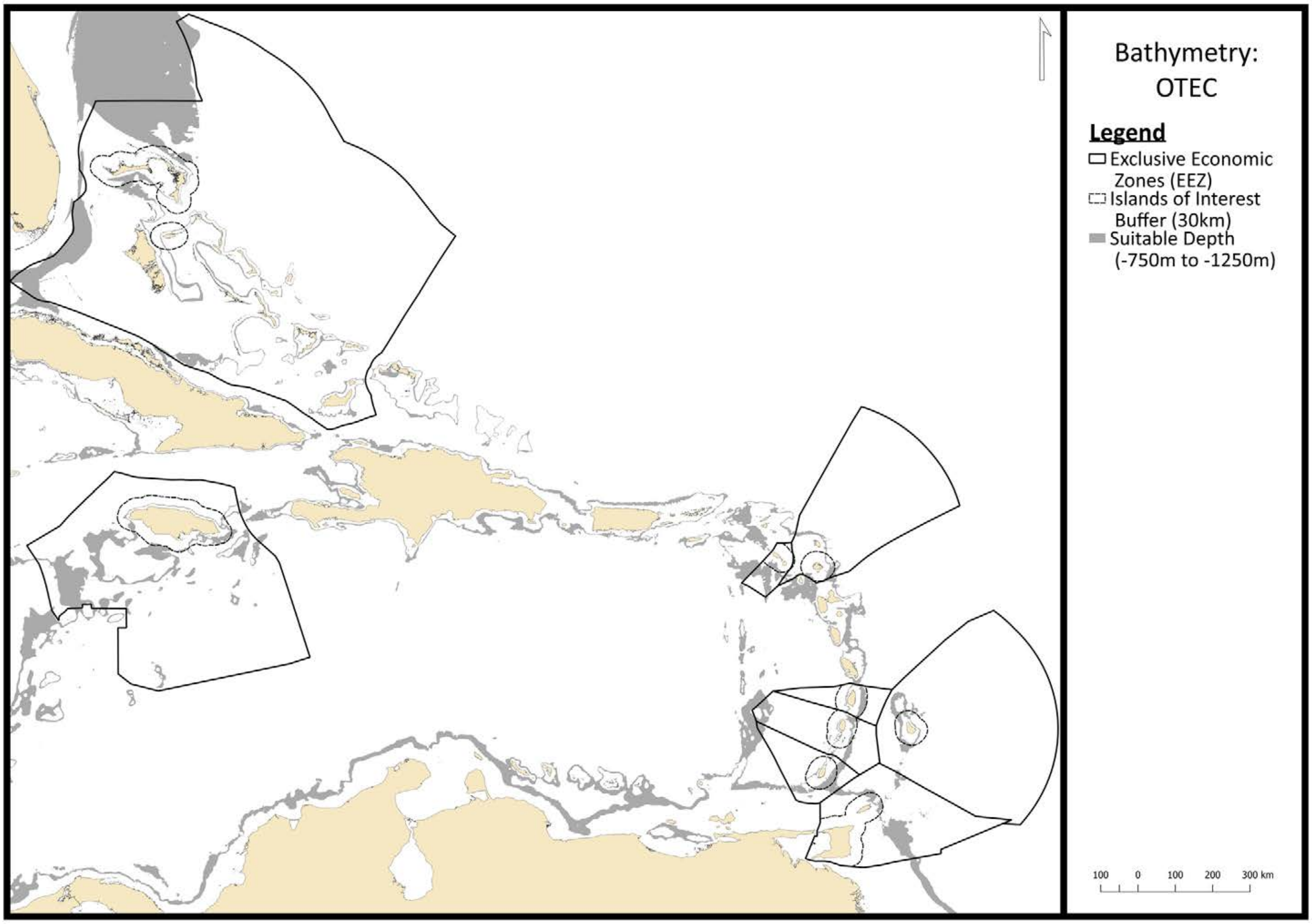
OTEC requires an overall temperature differential between sea surface and working water depth of about 20 degrees centigrade. This has been explored for the Caribbean in Figure 4.3 using interpolated data from the World Ocean Atlas (2018) which compares average ocean surface temperatures with the average temperature at 1000m deep. As one may intuitively expect, this shows that the temperature differential and suitability for OTEC generally decreases with distance from the equator and shows that the vast majority of the Caribbean seems to have high resource suitability for OTEC.

Figure 4.3 Relative resource potential for OTEC in the Caribbean



A depth of 1000m is generally sought for in locating OTEC plants and a range of between 750m and 1250m is considered appropriate for identifying candidate areas. Figure 4.4 presents all areas with suitable depth in the Caribbean for OTEC plants and these can be seen to be fairly widespread. In practical terms developers would look for locations with suitable depth and temperature as close to shore as practical and within close range of a substantive electrical grid connection or demand centre and port facilities for operations and maintenance. The relative suitability of OTEC projects in each COI is discussed in detail in Section 9.

Figure 4.4 Caribbean Sea: areas with suitable sea depth for OTEC (or SWAC)



4.4 / OTEC – TECHNICAL CONCLUSION

OTEC is a highly promising technology concept, but significant technology development work remains with no MW scale device having been proven in long term operation despite significant efforts dating back over a 50 year period. The industry is therefore still in an early demonstration phase and there are no commercially available OTEC solutions on the market at present or on the horizon.

There are several areas of the Caribbean which possess an excellent thermal resource with access to deep waters in close proximity to shore. The required temperature differential exists year-round and, in terms of potential for ancillary benefits, there is sure to be a strong match with year-round cooling demand at any given number of sites throughout the region.

Despite the strong resource and potential for baseload electricity and cooling supply there would be very real challenges and issues to resolve in order to deploy OTEC at scale in the region in the near to medium term. Not least of these is the very high capital cost coupled with the fact that any funder of or lender to such a project would need to have an acceptance of the technical risk involved.

The core premise of the technology is sound and in the long term, with sufficient technical progress, OTEC could prove to be a transformational technology for the region and elsewhere - however the timescales required to develop this technology mean it is an unsuitable choice for tackling the immediate need to substantially decarbonise energy generation in the region. OTEC and other technologies are further considered in section 10.3 of this technical note.

/ SEA WATER AIR CONDITIONING (SWAC)

5.1/ SWAC - OPERATING PRINCIPLE

SWAC systems utilise thermal energy contained in bodies of water such as rivers, lakes and oceans to provide heating or cooling. In cold climates the relative warmth of nearby water can be harnessed in a heat pump whereas in warm regions with cooling demand cool waters are used in the same way. The commercial proposition is that the technology, rather than using electricity to cool (or heat) the refrigerant in air conditioning systems, a comparatively lower amount of electricity can be used in pumping water around the system, leading to financial savings through improved energy efficiency and associated energy savings. SWAC systems are therefore generally well suited to consumers situated close to shore with large heating or cooling demand.

From the perspective of application of the technology in the Caribbean, SWAC systems would seek to utilise cold seawater from the deep ocean in a heat exchanger onshore to directly cool fresh water (or another working fluid) which could be used in traditional air-conditioning systems in buildings or district cooling systems. In doing so SWAC offers the potential for year-round supply of cost-effective cooling. The technology can also be complementary to OTEC in that the waste cold seawater from an OTEC cycle can be used in SWAC systems.

5.2 / SWAC - DEVELOPMENT STATUS

SWAC can be considered to be in a pre-commercial or early commercial phase where a significant amount of technology R&D activity has been undertaken, and a small number of individual projects have been deployed globally over a number of years. When heating as well as cooling projects are included in a global project count it can be said that there is a substantial base of projects installed and operational over a number of decades. There is however substantial variety in the operational projects, with many tapping in to close-to-surface water for heating or cooling purposes, some utilising deep lake water, and others using deep sea water. Generally, projects using surface fresh water would be viewed as more straightforward due to the lack of the need for deep water pipelines and corrosion protection from salt-water.

A typical SWAC project in the Caribbean, whilst using the same core technologies and principles, would be viewed as more complex due to the requirement to pump seawater from significant depth (~1000m) and considerations around ocean exposure and wave action. Existing projects are also not homogenous because of the specific geographical and resource conditions and cooling or heating demands of the host location. These differences in technical complexity, resource, and demand mean that viability must be carefully assessed on a project-by-project basis. In the context of the Caribbean, with generally high energy prices and consistent year-round demand for cooling, SWAC could be deemed to be closer to commercial readiness than many locations elsewhere, notwithstanding detailed technological considerations.

One SWAC specific study released by the CAF Development Bank in 2015 (CAF, 2015) analysed eight sites on four Caribbean islands. Sites in Montego Bay, Jamaica, and Puerto Plata, Dominican Republic, were selected for further modelling and assessment. This analysis concluded that these sites are “excellent candidates” for application of the technology and that SWAC could offer a significant financial savings to customers at these sites of around 50% over conventional air conditioning.

There are a small number of operational SWAC projects located on islands in tropical regions typically serving larger tourism centres such as hotels. There are also other larger projects said to be in the advanced development stage. Information on larger public utility type projects is generally freely available online or presented at conferences; however, detailed information on private projects is very limited.

Selected SWAC projects installed on islands to date include but may not be limited to:

- **French Polynesia, Bora Bora** - SWAC system installed in the InterContinental Hotel in 2006. Limited public information is available although it has been reported that this system has been out of service for approximately five years (Energies de la mer, 2021).
- **French Polynesia, Tetiaroa Atoll** - SWAC system installed at the Brando Resort in 2011. No detailed information is available although this system is reported as functioning at the time of writing. (Energies de la mer, 2021).
- **French Polynesia, Taaone** – A SWAC facility is currently under construction which will provide cooling to a local hospital. The project is described as being the longest commercial SWAC installed to date (Energies de la mer, 2021).
- **Hong Kong** - SWAC systems operational at the Excelsior Hotel and Hong Kong Shanghai Banking Corporation Office. Limited public information available.
- **United States, Hawaii** - Three projects in operation. Natural Energy Laboratory of Hawaii (NELHA) SWAC installed in 1987, and later upgraded. Two smaller projects at the University of Hawaii, and also Kahala Resort. A large-scale district cooling project had been mooted for development in Honolulu for a number of years with regulatory approval granted; however, this project was abandoned at the end of the 2020 citing escalating construction cost (US News, 2020).
- **Other** - Additional SWAC projects have been promoted and developed to varying degrees in Aruba, Mauritius, and Curacao but at the time of writing are not known to be operational.

Selected other SWAC projects installed to date include:

- **Canada, Toronto** - Deep Lake system for district air conditioning. Installed in 2003.
- **Canada, Halifax** - Seawater cooling system completed at Purdy's Wharf in 1989 providing cooling to a large office block.
- **Finland, Hamina** - Google data centre cooled by seawater. Operational since 2011.
- **Netherlands, Amsterdam** - District cooling utilising nearby deep-water lakes installed in 2006.
- **Sweden, Stockholm** - Industry leading project in Stockholm operational since 1995 as well as various other projects in other cities in Sweden.
- **United States, New York** - Lake Source Cooling project for cooling of Cornell University campus buildings. Installed in 2000.

5.3 / SWAC – OPERATIONAL REQUIREMENTS AND RESOURCE IN THE CARIBBEAN

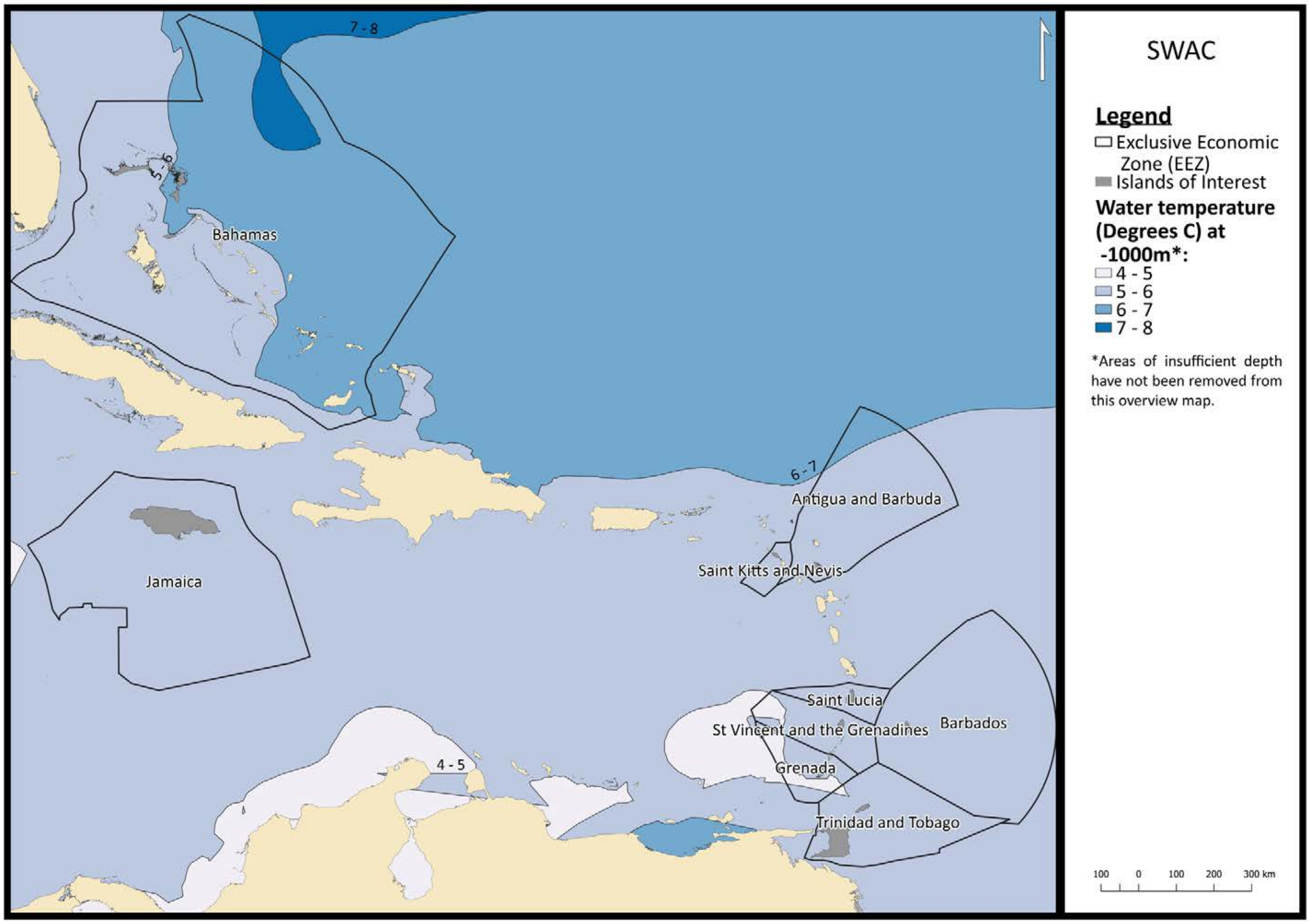
5.3.1 Operational requirements

Specific operational requirements for SWAC are highly site specific related to a number of technical and financial considerations such as level and nature of cooling demand, proximity to deep water, water column temperature profile, shoreline conditions and local energy pricing. Some generalisations can however be made that viable SWAC cooling projects must access cool deep water (5-8 degrees centigrade) at minimal distance from shore and as close to possible to a significant and preferably year-round cooling demand in a market where the price of electricity is relatively high.

5.3.2 Resource in the Caribbean

The temperature of seawater at depth, distance from shore to deep water, and availability of steady load are the key resource requirements for SWAC projects. In terms of temperature, consultation with industry experts suggest that water depths of around 1000m would be required as close to shore as possible for a viable project. Suitable sea depths are therefore almost identical to OTEC (with Figure 4.4 in Section 4.3.2 showing water depths between 750m and 1250m in the region). Industry also suggests that a temperature of 5-8 degrees centigrade would need to be available at this depth for a viable SWAC project. Figure 5.1 uses World Ocean Atlas (2018) data to show sea temperature at 1000m depth. This shows acceptable water temperatures for SWAC projects across the Caribbean, but interestingly there is a general trend of cooler deep waters to the south of the region (which is in contrast to the trend seen in sea surface temperatures which are warmer to the south).

Figure 5.1 Relative resource potential for SWAC in the Caribbean



Analysis for SWAC resource demonstrates that there are cool deep waters in close proximity to the shore in many areas of the Caribbean. There are also expected to be numerous heavy users of cooling load (notably hotels) for which a SWAC project could be suitable and energy prices are known to be generally high across the region. It therefore seems intuitive that numerous suitable locations for SWAC projects could exist, but further work is required to identify optimal locations.

5.4 / SWAC – TECHNICAL CONCLUSION

In terms of technology readiness, the relatively small number of projects installed globally and an apparent lack of momentum in the sector globally does raise some questions. The smaller scale nature of the technology and the fact that projects are generally developed for private off-takers perhaps contributes to this perception. Market uptake questions aside, the technology is simpler than OTEC and, other than potential complexities around pipelines, should be relatively straightforward to implement.

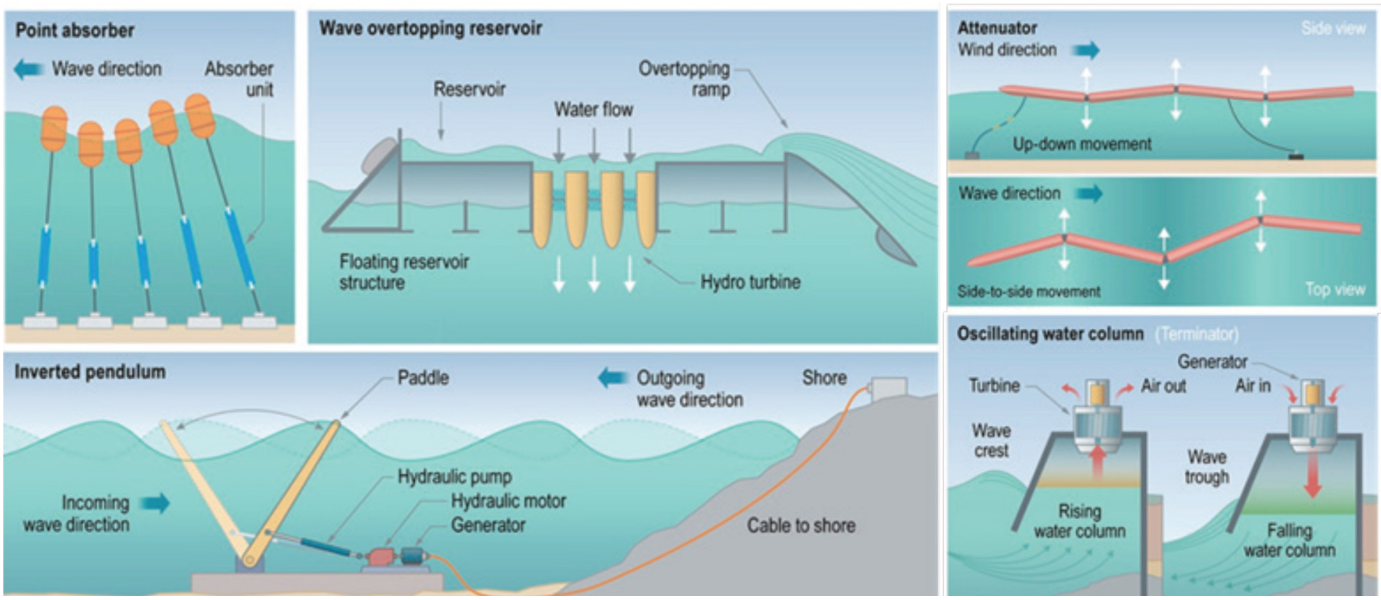
Like OTEC, SWAC can also be considered to be an attractive technology for the Caribbean. However, it is determined that, due to its highly site-specific nature, the potential for its implementation is on a significantly smaller scale than the other offshore renewable energy technologies discussed in this technical note. These points are elaborated upon further in section 10.3.

WAVE ENERGY CONVERSION

6.1 / WAVE - OPERATING PRINCIPLE

Waves are created by the action of the wind on the surface of the oceans. Wave energy conversion involves utilising the movement of waves to drive an electric generator. There are numerous and highly varied concepts under development, some of which are outlined in Figure 6.1. The majority of concepts convert the movement of waves into mechanical movement of the device or device parts, with that movement then used to drive an electrical turbine. Other concepts use the movement to pump water to shore and drive a hydro turbine or use the waves to fill a reservoir for a very low head hydro turbine. Many pumping concepts have the potential to integrate energy production with provision of desalinated water by utilising accumulated pressure to drive a reverse osmosis process. Depending on the wave climate in which they are deployed, wave energy technologies offer the potential for relatively consistent energy capture which can overlap and potentially complement other sources of renewable generation – in particular wind energy.

Figure 6.1 Examples of wave energy device types



Source: US DOE (2015)

6.2 / WAVE - DEVELOPMENT STATUS

The Wave Energy sector can be described as being in a prototype demonstration development phase with no real commercial application of the technology to date. A number of full-scale prototypes have been installed in open ocean conditions with various degrees of success; however, the first fully commercial array projects have yet to be deployed. A handful of high-profile industry-leading companies, such as Pelamis Wave Power and

Aquamarine Power have previously entered receivership; however, there are many other competing concepts still being actively developed. The European Marine Energy Centre (EMEC) maintains a register of companies actively developing wave energy concepts. The number of companies on this register currently stands at 255 (EMEC, 2021).

Selected projects of significant scale installed to date by companies which are still active in the sector include:

- **Australia / UK** – Bombora Wave Power are developing a flexible rubber membrane technology which can be deployed 'standalone' or potentially incorporated into new breakwater structures or on floating platforms. First in-ocean trials were held in 2017. A 1.5MW EU supported demonstrator project is currently under construction in Wales and is scheduled for completion in Summer 2021. The company has recently announced a partnership with TechnipFMC to develop a hybrid floating offshore wind and wave system
- **Finland / United Kingdom / Spain** – Wello Oy, Penguin. 500kW iteration of technology tested at EMEC from 2011. The same device was refitted and was installed at EMEC through 2017 and 2018. The company subsequently manufactured an updated 1MW version of this device which was intended for deployment as part of an array project at EMEC. The company altered its strategy however following an investment deal and in October 2020 this device was transported from Scotland to the BiMEP facility on the north coast of Spain for testing. At the time of writing, it appears that testing has yet to commence.
- **Norway / United States** – Fred. Olsen, BOLT. The 50kW BOLT Lifesaver was originally tested in Falmouth, England and was refitted and redeployed in Hawaii in 2016. In 2019, the device was installed again and was reported to be operational for 100 days with 100% uptime. Following this deployment, it was reported that the device would be decommissioned. A next iteration of the technology is intended to be deployed to host a 4G communications mast in the North Sea.
- **Sweden / United Kingdom / Portugal** – Corpower Ocean, C-WEC. The technology has graduated through tank and sheltered ocean testing, most recently at 1:2 scale at the EMEC scaled test site from 2015 – 2018. The company intends to deploy a first 'commercial scale' device in Portugal in late 2021 which will be followed by three further larger devices in 2022 – 2023. The company has plans for a follow-on larger scale array project in Ireland to be developed from 2026 – 2028.
- **United Kingdom** – Mocean Energy, Blue Star / Blue Horizon. The company has developed the smaller scale Blue Star concept to provide power to a range of subsea equipment. Blue Horizon is a larger scale version of the same concept which is intended to provide grid-scale electricity. The company intends to conduct a testing programme of a large-scale prototype at both EMEC's scaled and open ocean sites during 2021.
- **United States / Italy** – Ocean Power Technology (OPT), PowerBuoy. OPT has tested its PowerBuoy technology in a variety of locations and conditions. Previously deployed at 150kW scale in Scotland in 2011, and deployed at 15kW scale for a US Navy project in New Jersey, USA in 2017. Most recently, the company installed a device off Italy in a project linked to battery storage for charging autonomous underwater vehicles.

6.3 / WAVE – OPERATIONAL REQUIREMENTS AND RESOURCE IN THE CARIBBEAN

6.3.1 Operational requirements

With such a nascent industry and so many varied technology concepts under development it is not possible to accurately specify operational requirements for the full breadth of wave energy devices. That said, cost considerations mean that developers generally prefer sites close to shore and suitable shoreside operations bases and port facilities, in water of generally 10m to 100m depth. Some developers also actively look to install on breakwaters or piers. There are also some concepts which are intended for deployment on offshore platforms or coupled with wind turbine structures as part of a hybrid system and these are obviously dependent on the location of their hosting structure.

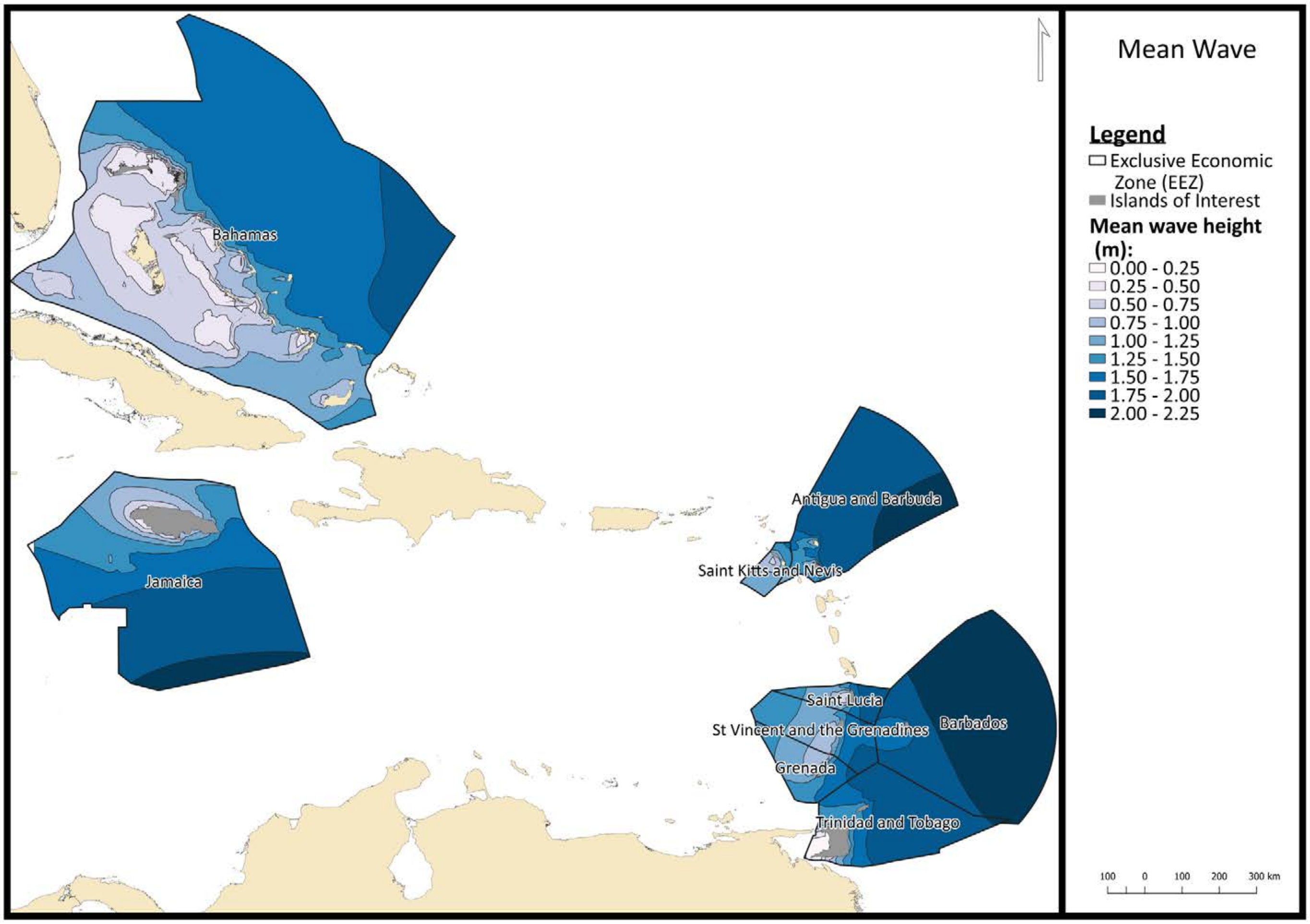
The required wave resource varies by technology. Different concepts are designed to operate within a given range of wave heights and periods – although some scope exists to optimise or 'tune' individual concepts to a particular wave climate. As with any renewable technology, the consistency of the resource is important and long periods of low resource levels will adversely affect the commercial viability of any project. Areas exposed to extreme wave and storm conditions are also to be avoided – although systems have been installed in high-energy environments such as the EMEC wave test site in Orkney, Scotland which sees waves of 15m with reasonable regularity. In general developers will tend to prefer sites with a regular wave regime with an absence or low incidence of extreme conditions.

6.3.2 Resource in region

Many Caribbean nations are exposed to the long fetch of the Atlantic Ocean and the prevailing south-easterly wind and swell direction. Islands with an east coast exposure to this fetch are likely to offer the best and most consistent wave resource in the region. The consistency of this resource in certain parts of the region is notable, although it is relatively low level in terms of overall energy density when compared to other regions at higher or lower latitudes. Nonetheless it is possible that such a lower level, but relatively consistent resource could be adequate and even favourable for certain technologies.

Figure 6.2 and Figure 6.3 below present the results of a broad assessment of long-term wave and wind climate undertaken by RPS (2019) using data taken from NOAA's Wavewatch III Gulf of Mexico model for the period from February 2005 to June 2019 with respect to the EEZ of the COI's but, due to scarcity of available data, not for the entire Caribbean region. It should be noted that, while this assessment is appropriate and useful as an initial starting point to understand the wave climate of in the COI's, the spatial resolution is low, and coastal and near-shore geography are not fully taken into consideration by the model. Therefore, a more detailed assessment, utilising data gathered at a local level, is strongly recommended prior to further consideration of any specific sites or areas identified.

Figure 6.2 Resource potential: Mean wave height in COI's



As can be seen above, the mean wave height (a standard metric in wave climate assessment) is calculated to be below 2.25m in all areas studied. The resource is shown to be greatest towards the east of the region. The mean wave height on the west coast of all islands drops due to the 'shadowing' effect of the land masses from the prevailing wind and swell direction to the south east.

Figure 6.3 Resource potential: Maximum wave height in the COI's

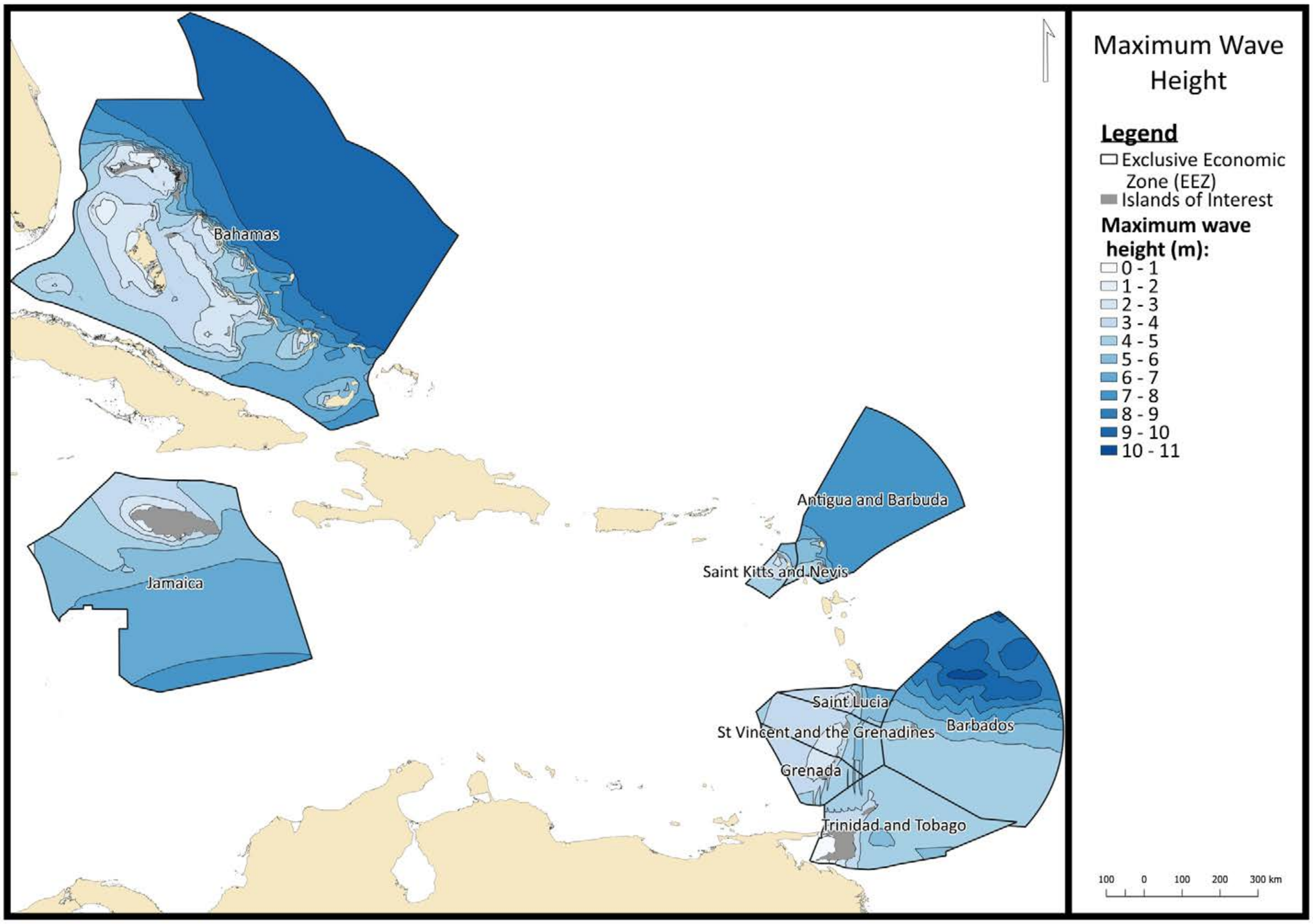


Figure 6.24 shows maximum significant wave heights recorded over a 14 year period. 'Significant wave height' is a commonly used technical term referring to the average of the highest third of all waves recorded over a specific timeframe – as such the largest waves observed will be above the significant wave height.

The largest waves were observed in the east coasts of land masses with maximum significant wave heights of between 10m – 11m in some areas. This is in marked contrast to areas on the 'sheltered' west coast of land masses where maximum significant wave heights were generally less than 5m. There also appears to be a general trend of lower maximum wave heights moving north to south through the region. The variation in wave heights observed can almost certainly be attributed to hurricanes or tropical storms tracking towards the northern and western Caribbean, along with the shadowing effect of the island land masses.

In terms of suitable depths for deployment of wave energy conversion devices, given the generally steep bathymetry in the region, it is expected that any wave energy project would be in very close proximity to land, which, depending on the technology deployed, may or may not be an issue.

6.4 / WAVE – TECHNICAL CONCLUSION

The wave energy sector is in a pre-commercial demonstration phase. There are no commercially available technologies currently on the market although there are signs that this may change towards the middle and end of the current decade – particularly for niche project applications.

The wave resource in the Caribbean is not particularly energy-dense or attractive in global terms. This would have a negative impact on the economics of any wave project when compared with projects in other parts of the world. Suitable seawater depths and bathymetry are an additional consideration which will further limit the deployment options for the technology. Wave energy is considered in further detail later in this technical note in section 10.3.

/ TIDAL STREAM/OCEAN CURRENT ENERGY CONVERSION

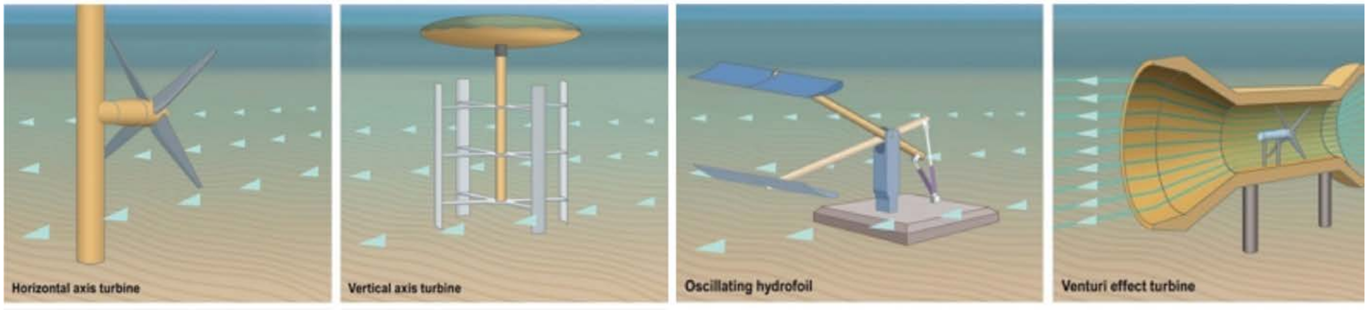
7.1 / TIDAL STREAM/OCEAN CURRENT - OPERATING PRINCIPLE

Ocean current energy involves conversion of flowing water into mechanical movement which drives an electrical generator. Flows of water in the ocean can be mono-directional and highly consistent, such as those present in the Gulf Stream, and are a natural phenomenon caused by the interaction of numerous forces such as wind, waves, salinity, bathymetry and the rotation of the planet (Coriolis Effect). These ocean currents, which differ from tidal and wind driven surface currents, are almost always located at significant depth below the ocean surface. These flows can occur globally in numerous locations, but generally follow continental coastlines, and form large inter-continental cycles.

Tidal energy differs from ocean current energy in that flows of water are created by the rise and fall of the tides caused by the gravitational pull of the sun and moon. These flows are generally bi-directional, changing direction four times every day, and are entirely predictable. Tidal flows are often fastest between nearby islands or around peninsulas where the natural features concentrate the movement of water.

There are many concepts under development for converting ocean and tidal currents into electrical energy, some of which are outlined in Figure 7.1. These can broadly be considered to be analogous to wind turbine designs except that instead of converting the flow of air (wind) into energy, these devices are converting the flow of water into energy. Due to the nature of the resource, deployment of ocean current and tidal energy devices is highly site specific.

Figure 7.1 Examples of ocean current, tidal flow and river flow device types



Source: US DOE (2015)

7.2 / TIDAL STREAM/OCEAN CURRENT - DEVELOPMENT STATUS

The ocean current energy sector is at a nascent stage of development. To date there is thought to have only been one ocean current energy converter installed in full ocean conditions.

- **Japan** – IHI, Mitsui, Toshiba and the University of Tokyo have formed a long-term consortium for the development of an ocean current turbine to be deployed in the Kuroshio Current off the coast of Japan. It is understood that a 100kW device has been tested in 100m of water since 2017, and was planned to be further tested in 2020. No further information on this trial was found to be available in the public domain.
- **Taiwan** – Swedish tidal and ocean current technology developer Minesto is known to be carrying out site development work on a project located off of the north coast of Taiwan in the Kuroshio Current. At the time of writing the project does not appear to have reached financial close or build out stages.

The tidal energy sector, although still in a pre-commercial stage of development, is relatively advanced compared with the other emerging technologies of wave and ocean current energy. A large number of developers are actively developing tidal technologies. The number of companies on the EMEC tidal energy technology developer register currently stands at 97 (EMEC, 2021).

The tidal sector does exhibit some parallels with the wind energy industry and, as in wind, the sector has converged on the use of horizontal axis turbine technology. A number of companies are testing individual full-scale prototypes but the industry has now advanced to the stage where the first array projects have been deployed and are operational providing electrical power into the grid.

The number of active projects is too great to list in detail but selected 'flagship' projects include:

- **United Kingdom** – EMEC in Orkney has hosted around 17 tidal energy devices at various scales at its Falls of Warness tidal test facility since 2006.
- **United Kingdom** – Meygen, in the north of Scotland, is the world's first large-scale array project with 6MW currently installed, and consent for a total potential capacity of 398MW. The project, consisting of four 1.5MW turbines has been operational since 2016. A further 4MW of capacity comprising of two 2MW turbines is reported as currently being under construction.
- **United Kingdom** – Nova Innovation installed, commissioned and grid connected an array of three 100kW subsea turbines in Shetland, Scotland in 2016. The project is still operational. The company has further projects under development in Wales and Canada.
- **United Kingdom** – Orbital Marine (formerly Scotrenewables Tidal Power) has tested a 2MW iteration of its technology at EMEC. A second generation 2MW machine was installed at EMEC in 2021 as part of a long-term commercial demonstration project. The company has announced intentions to develop a 15MW project off the Isle of Wight in southern England by the end of 2025.
- **Canada** – A small number of developers including Open Hydro (now defunct), Big Moon Power and Sustainable Marine Energy have installed and tested large scale devices at the Fundy Ocean Research Centre for Energy (FORCE), and elsewhere in the province of Nova Scotia.
- **South-East Asia** – A small number of individual devices have been installed in Singapore and Indonesia. An early-stage project pipeline exists in Indonesia and the Philippines, aiming to build on initial success in demonstrating the technology in the region.

7.3 / TIDAL STREAM/OCEAN CURRENT – OPERATIONAL REQUIREMENTS AND RESOURCE IN REGION

7.3.1 Operational requirements

There is limited information related to operational requirements for tidal and in particular ocean current projects. For most tidal projects there is general industry consensus that flow speeds of at least 2.5 meters per second or greater are required for commercial viability. There are, however, some industry players (notably Minesto utilising 'kite' technology) which look to utilise flow speeds of less than 2.5 meters per second.

In terms of distance to shore, fast tidal streams are generally only found close to shore where geographic features naturally speed up the flow of water, hence such projects are almost always sited within about 3km of shore, often much closer. Ocean currents also tend to follow coastlines, but may be situated much further of shore. The flow rate of ocean current tends to be low so accessing low resource far offshore is unlikely to be commercially viable and developers would probably search for suitable sites as close to shore as possible.

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In terms of depth, most tidal projects are installed in waters of around 30m to 60m. Ocean currents are likely to be in deeper water and the main flow may not be at the surface, making site and depth selection more complex. Water close to the surface will generally move fastest in tidal streams (due to seabed friction effects) and turbines need enough depth of water to allow space for the rotor diameter (about 18m for a 1MW machine), and to avoid the wave turbulence at the surface and slow-moving water at the seabed. Additionally, bladed turbines must be adequately submerged in order to avoid the effects of cavitation. For reasons of maritime safety and avoiding collisions with navigational users of the sea, turbines must also either be sufficiently below sea surface, or positioned away from shipping routes with adequate demarcation.

7.3.2 Resource in region

No high-quality data on tidal or ocean current speeds have been found for the Caribbean. It is therefore not possible to determine the suitability of the resource with certainty. It seems however that due to the open coastal geography of the region, generally lacking major inlets, it is highly unlikely that suitable sites of any scale exist for tidal projects. For ocean currents it is understood that flow rates are around 0.5 meters per second maximum which is too low for a viable project given the current state of technological development. The appearance of new or better data or local knowledge may challenge these assumptions.

7.4 / TIDAL STREAM/OCEAN CURRENT – TECHNICAL CONCLUSION

Ocean current energy, whilst sharing synergies with tidal energy, is at a very early stage of development with no active demonstrations in real sea conditions known. It therefore represents a very high technology risk. The resource and its suitability are also an unknown. Therefore, it is considered that Ocean Current Energy has low potential in the Caribbean in the near to medium term. In the long term with further technology development and advancement of the understanding of major currents such as the Gulf Stream, ocean current may have a role to play.

Tidal technology, whilst deployed in arrays in the UK, is considered likely to be unsuitable for deployment in the region due to the apparent lack of sufficient current velocities near to the coast. This is as a result of the natural 'open' coastal geography of the islands in the region, although not backed up by data, this can be considered a firm assumption based on professional judgement and extensive experience in site identification for tidal energy projects. Unless unexpected data regarding current speed is forthcoming it is considered that tidal technology is unsuitable for deployment in the region. Given this conclusion and the apparent lack of potential of both ocean current and tidal energy in the region there will be limited further discussion of these technologies in this technical note.

Photograph source: Jamaica

/ POTENTIAL RESOURCE

/ THEORETICAL RESOURCE AND TECHNICALLY EXPLOITABLE RESOURCE

8.1 / INTRODUCTION AND AIM

Understanding the overall potential for the exploitation of different ocean energy technologies at a high level is the first step in understanding the scale of opportunity that exists. This section presents headline figures for the Theoretical Resource and Technically Exploitable Resource potential for the selected technologies in the COI's. A brief overview of the methodology used is provided alongside the results obtained.

The Theoretical Resource as defined in this technical note considers the area of sea with suitable depth and within suitable distance from shore (set depending on the technology but up to a maximum of 50km as informed by background research and consultation with industry) and calculates the number of megawatts (MW's) that could be installed in the area identified. The Technically Exploitable Resource differs from the Theoretical Resource in that it includes consideration of other sea uses and constraints beyond simply water depth and distance from shore. The Technically Exploitable Resource is therefore a smaller, but more realistic estimate of the potential for each technology. While a large number of sea-use datasets have been included in the analysis it should be noted that the availability of additional datasets will further influence and enhance the outcome of this exercise.

8.2 / METHODOLOGY

A seven-step process was used to calculate Theoretical Resource and Technically Exploitable Resource potential for each technology in each of the COI's.

- STEP 1 – Identify broad areas of interest
    - EEZ's of COI's
- STEP 2– Identify islands of interest
    - Islands with minimum average electrical demand of 10MW to enable hosting of project
- STEP 3 – Map appropriate distance from shore for islands of interest
    - As determined by technology review
- STEP 4 – Map suitable sea depth
    - As determined by technology review
- STEP 5 – Calculate Theoretical Resource potential
    - Estimate the number of MW's of generation that could be installed in the available sea area identified in STEP 4 considering typical device size and spacing

- STEP 6 – Identify and map constraints to development using available datasets
    - Including but not limited to areas encompassing, Marine Protected Areas, very rugged bathymetry, high density shipping, existing infrastructure, explosive dumping grounds etc.
- STEP 7 – Calculate Technically Exploitable Resource potential
    - As per STEP 5, but with reduced area available for development taking account of mapped constraints in STEP 6.

The output of STEP 2 above is presented below in Table 8.1. This step identified at least one island in each COI to take forward for further consideration.

Table 8.1 Population and electrical demand for islands of the COI's

Country	Island	Population	Peak demand (MW)	Average demand (MW)	Scope in or out
Antigua and Barbuda	Antigua	93,231	49	37	⚪⚪🟢
	Barbuda	1,500	1	1	🔴⚪⚪
Barbados	Barbados	292,336	155	104	⚪⚪🟢
The Bahamas	New Providence	210,832	214	153	⚪⚪🟢
	Grand Bahama	46,994	48	34	⚪⚪🟢
	Abaco	13,170	13	10	⚪⚪🟢
	Acklins	428	0	0	🔴⚪⚪
	Andros	7,686	8	6	🔴⚪⚪
	Berry Island	709	1	1	🔴⚪⚪
	Bikinis	1,717	2	1	🔴⚪⚪
	Cat Island	1,647	2	1	🔴⚪⚪
	Crooked Island	350	0	0	🔴⚪⚪
	Eleuthera	7,999	8	6	🔴⚪⚪
	Exuma and Cays	3,571	4	3	🔴⚪⚪
	Harbour Island	1,639	2	1	🔴⚪⚪
	Inagua	969	1	1	🔴⚪⚪
	Long Island	2,992	3	2	🔴⚪⚪
	Mayaguana	259	0	0	🔴⚪⚪
	Ragged Island	72	0	0	🔴⚪⚪
	San Salvador	970	1	1	🔴⚪⚪
	Rum Cay	80	0	0	🔴⚪⚪
	Spanish Wells	1,527	2	1	🔴⚪⚪
Grenada	Grenada	101,006	30	24	⚪⚪🟢
	Carriacou	4,761	1	1	🔴⚪⚪
	Petit Martinique	900	0	0	🔴⚪⚪
Jamaica	Jamaica	2,728,864	667	498	⚪⚪🟢
St. Kitts and Nevis	St. Kitts	41,607	24	17	⚪⚪🟢
	Nevis	11,108	10	6	🔴⚪⚪
St Lucia	St Lucia	164,994	62	46	⚪⚪🟢
St. Vincent and the Grenadines	St. Vincent	98,954	21	16	⚪⚪🟢
	Bequia	4,946	1	1	🔴⚪⚪
	Mustique	1,238	0	0	🔴⚪⚪
	Canouan	1,683	0	0	🔴⚪⚪
	Mayreau	271	0	0	🔴⚪⚪
	Union Island	2,096	0	0	🔴⚪⚪
Trinidad and Tobago	Trinidad	1,157,208	1,284	1,008	⚪⚪🟢
	Tobago	61,000	71	56	⚪⚪🟢

Source: Compiled using CARICOM (2018) as well as supplementary data. Where energy data was not available at individual island level population was used to estimate the split between islands.

8.3 / RESULTS

The outcome of STEP 5 in section 8.2 is to identify the theoretical resource potential for each technology for each COI. This is presented in Table 8.2.

Table 8.2 Theoretical Resource for each technology and each COI

	Maximum Theoretical Resource (MW)					
Country	Fixed OSW	Floating OSW - Conventional	Floating OSW - Deep	OTEC	Total	Average electrical demand (MW)
Antigua & Barbuda	6,489	1,890	15,379	120	23,878	38
The Bahamas	12,166	7,903	33,579	300	53,948	220
Barbados	0	189	8,344	160	8,693	104
Grenada	3,507	861	12,530	170	17,068	25
Jamaica	3,885	3,864	21,014	260	29,023	498
Saint Kitts & Nevis	889	504	11,690	40	13,123	24
Saint Lucia	469	392	5,152	130	6,143	46
Saint Vincent & the Grenadines	4,011	805	5,467	110	10,393	17
Trinidad & Tobago	28,490	21,728	7,896	100	58,214	1,064
Total	**60,137**	**38,136**	**121,051**	**1,390**	**220,714**	**2,036**

The analysis shows vastly more theoretical potential than demand in each COI, with across all COI's about 100 times more theoretical potential than electrical demand within a distance of 50km to shore. Whilst this doesn't allow for the capacity factor of technologies installed, it does indicate that the selected MRE technologies have substantial potential to contribute to the energy mix in the region.

Note that whilst the assumptions for OSW are robust and determined by analysis of industry data the figures for OTEC are not. There are few operational examples of this technology at scale and no information on appropriate spacing of devices. It is however unlikely that two plants could be placed in close proximity to each other due to the potential interaction between water intakes and outputs so, in the absence of data, a conservative estimate of required spacing was made. In practical terms if looking to scale up from 10MW to 20MW for example it is recognised that it would be likely that this would be done by expanding an existing plant rather than by building another in proximity. Nonetheless the assumptions used are useful in providing a country-by-country comparison of overall potential.

Analysis of theoretical potential should always be read carefully as there are numerous factors which effect the technically exploitable resource which are not considered in such calculations. STEP 6 in section 8.2 therefore sought to build on this analysis by considering constraints which might exclude development from areas of sea in order to identify a more realistic figure for the Technically Exploitable Resource for each technology in each COI. The results of this analysis are presented in Table 8.3.

Table 8.3 Technically Exploitable Resource for each technology and each COI

	Maximum Technically Exploitable Resource (MW)					
Country	**Fixed OSW**	**Floating OSW - Conventional**	**Floating OSW - Deep**	**OTEC**	**Total**	**Average electrical demand (MW)**
Antigua & Barbuda	4,935	1,477	11,718	100	18,230	38
The Bahamas	10,955	6,321	16,723	220	34,219	220
Barbados*	0	112	7,063	140	7,315	104
Grenada	2,618	476	7,196	110	10,400	25
Jamaica	1,211	1,848	9,709	180	12,948	498
Saint Kitts & Nevis	399	196	9,135	40	9,770	24
Saint Lucia	105	224	4,025	90	4,444	46
Saint Vincent & the Grenadines	3,227	385	3,017	70	6,699	17
Trinidad & Tobago	16,597	12,460	4,963	50	34,070	1,064
Total	**40,047**	**23,499**	**73,549**	**1,000**	**138,095**	**2,036**

*Recent work using higher resolution country specific data has shown that there is in fact some limited potential for fixed wind in Barbados (Barbados Government, 2021).

Whilst the Technically Exploitable Resource figure is arguably a more useful tool than the Theoretical Resource in gauging the relative potential for each technology across the COI's, care must be taken in analysing the results. The figures themselves are still expected to significantly overestimate the potential, as they are based on the results of a high-level assessment and assume every area identified in the high-level assessment is suitable and will be utilised to its maximum extent, which is unrealistic. Nonetheless the Technically Exploitable Resource figures show that there is technically enough suitable space to provide all the electricity needs for COI's about 30 times over (including a correction for the capacity factor of the technologies used). The figures also provide a useful indication of the relative limits on the potential for certain technologies in certain islands. In this respect the analysis highlights the overwhelming abundance of potential in the region and the scale of the opportunity that exists.

Photograph source: Saint Lucia

/ LOCATIONAL GUIDANCE

/ LOCATIONAL GUIDANCE

9.1 / INTRODUCTION AND AIM

Building on the outputs of the Technically Exploitable Resource estimates (Section 8.3), work was undertaken to expand on the analysis to provide 'Locational Guidance' as to areas of sea likely to be more or less suited to commercial deployment of selected ocean energy technologies.

This was achieved by collecting and combining numerous additional 'layers' of data related to resource, biophysical characteristics, infrastructure, management/protected areas, and sea use. For each layer of data appropriate scoring of suitability across the COI's for that data set was undertaken and, with all individual layers scored, the relative importance of each layer against others was also scored. These scores were then combined in a 'weighted sum analysis', the aim of doing so being to identify the relative suitability of waters around each of the COI's and aid in early identification of the most promising sites for further consideration. This chapter briefly outlines the methodology for this work before the outputs are presented, firstly for each technology across all the COI's, and then for each technology in each COI individually.

9.2 / METHODOLOGY

In order to compile the Locational Guidance mapping outputs a five-step methodology was undertaken;

- STEP 1 – Data gathering
  - Collection, analysis and interpolation of existing data
- STEP 2 – Determine how to use the data
  - Determining which data to include, exclude, and display
- STEP 3 – Creation of layers to be utilised in the weighted sum calculations
  - Processing data into GIS layers
- STEP 4 – Preparation of layers for weighted sum calculation
  - Processing layers into appropriate format for use in the analysis
- STEP 5 – Weighted sum calculation
  - Weighting and combining layers to derive cumulative 'suitability' Locational Guidance outputs

Full details of the methodology and scoring system used are not presented here for brevity.

9.3 / RESULTS

The analysis outlined in Section 9.2 above culminates in the production of a map for each technology showing the relative suitability for the technology across the COI's. In each map, areas with the highest suitability scoring are rescored as '1' and coloured bright green and areas with the lowest are rescored as zero and coloured red. All intermediate scores are the graded appropriately between these two points. Areas coloured red are therefore not deemed unsuitable for development, rather they are considered to be likely to be less preferred. The outputs are presented in two formats with either a technology specific focus (section 9.3.2 to 9.3.5), or country specific focus (section 9.3.7 to 9.3.15).

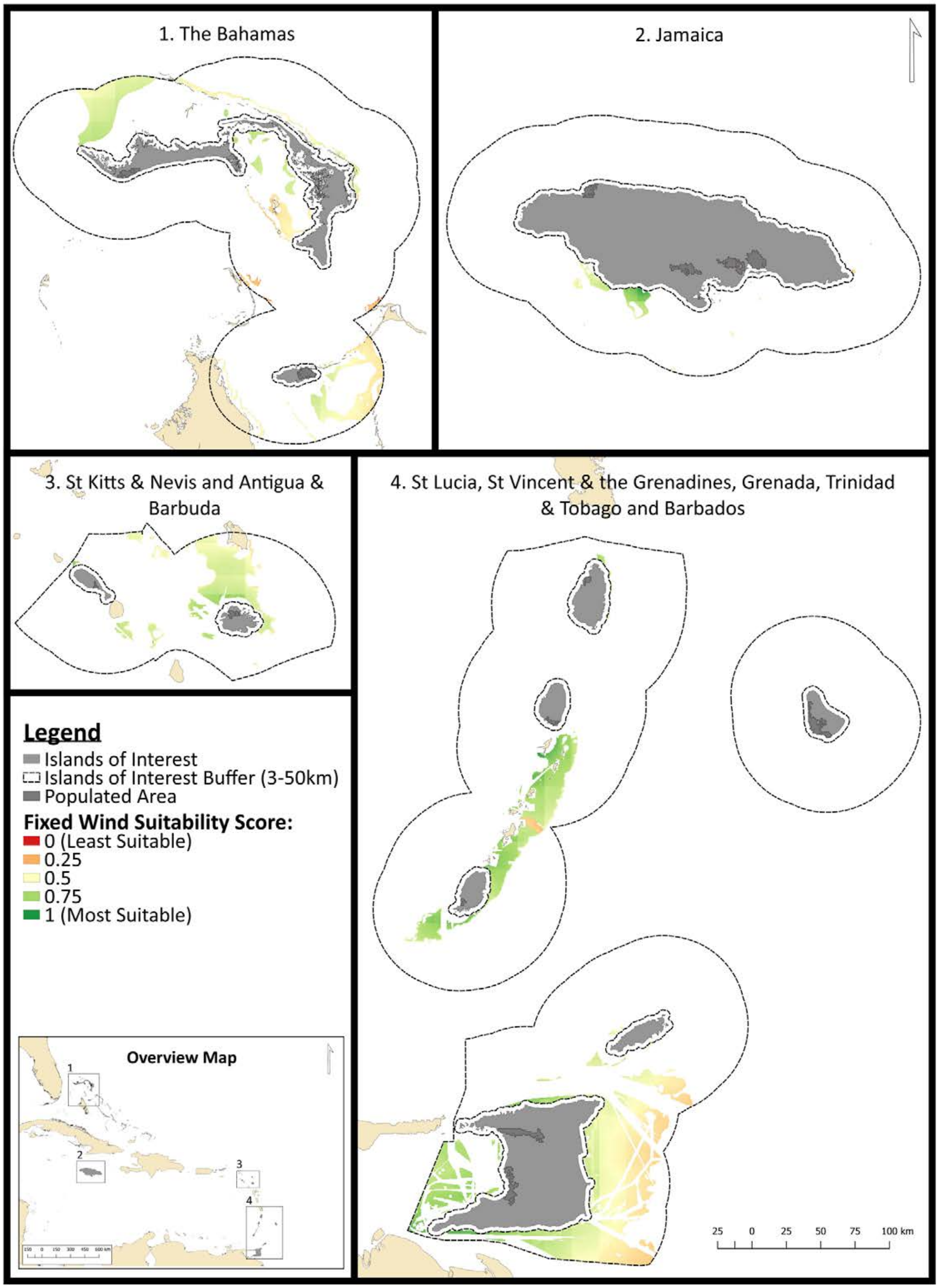
9.3.1 Results for each technology across all countries

The results for each technology are presented over the following four pages. Note that no discussion of the results is provided at the technology specific level here as this is covered subsequently a country-by-country level.

9.3.2 Fixed OSW

Figure 9.1 shows the results of the weighted sum analysis for relative suitability of Fixed OSW in the COI's.

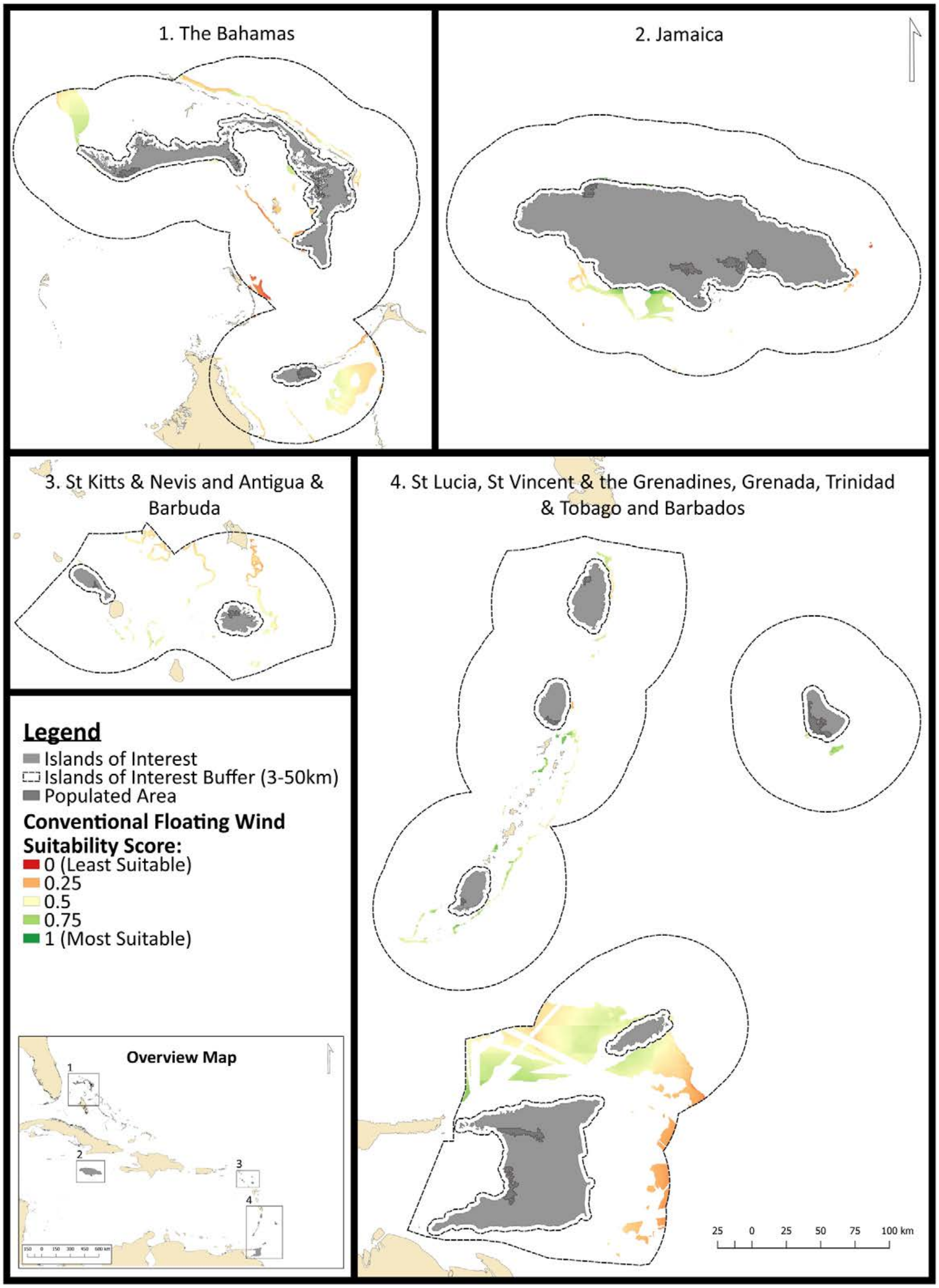
Figure 9.1 Fixed OSW - Weighted sum analysis for relative suitability



9.3.3 Floating OSW (conventional)

Figure 9.2 shows the results of the weighted sum analysis for relative suitability of Floating OSW (conventional) in the COI's.

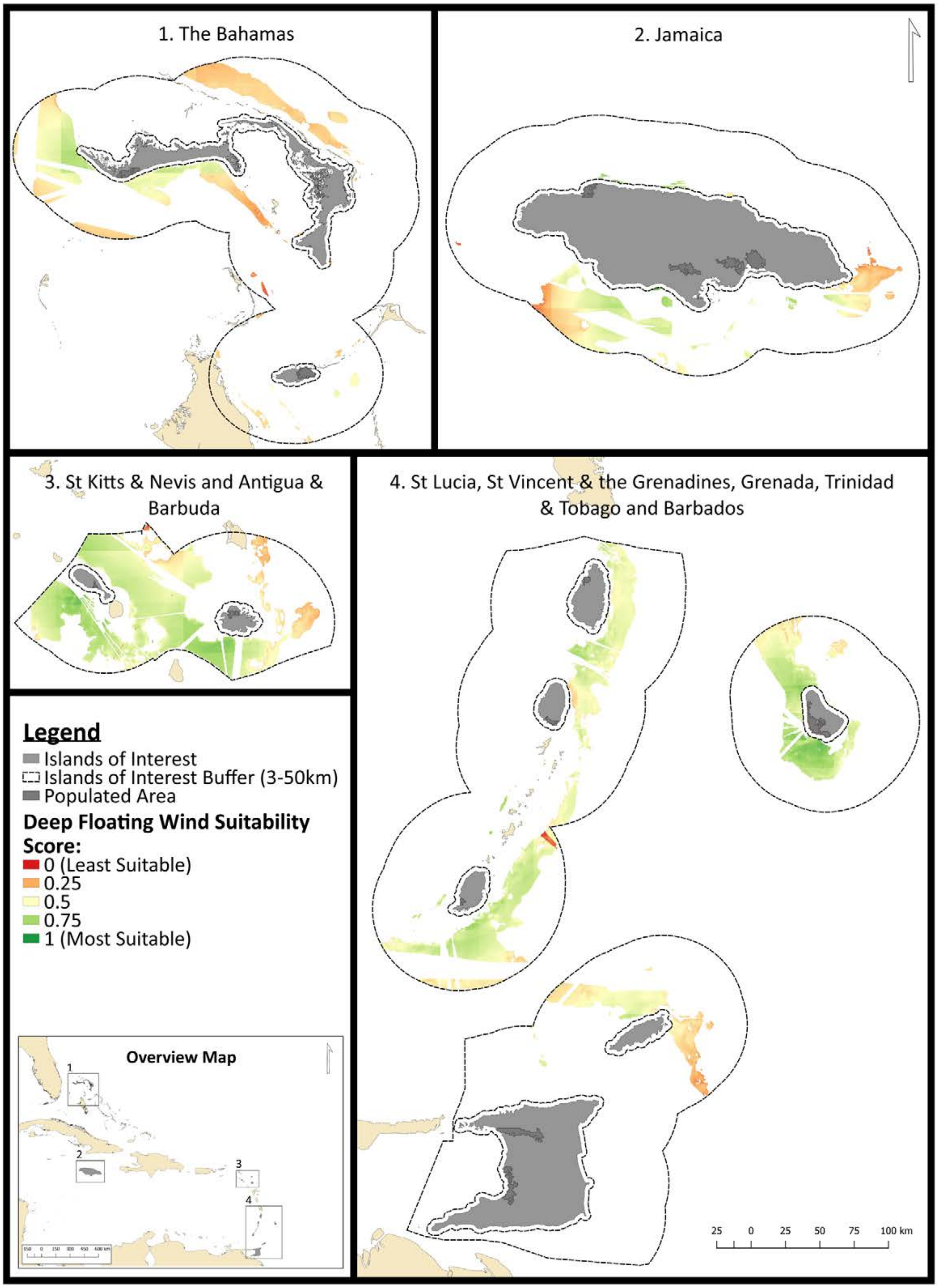
Figure 9.2 Floating OSW (conventional) - Weighted sum analysis for relative suitability



9.3.4 Floating OSW (deep)

Figure 9.3 shows the results of the weighted sum analysis for relative suitability of Floating OSW (deep) in the COI's.

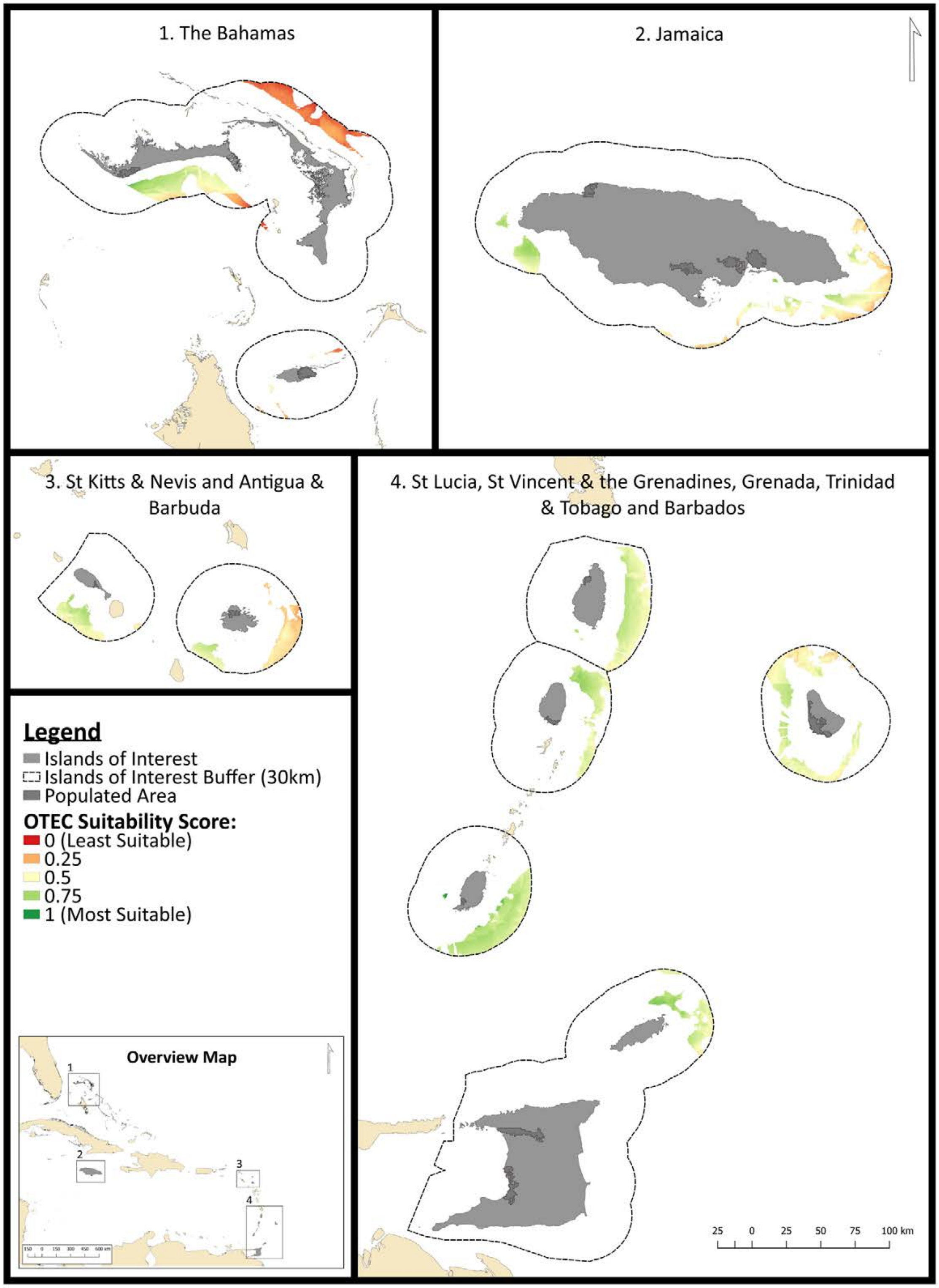
Figure 9.3 Floating OSW (deep) - Weighted sum analysis for relative suitability



9.3.5 OTEC

Figure 9.4 shows the results of the weighted sum analysis for relative suitability of OTEC in the COI's.

Figure 9.4 OTEC - Weighted sum analysis for relative suitability of OTEC



9.3.6 Country by country results for each technology

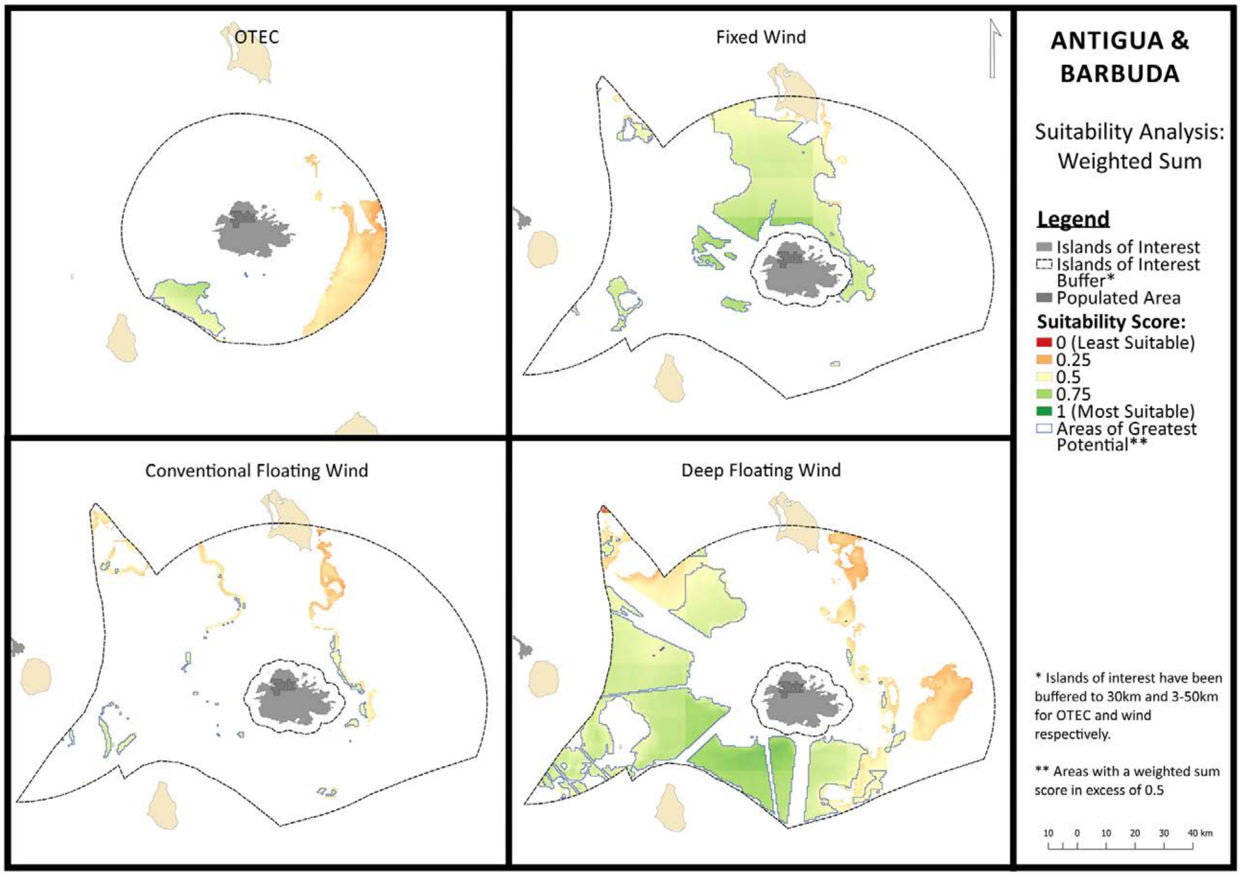
The results of the weighted sum analysis presented in sections 9.3.2 to 9.3.5 above, are presented again here, but with a country specific focus. Section 9.2 explained that the weighted sum maps had been rescaled such that 0 represents the least suitable areas and 1 represents the most suitable areas for each technology. The maps in this section have an overlay to outline any areas scoring 0.5 or above to help highlight the areas analysed as likely to be most suitable. Choosing to focus on sites scoring more than 0.5 allows effective analysis and discussion however it should be noted that is an arbitrary cut off and a greater or lesser proportion of areas could be considered in any future analysis. The overlay does however aid viewers of the output maps in easily identifying the areas of greatest potential for each of the four technologies at a glance.

Maps for each of the nine countries of interest are presented in turn (alphabetically) in the following subsections.

9.3.7 Antigua & Barbuda

The overall results of the Antigua & Barbuda weighted sum analysis and identification of areas of greatest potential for each technology are presented in Figure 9.5. Note that for this analysis only Antigua with an approximated average electricity demand of 37MW was scoped in and Barbuda with an approximated average electricity demand of 1MW was scoped out (as having insufficient electricity demand to support an OSW project).

Figure 9.5 Antigua & Barbuda - Indicative areas of greatest potential for each technology



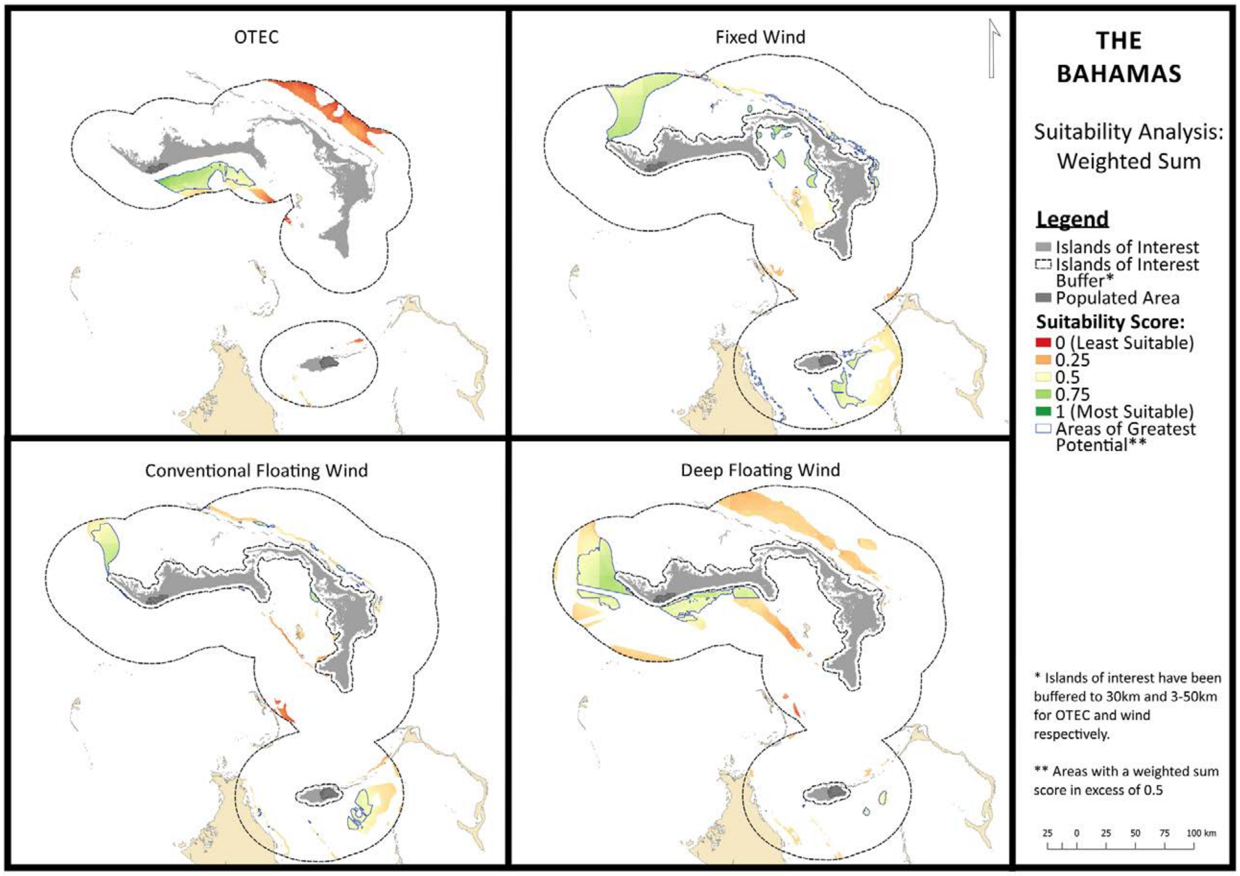
The analysis suggests that, for Antigua, there are excellent options for fixed OSW, particularly to the north of the islands where there is a large area of suitability within a limited distance from shore. The prospects for conventional floating OSW are much more limited, although there are a scattering of potential areas around the islands of sufficient size to host a project but with more limited flexibility. For deep floating OSW there are large swathes of suitable sea space both to the south and west, noting the presence of shipping routes and predicted cable routes will need to be taken account of.

The best area for OTEC has been identified to the southwest, albeit at reasonably distant range from the coast. The preference shown by the mapping exercise to this area over that to the east of the islands most probably relates to predicted fishing density as well as wave exposure.

9.3.8 The Bahamas

The overall results of The Bahamas weighted sum analysis and identification of areas of greatest potential for each technology are presented in Figure 9.6. Note that for this analysis only the islands of New Providence (approximated average electricity demand of 153MW), Grand Bahama (34MW), and Abaco (10MW) were scoped in. All other islands have an approximated average electricity demand of less than 6MW and were scoped out.

Figure 9.6 The Bahamas - Indicative areas of greatest potential for each technology



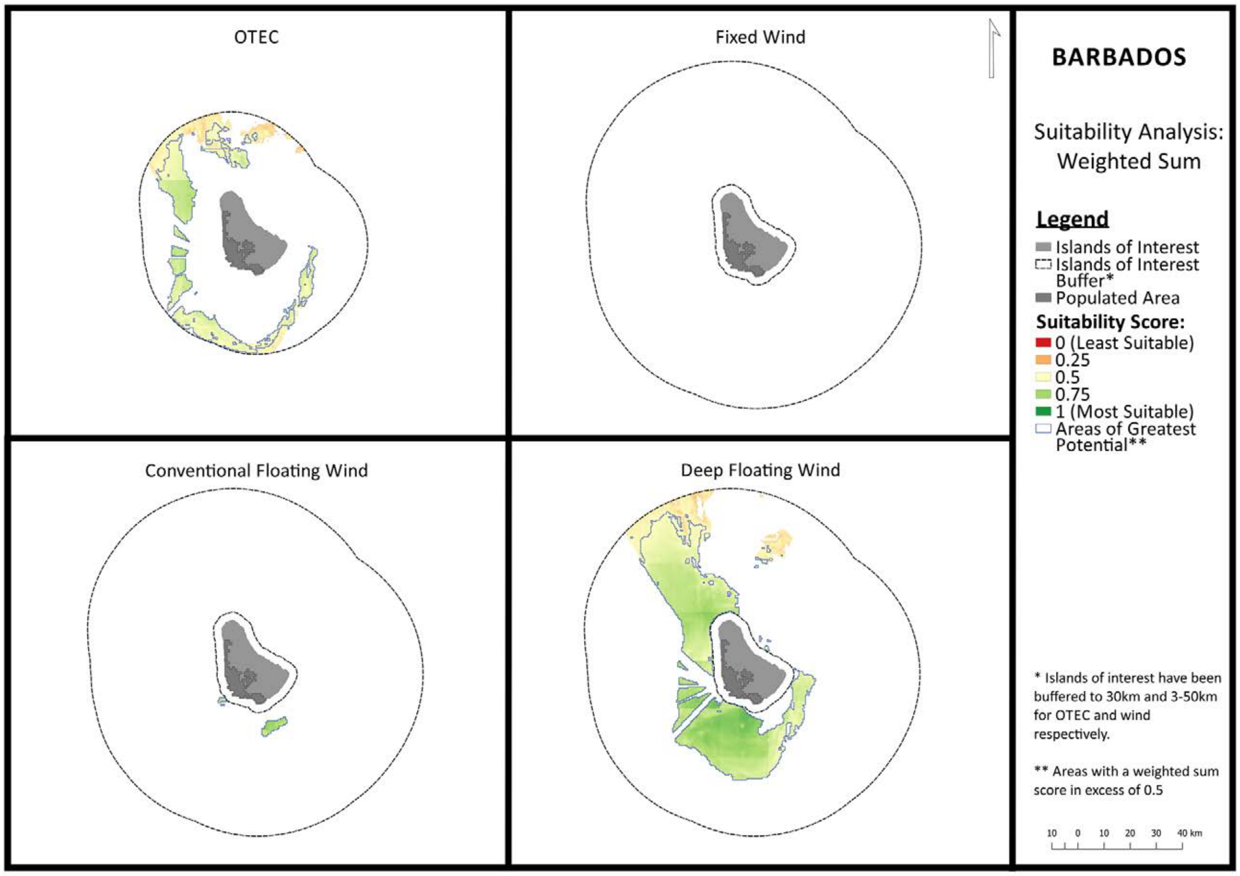
For fixed OSW the analysis suggests there are a number of options. The largest area is to the north of Freeport on Grand Bahama although there are a number of smaller suitable sites between Grand Bahama and Abaco. The most promising site may however be on the southeast of Nassau on New Providence where proximity to demand and port may help viability. There are limited but realistic options for conventional floating OSW and for deep floating OSW, whilst suitable areas are relatively constrained, there are notably some areas very close to shore on Grand Bahama which may be promising demonstrator sites. Similar areas are also identified for OTEC on Grand Bahama where, with suitable depths reached close to shore and close to demand (Freeport), there could be high potential for a viable project.

In spite of the above special consideration must also be given to hurricane risk in The Bahamas. A notable limitation of the analysis undertaken for this study is that the low resolution of hurricane risk creates arbitrary lines of high and low risk. This is particularly stark in The Bahamas where the data identified areas of the highest risk directly adjacent to areas of low risk. This will impact the results and therefore hurricane risk should be given further consideration by hurricane experts in ground-truthing the results obtained here.

9.3.9 Barbados

The overall results of the Barbados weighted sum analysis and identification of areas of greatest potential for each technology are presented in Figure 9.7. Barbados has an approximated average electricity demand of 104MW.

Figure 9.7 Barbados - Indicative areas of greatest potential for each technology



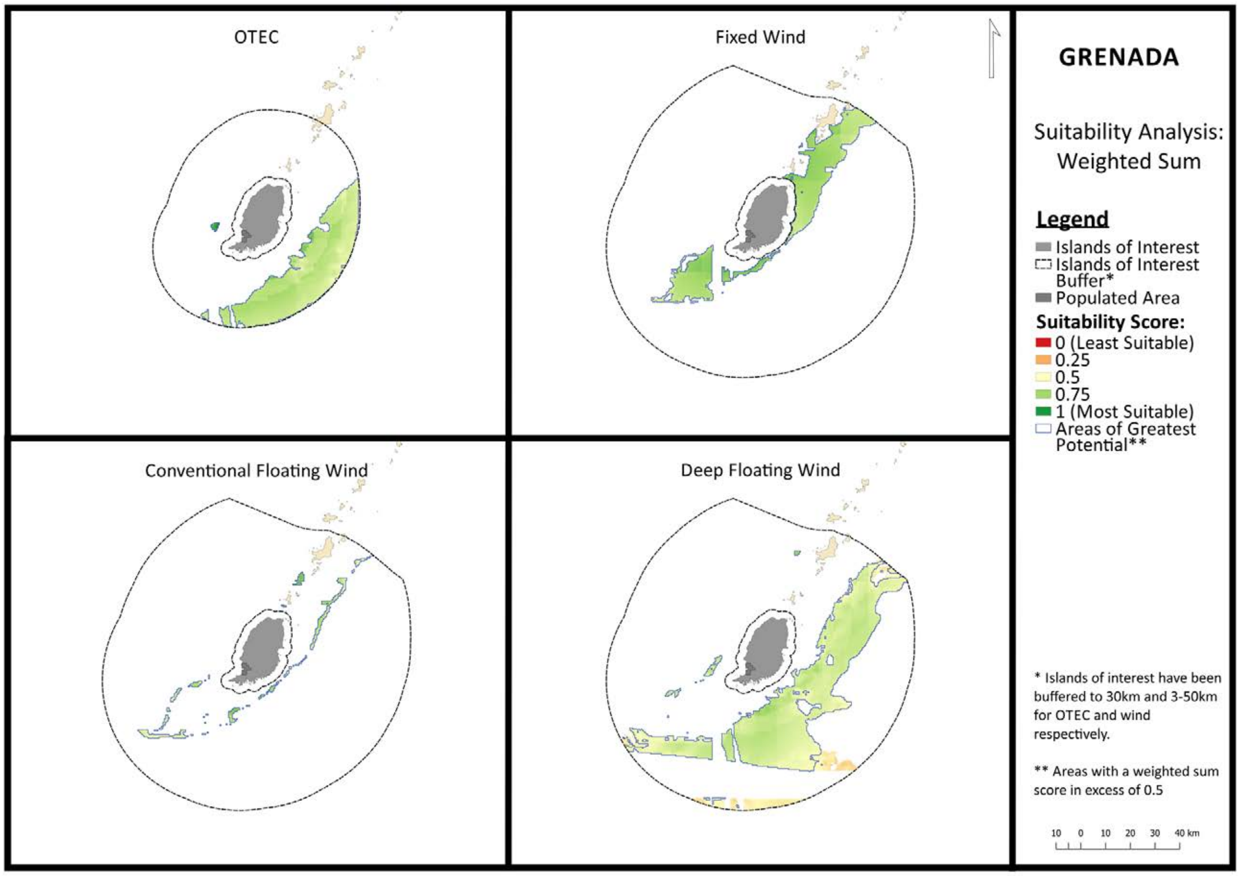
The sharp transition to deep waters off the coast of Barbados can be seen to substantially limit potential for both fixed OSW and conventional floating OSW.. There may be suitable locations for fixed OSW within 3km from land (scoped out in this assessment) but any such project would be highly visible from shore. For conventional floating OSW there is good potential to the south of Barbados with a high scoring area of reasonable size, albeit options for optimising location would be limited. For deep floating OSW there are numerous expansive high scoring options all around the island, with the exception of the northeast coast. There are also good options for OTEC, particularly on the more sheltered west coast at an acceptable distance from shore, but not particularly close.

It should be noted that the Government of Barbados has undertaken Locational Guidance work for ocean energy technologies using higher resolution country specific data (as reported in IDB, 2020) and that this has been built on substantially in more recent (unpublished) work (Barbados Government, 2021). The outputs provided here, whilst not as detailed or extensive as others undertaken, are however valid and useful for comparison.

9.3.10 Grenada

The overall results of the Grenada weighted sum analysis and identification of areas of greatest potential for each technology are presented in Figure 9.8. Note that for this analysis only Grenada with an approximated average electricity demand of 24MW was scoped in with Carriacou and Petit Martinique both scoped out due to an approximated average electricity demand of less than around 1MW.

Figure 9.8 Grenada - Indicative areas of greatest potential for each technology



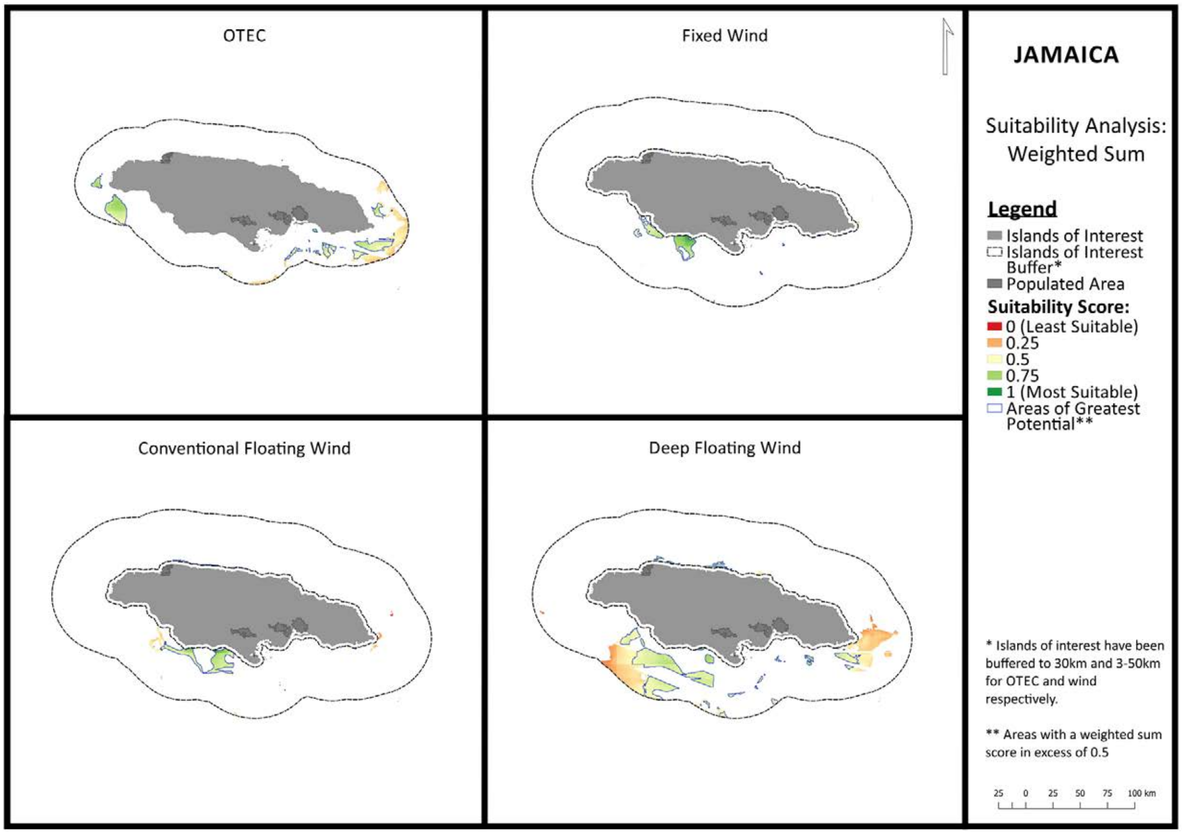
There are a range of high scoring options for fixed OSW around Grenada, ranging from relatively close to shore to further offshore. Given the comparatively low electrical demand (and therefore limited scale of any project) this proximity to shore could aid in project economics. There are some limited narrow ribbons of ocean identified for conventional floating OSW, constrained due to the steady slope, again close to shore but not as expansive as for fixed OSW which would look to be the better option of the two. Deep floating OSW analysis identified very large areas of sea of reasonable suitability. For OTEC there are good options anywhere on the southeast of Grenada at 10-15km form shore. A small area of very high suitability is also identified about 10km west of Saint George. This could be a promising site considering proximity to demand and shelter however there are expected to be cable routes in the area which may present some additional constraint.

Note that the paucity of suitable sites on the northwest of the islands is mostly due to high density shipping and slope exclusions used in the analysis.

9.3.11 Jamaica

The overall results of the Jamaica weighted sum analysis and identification of areas of greatest potential for each technology are presented in Figure 9.9. Jamaica has an approximated average electricity demand of 498MW.

Figure 9.9 Jamaica - Indicative areas of greatest potential for each technology



Jamaica's comparatively high electrical demand means that it may be able to host a MRE project of sufficient scale to drive down costs. There are however a number of constraints included in the analysis which have restricted the area available for development. Of note are substantive shipping channels, a large MPA south of Kingston, and a large area to the north of the island excluded due to slope and roughness. With higher resolution data it may well be possible to find areas within the slope and roughness exclusions which are suitable for development.

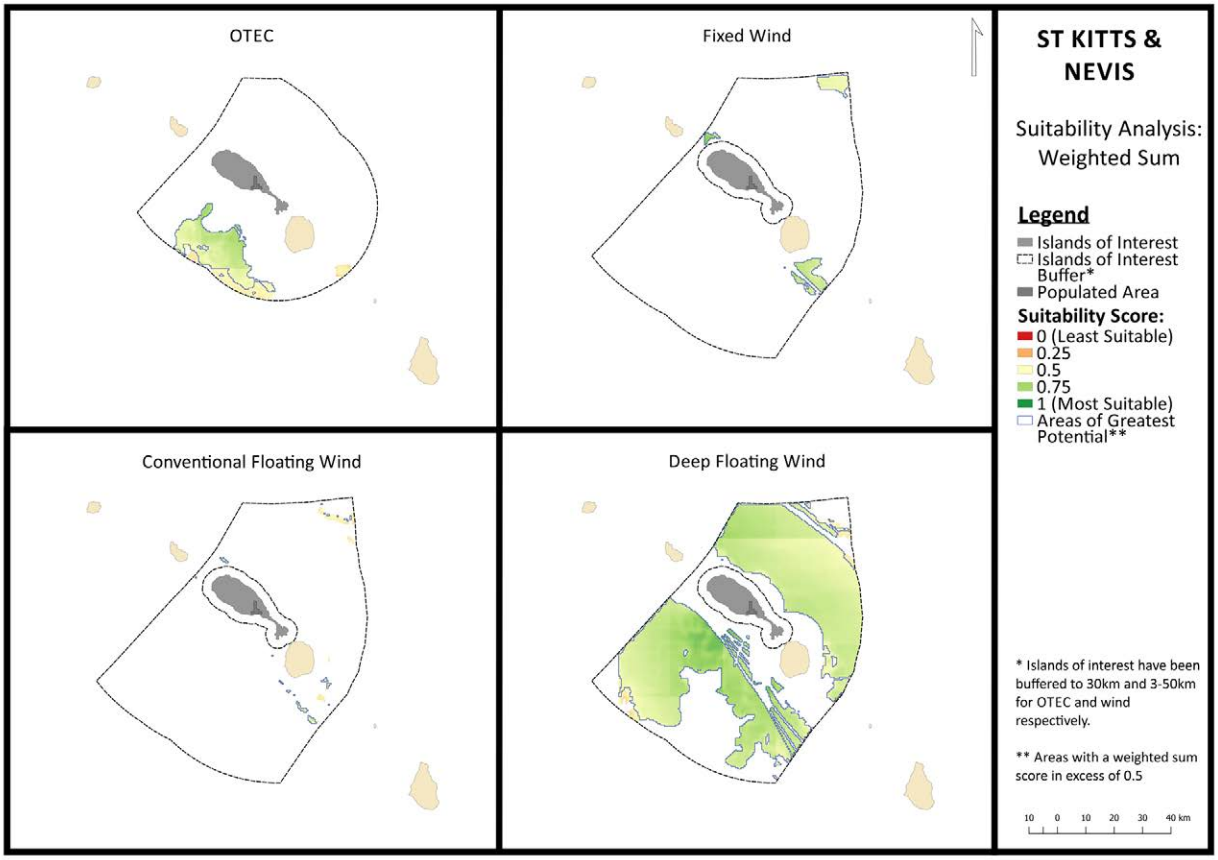
For fixed OSW two areas are identified close to shore to the south in reasonable proximity with good scores for suitability. The identified areas for conventional floating OSW are located in deeper adjacent waters, with most of the deep floating OSW also in the same vicinity, albeit slightly further offshore in deeper water. For each OSW technology there is sea space available for substantial developments, although options for locating such developments are relatively limited.

Analysis for OTEC identifies several potential areas along the west, south and east coasts. Notably no areas in the north coast are identified. As discussed above this is due to slope and roughness exclusions, which for a floating OTEC plant are considered to pose technical challenges – particularly in anchoring and mooring of offshore plant. It is however probable that for a shore based OTEC plant (or SWAC plant) the extreme slope would be advantageous. The north coast of Jamaica could therefore have good potential for such installations, notwithstanding the fact that OTEC developers in general seem to be focussed on floating offshore plant.

9.3.12 St. Kitts & Nevis

The overall results of the St Kitts & Nevis weighted sum analysis and identification of areas of greatest potential for each technology are presented in Figure 9.10. Note that for this analysis only St. Kitts with an approximated average electricity demand of 17MW was scoped in and Nevis with an approximated average electricity demand of 6MW was scoped out.

Figure 9.10 St. Kitts & Nevis - Indicative areas of greatest potential for each technology

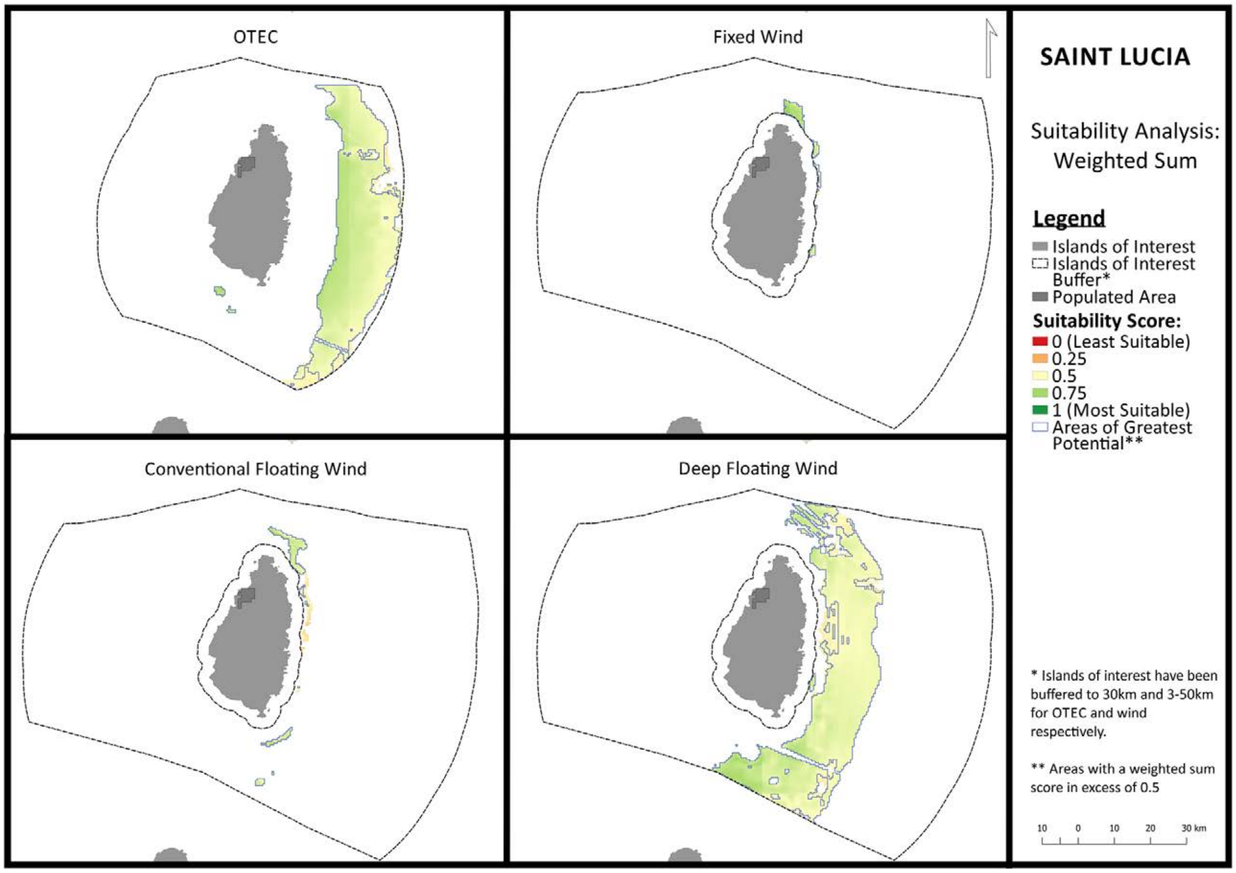


The bathymetry of St. Kitts is such that shallow waters are only encountered very close to shore. There is also an MPA surrounding the islands and this limits the potential for technologies requiring shallow waters. There are however two options for fixed OSW with limited but ample space available considering the low local electricity demand, one to the north of St. Kitts close to shore, and another larger area to the south of Nevis. Options for conventional floating OSW are so limited and scattered as to most probably make them unviable. Deep floating OSW analysis to the contrary identifies wide spaces of high scoring sites to the northeast and southwest, both in proximity to shore and further afield. For OTEC however the only suitable areas are to the southwest which may align well with proximity to Basseterre. Waters to the northeast, although suitable depth for deep floating OSW, are not deep enough for OTEC.

9.3.13 St. Lucia

The overall results of the St. Lucia weighted sum analysis and identification of areas of greatest potential for each technology are presented in Figure 9.11. St. Lucia has an approximated average electricity demand of 46MW.

Figure 9.11 St. Lucia - Indicative areas of greatest potential for each technology



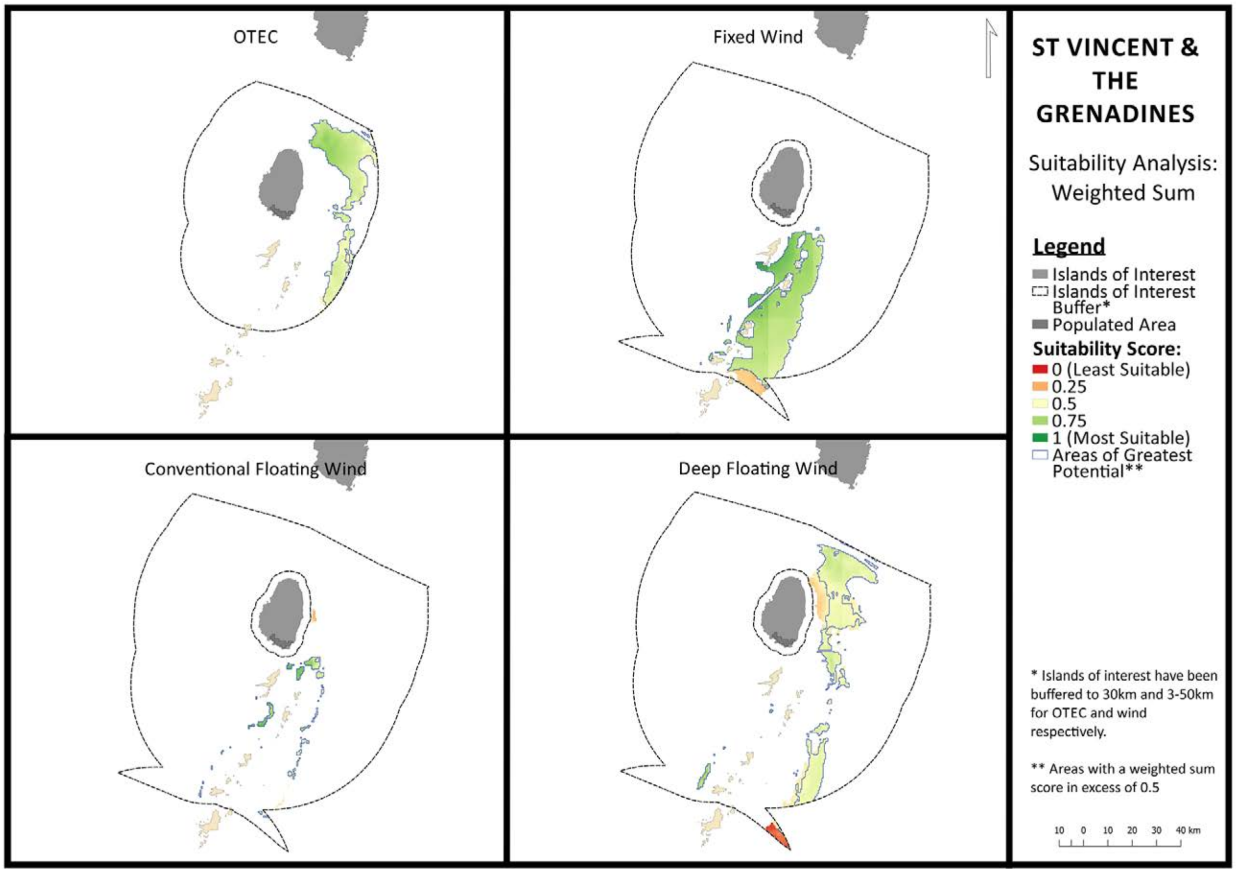
The west coast of St. Lucia is excluded from consideration for development due to high density shipping areas, steep slopes, roughness and the presence of an MPA. Beyond these restrictions the water depth is such that it is too deep for consideration and so this only leaves the more exposed east coast for development.

The potential for fixed OSW is highly restricted with some small areas close to shore on the northeast coast identified. Conventional floating OSW is similarly restricted to a few narrow strips on the east coast. Deep floating OSW analysis identifies a large band of developable area to the east however this is not particularly high scoring, most probably due to wave exposure scoring. OTEC similarly identifies a large band on the east coast with reasonable, but not very high, scoring. Despite the constraints and mediocre scoring of the analysis there could be potentially viable projects for all technologies in St Lucia, considering the limited local electrical demand and therefore limited space required to make a meaningful contribution.

9.3.14 St. Vincent & the Grenadines

The overall results of the St. Vincent & the Grenadines weighted sum analysis and identification of areas of greatest potential for each technology are presented in Figure 9.12. Note that for this analysis only St. Vincent with an approximated average electricity demand of 16MW was scoped in and all other islands were scoped out due to each having an approximated average electricity demand of less than 1MW.

Figure 9.12 St Vincent & the Grenadines - Indicative areas of greatest potential for each technology



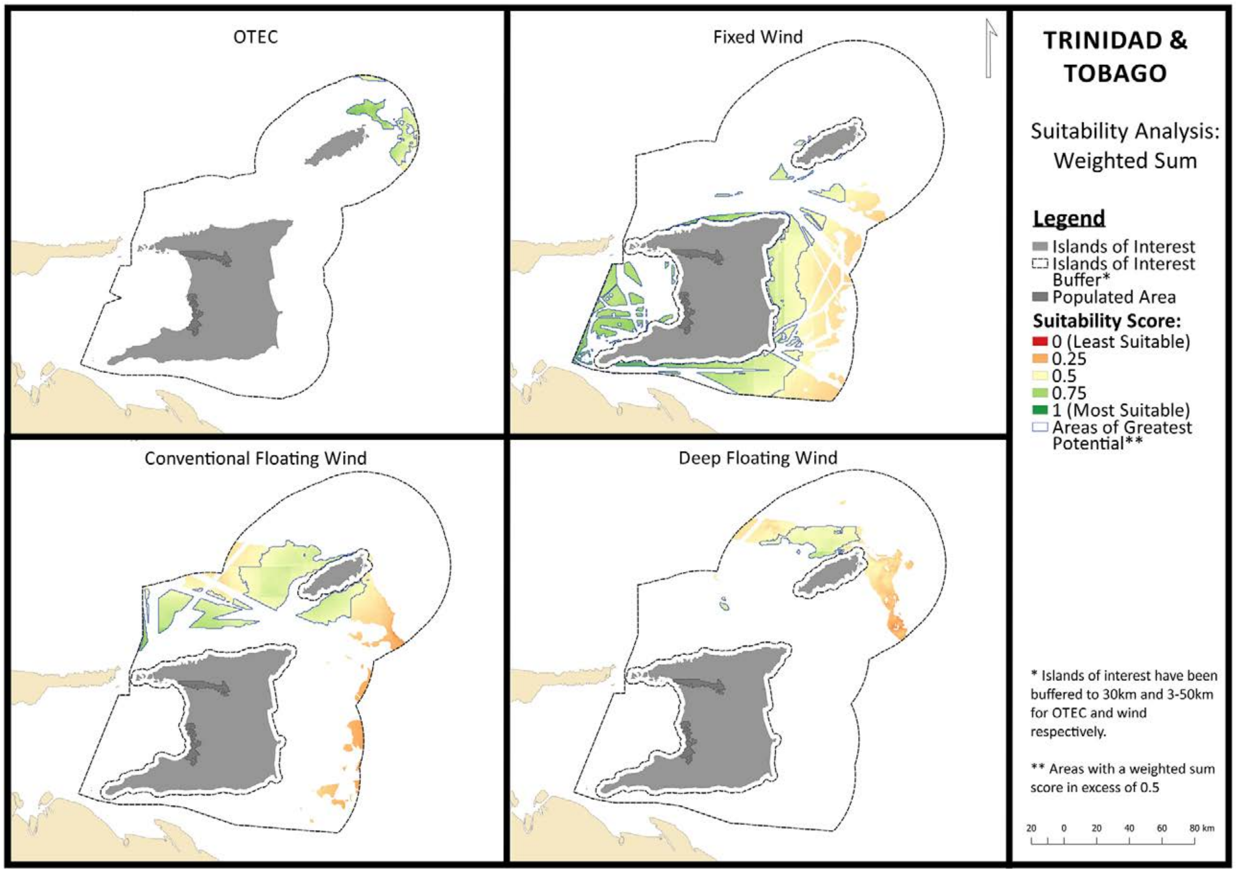
As was the case for Grenada and St. Lucia the east coast of St Vincent is deemed unsuitable for development due to the presence of a high shipping density coupled with steeply sloped and rough bathymetry, and thereafter water depth unsuitable for consideration.

There appear to be excellent areas for fixed OSW to the south of St. Vincent in proximity to Bequia. There are also some suitable areas to the southeast of St. Vincent for conventional floating OSW. Although limited viable space has been identified there is more than enough space available for a project considering the low electrical demand. For deep floating OSW the main large area of suitability is to the east and northeast of St. Vincent, although suitability scores are not the highest, probably due to wave exposure scoring. The northeast also appears to be the best location for an OTEC project with a large and relatively high scoring area identified by the analysis.

9.3.15 Trinidad & Tobago

The overall results of the Trinidad & Tobago weighted sum analysis and identification of areas of greatest potential for each technology are presented in Figure 9.13. Note that for this analysis both Trinidad with an approximated average electricity demand of 1,008MW, and Tobago with an approximated average electricity demand of 56MW were scoped in.

Figure 9.13 Trinidad & Tobago - Indicative areas of greatest potential for each technology



Trinidad's comparatively high electrical demand, much like Jamaica, means that it may be able to host an ocean energy project of sufficient scale to drive down costs. There are however a number of constraints which were considered in the analysis, and these have restricted the area available for development. Of note are substantive high density shipping channels on the north and west coast, as well as oil and gas infrastructure on both the west and east coast of Trinidad.

Trinidad and Tobago have greater expanses of shallow water than other countries under consideration in this analysis and this translates into a large amount of space being identified as suitable for fixed OSW all around Trinidad, although the highest scoring areas are either close to the north or south coast or slightly further from shore on the west coast. Areas identified for conventional floating OSW are to the north of Trinidad or surrounding Tobago, whilst high scoring deep floating OSW area are only identified to the north of Tobago. Similarly, the northeast of Tobago appears to be highly suitable for OTEC, but no areas close to Trinidad are identified for OTEC.

9.4 / FURTHER WORK AND LIMITATIONS

For each of the COI's and for each technology this section has analysed the relative suitability of each technology and identified areas of interest for each country. In doing so, this work constitutes an important first step in highlighting the potential that exists and moving forward in developing the offshore renewable energy resources of the region.

However, this assessment has been carried out at a high level and is limited by access to and quality of data at hand. Additional work in this regard is therefore recommended an essential next step inclusive of the following activities and studies;

- Acquisition of more detailed datasets – including commercially available data and proprietary datasets provided by local and regional public sector bodies and stakeholder groups.
- Gathering, assessment and inclusion of information on onshore electrical grid infrastructure and suitable cable landing points. This has not been considered in this work.
- Further, more detailed consideration of key environmental factors with the aim of cross-checking highlighted areas with any known sensitive receptors.
- Rerunning the model at a country specific level with all and any of the above enhancements or improvements. This would be expected to lead to identification of a number of individual and specific project site options and would further aid in defining and informing the opportunity, enabling more detailed technical and financial studies to be carried out which are considered to be an essential precursor to further commercial project development.

Photograph source: Antigua and Barbuda

/ OVERVIEW DISCUSSION AND RECOMMENDATIONS

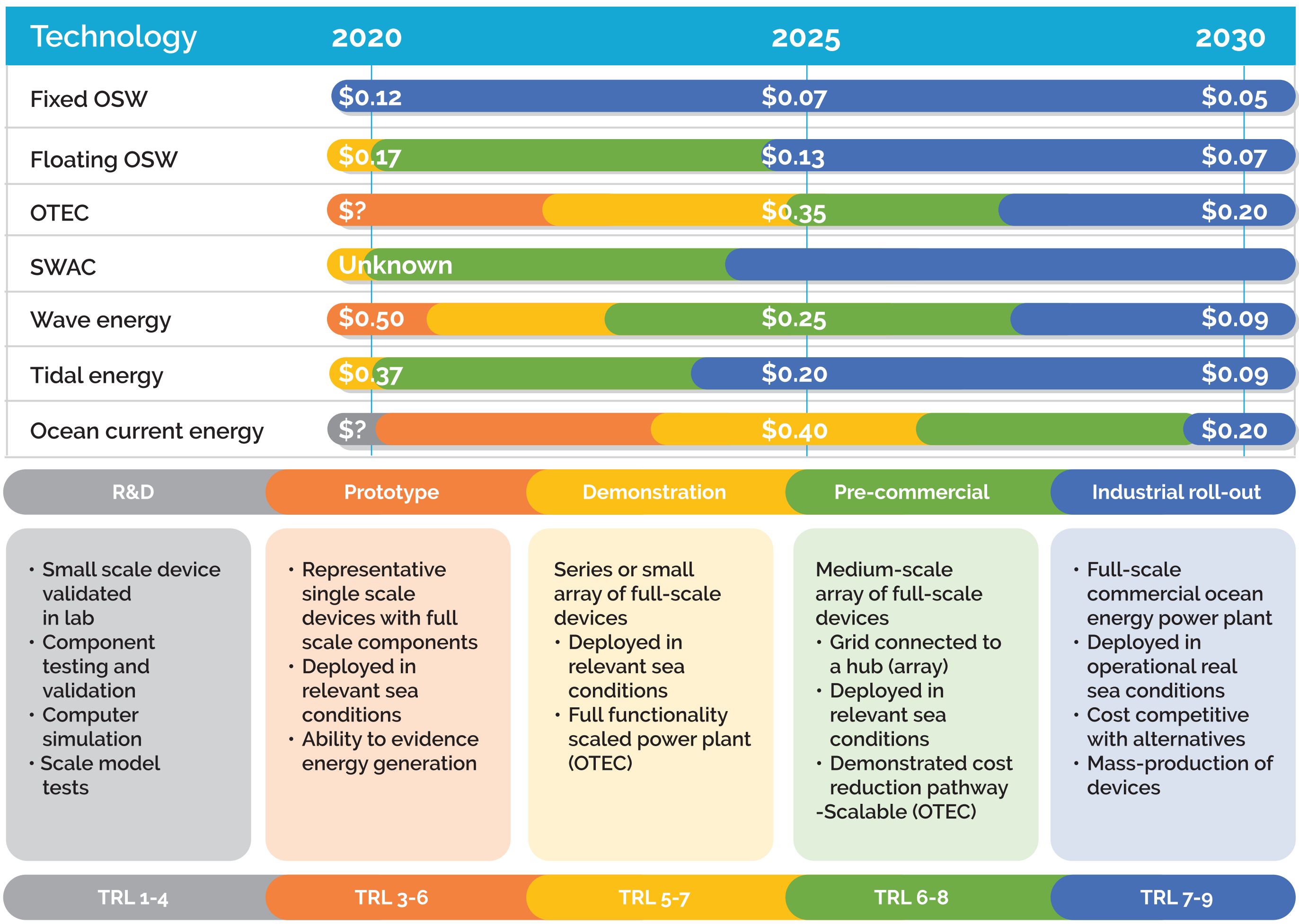
/ OVERVIEW, DISCUSSION, AND RECOMMENDATIONS

10.1 / OVERVIEW OF CURRENT DEVELOPMENT STATUS OF SELECTED TECHNOLOGIES

The development status of each of the selected technologies discussed in this technical note are summarised in Figure 10.1 along with a 'best informed estimate' of projected development pathway and LCOE now and in the future. The commonly used Technology Readiness Level (TRL) benchmarking scale is used in this assessment and an overview of the meaning of wide TRL brackets is also provided in Figure 10.1. This assessment is by its nature subjective but is based upon solid up-to-date information of the latest technology development status and knowledge of the Caribbean market and context. The projected development pathway is intended to reflect general 'global' technical readiness and commercial availability; however some consideration has been given to local market factors and their impact upon this timeline.

For OSW and tidal energy LCOE values are backed up by industry studies. For other technologies, due to a lower level of technical and commercial maturity, there is a paucity of cost information available and so figures given are estimates and are unavoidably subject to a significant margin of error. For some cases no cost figures are given where no reliable cost information is available from the industry.

Figure 10.1 Summary of the technology readiness and likely development timescales of the selected technologies for global application with LCOE estimates



Source: Adapted from Ocean Energy Forum (2016).

10.2 / DISCUSSION BY TECHNOLOGY

This section builds upon the previous analysis to offer in-depth discussion on a technology-by-technology basis. As a general point, the countries in the Caribbean region discussed in this technical note are in faced with high electricity prices with a high carbon footprint from electricity generation, and exploring how the technologies considered in this technical note could be utilised in addressing these issues is a sensible and worthwhile endeavour. In fact, conducting a review of this nature is a highly valuable exercise in that identifying priority technologies and screening technologies with limited promise provides clarity and enables concentration of resources in the areas in which they can be most impactful. Some key discussion points are listed below for each technology with a focus on costs, timescales for deployment and general 'pros' and 'cons'.

10.2.1 Fixed OSW

Fixed OSW offers enormous potential as an established technology with no technical impediment to deployment at scale in the Caribbean. Fixed OSW is the most mature and best currently available option for large scale deployment of offshore renewable energy in the Caribbean or indeed anywhere where installation is technically viable. The key considerations are around cost, timescales for deployment and ensuring that the appropriate regulatory framework is in place to enable projects to proceed. An important additional consideration is ensuring that environmental and local stakeholder factors are adequately incorporated in planning and project siting.

In cost terms, it is notable that the LCOE from fixed OSW projects has reduced sharply and recent projects have shown prices as low as $0.06 USD/kWh. This cost reduction is however largely driven by and linked to economies of scale and the ready availability of an advanced and highly competitive supply chain which will not exist to the same extent in the Caribbean.

Further cost reduction is largely predicated on projects reaching GW-plus scale. Considering the overall relatively low level of electricity demand of many of the islands and countries considered as part of this assessment, and notwithstanding the potential for availability of concessional or innovative financing instruments to facilitate project development in the region, it would be challenging in the near to medium term to deliver the scale required to achieve LCOE levels seen in larger markets elsewhere. That said, the higher cost of electricity in the Caribbean when compared with prices in traditional OSW markets means that cost reductions achieved elsewhere are of limited relevance when assessing viability. A projected LCOE that in other markets wound not be deemed to be attractive and worth pursuing may be strongly competitive against, or indeed may significantly undercut, electricity prices in the Caribbean.

Additional factors worthy of discussion are the size of port facilities required for construction and loadout of a fixed OSW project and the requirement for specialised vessels for turbine installation. In terms of port requirements, smaller islands in the region are not likely to have facilities of suitable size or loadbearing capacity. Access to sufficiently deep water portside for turbine loadout is also required. Considering the size and mass of OSW turbines and the scale of project it is likely that port upgrade works would be needed and this should be factored into overall project cost estimation and budgeting.

Availability of the specialist vessels required for OSW turbine installation, as discussed in Section 2.3, is an additional challenge. The current vessel fleet is undersized and demand is far outpacing new vessel construction. Both port upgrade investment requirements and vessel availability are strong reasons in favour of potential co-development and grouping of multiple projects across the region. Aggregating projects in this way would also provide economies of scale and would also be beneficial in helping to attract project developers who are likely to be most interested in the largest project opportunities – particularly in the more established fixed OSW sector when compared with floating OSW.

10.2.2 Floating OSW

Floating OSW offers vast promise as a rapidly emerging technology with strong technology 'fit' for the Caribbean. The technology is applicable to a wide range of sea depths. As a result, projects utilising floating rather than fixed wind technology will be much less constrained in terms of where they can be deployed and overall scale of project. The sector is performing strongly and there appears to be a clear and rapid route through the remaining development work required to take this technology to full maturity – although until this is the case then the technical risk remains higher than with fixed OSW.

As with fixed OSW, the key considerations are around cost, timescales for deployment and ensuring that the appropriate regulatory framework is in place to enable projects to proceed. Again, an important additional consideration is ensuring that environmental and local stakeholder factors are incorporated in planning and project siting.

The first array projects are now operational and while it is true that these initial projects have required substantial financial assistance in the form of grants and often revenue support to be realised, the rate at which the technology is maturing and scope for further cost reduction leaves no doubt in terms of its viability in the medium to long term alongside fixed OSW as a large-scale renewable ocean energy technology. The projected pipeline of international projects predicts an explosion of activity in the next five years. This can be interpreted as an acceptance of the technological risk by the developer community and an indication of the increasing maturity of the sector.

Currently and in the near term the technology does exhibit a significantly higher cost. As a general guide this can be considered to be up to double the cost of fixed OSW at present (GWEC 2020). Fixed-bottom offshore is expected to remain less expensive than floating in the period to 2035 however the gap between fixed-bottom and floating offshore costs is expected to narrow substantially (Nature Energy, 2021).

As with fixed OSW, projected future cost reduction is largely driven by and linked to economies of scale and the ready availability of an advanced and highly competitive supply chain. Again, considering the relatively low overall level of electricity demand in the region, it will be challenging in the near to medium term to deliver the scale required to achieve LCOE levels seen in larger markets elsewhere. However, the consistently high price of electricity seen in the Caribbean and other similar island settings may boost commercial viability and lead to acceptance of the technology at LCOE levels that are higher than those expected in other larger markets. The potential availability of concessional or innovative financing instruments to facilitate project development could also be important in achieving an acceptable business case for smaller scale projects in the region.

Possible additional benefits of floating OSW include compatibility with smaller scale port infrastructure, reduced port-side water depth requirement, possible reduced requirements in terms of supply chain capability, and reduced visual impact with turbines located further from shore than fixed OSW. Many floating OSW concepts can be assembled port-side and towed to the deployment location. This means that installation vessel requirements for floating OSW are, although not insignificant, generally less specialised than for fixed OSW.

Lastly, again as with fixed OSW, there are a relatively small number of project developers in a burgeoning global marketplace. It may be difficult to place the Caribbean region in the minds of these developers when there are opportunities in many markets. Again, aggregating projects across the region may be an effective way to counteract this.

10.2.3 OTEC

OTEC technology presents an attractive proposition in the Caribbean region in general because of the excellent thermal resource, access to deep waters in close proximity to shore, and the potential to generate a steady baseload of electricity alongside other ancillary activities such as SWAC, desalination, aquaculture, and chilled soil agriculture. Nonetheless, technology risk and extremely high capital cost is a significant issue due to the limited track record of the sector and small number of operational plants installed globally. The continued presence of any medium to large maritime construction companies in the sector could provide a means to manage this risk through provision of warrantees and guarantees.

Significant research and consideration would be required in determining an appropriate location and scale of such projects. Onshore OTEC plant is highly site-specific requiring access to suitable depths and temperature gradient within as short a distance as possible. Offshore OTEC plant is much less site specific but would need to be located within a reasonable distance to shoreside electrical connection and water connection in the case of a desalinating plant.

The design of project to be pursued will be important in determining the range of ancillary benefits achievable. Market players seem to be focussed on closed-loop offshore plants. With a closed-loop design freshwater production is not a natural by-product (but can be produced with the electricity generated), and with offshore plants SWAC and fresh water production are logistically challenging.

In terms of scale of such demonstration projects, it seems logical that efforts will continue to focus on either 'scaled' prototype demonstrations under 1MW which are less capital intensive, or larger scale commercial demonstrator project towards the 10MW range. There seems to be little activity or attraction in development of projects within the centre of this range as small projects can be entirely considered as R&D whereas for larger projects the economics will improve markedly in line with increases in rated output due to the high fixed capital costs of the technology.

Achieving an acceptable cost of energy is likely to be an issue for the next generation of demonstrator projects. It is however essential for this next generation to be built somewhere in order for future installations to benefit from the learning and reduced LCOE. To make projects viable it may be necessary to attract significant grant funding, and consultation with developers revealed their opinion that it may be necessary for upcoming projects to be situated onshore to enable added value through ancillary benefits to deliver an acceptable financial outcome and LCOE.

Additionally, while a number of the elements of an offshore OTEC plant (such as anchors, pipelines, heat exchangers) have been deployed as part of projects, in other offshore sectors significant gaps remain in the understanding of the likely environmental impacts – both positive and negative – of a large scale OTEC plant. Some key questions include; the impact of continuous mixing of surface and nutrient rich deep water layers, potential impacts on deep water species, organism attraction and biofouling, noise pollution, and others. These questions will remain largely unanswered until a track record has been established through the operation of the first pilot projects offshore.

Overall, whilst OTEC as a technology concept has significant merits, there is a requirement for someone or somewhere to be first mover on commercial scale deployment of this technology. This will undoubtedly entail a very high capital outlay and not insignificant technology risk. With other ocean energy technologies, in particular OSW, offering a solution at an apparently acceptable cost and being commercially viable now or in the near term it is understandable that activity in the OTEC sector appears to be struggling to get beyond the prototype demonstration stage.

10.2.4 SWAC

In terms of technology readiness, the relatively small number of projects installed globally does raise some questions. There is an apparent lack of momentum for widescale uptake of the technology generally at a global level. The small-scale, site-specific and privately developed nature of projects could be skewing this perception however in that there may indeed be a larger base of installed projects, but these have not been publicly announced or reported.

Market uptake questions aside, the technology is simpler than OTEC and, other than potential complexities around pipelines, should be relatively straightforward to implement. By way of an illustration of the importance of this point, the project installed in Bora Bora in 2006 was reported as being operational for approximately ten years but then issues with the pipework meant that it ceased functioning around 2016. This could be taken as a cautionary tale for subsequent projects – although the fact that a second and now third such project is being installed in French Polynesia indicates an advancement in the technology and it can be reasonably assumed that measures have been taken leading to a reduction in technical risk. This is a clear example of how learning from the first pathfinder projects is critical to subsequent projects and eventual rollout of the technology. Examples of potential pipeline considerations include the need for enhanced engineering design to deal with wave action such as armouring of pipelines or a requirement to protect pipelines altogether through onshore directional drilling. These engineering solutions do not prohibit development, but rather need to be factored in at the design stage and can therefore be considered as part of an assessment of overall project viability. It should also be noted that there may be scope and potential for further evolution and improvement of the technology which again would improve its attractiveness.

Market fit would seem to be good given that energy prices in the Caribbean are generally high and, as with many other tropical island locations, cooling accounts for a significant proportion of energy usage across all sectors. It therefore seems likely that numerous suitable locations for SWAC projects could exist. This assertion is backed up by the results of the SWAC study for the region carried out in 2015 (CAF, 2015).

An additional factor influencing the appeal of the technology is the relative value placed on security of supply. A number of early projects have been installed in luxury hotels and resorts which place a high importance on reliable air conditioning to ensure their customer experience meets expectations. Therefore one can conclude that the technology is more attractive for prospective customers in areas or markets which have unreliable electricity service and/or are dependent on supplies of fuel or oil brought from elsewhere for air conditioning.

The potential for SWAC to deliver baseload cooling supply is also a relevant consideration which boosts the importance of the technology in the context of the region when the technology is compared against intermittent or variable renewable energy technologies such as solar photovoltaics or wind. Interestingly there is also potential that seawater cooling could be coupled with variable renewable energy sources. Under this model, excess renewable electricity could be used to pump cold seawater into thermal storage tanks, which could be used to meet cooling demand later when needed. For longer-term seasonal storage, cold pumped seawater could be used to freeze freshwater in the storage tanks. Then, when cooling demand is high, both the seawater air-conditioning system and the energy stored as ice could meet cooling needs (Hunt et al., 2020).

Identification of suitable customers for cooling load (such as a new or existing industrial, commercial or hospitality sector users) with close nearshore access to deep cool waters would seem to be a logical next step and pre-requisite for progression of any SWAC project in the region. Examples of such users could include airports, data centres, hotels, resorts, government and military facilities, universities, large offices and commercial buildings, shopping malls, department stores, museums, residential districts, industrial processes, entertainment facilities, temperate fruits and vegetables farming, and food and grain storage (Hunt et al., 2020). It is also worth noting that a SWAC project or projects may be suitable for consideration as a lower risk 'steppingstone' to a larger onshore OTEC project and need not be considered on a standalone basis.

10.2.5 Wave energy

Wave projects have some potential in the Caribbean region but would present some challenges both in terms of technology readiness and site selection. The consistency of the wave regime, or lack thereof in large parts of the region, also raises some questions on the suitability of this technology. The best deployment locations are highly likely to be on the eastern coasts of islands open to the full fetch of the Atlantic Ocean.

Wave technologies are generally designed for waters of less than 100m depth. Coastal bathymetry and potential anchoring and mooring challenges at any intended deployment site would need to be investigated thoroughly. In areas with steep bathymetry close to shore siting of wave energy devices is challenging. An additional challenge may be the presence of coral reefs or other protected natural features or indeed touristed areas. These are typically located in shallower depths and there is potential for conflict when considering the siting of any potential wave energy project.

Whilst a large-scale commercial application of wave energy technology is not feasible at present as the technology has not been sufficiently proven at demonstrator scale there could be an opportunity for the region to take the lead in demonstrating wave energy technology by potentially facilitating deployment testing and research of wave energy devices. Efforts could range from potentially facilitating testing and research centred on individual wave energy devices at varying scales to attraction and hosting of larger pre-commercial devices or commercial demonstrator arrays at full scale. This point notwithstanding, it is somewhat difficult to reconcile the small number of wave developers in the sector which have advanced to large-scale prototype demonstration with the numerous wave energy ocean test facilities that already exist in Europe, the USA and China. These existing centres have plenty of capacity and any newly established Caribbean wave energy test centre would have to compete to attract developers which could be challenging given that other regions have had time to establish track record, supply chain knowhow and technology specific grant funding resources.

The combination of wave energy technology in any new build breakwater projects may also be worthy of consideration generally in the region as a less technologically risky option. An additional option may be to encourage 'co-location' of floating OSW, and potential future wave energy pilot demonstration and eventual wave energy commercial projects. A small number of developers are progressing hybrid systems which combine wave energy with fixed or floating OSW and these technologies could represent a viable pathway to deployment of wave energy technology in the region.

10.3 / TECHNOLOGY ASSESSMENT SUMMARY AND SCREENING

This technical note has shown that, in terms of resource potential and availability of suitable sea depths in proximity to land, the region has good, but varying, potential for fixed OSW, floating OSW, OTEC and SWAC with wave energy, tidal and ocean current being much more limited. Table 10.1 below combines this information with an assessment of the different stages of readiness of each technology. This enables final summarising recommendations to be made on which technologies should have a priority focus, which should be continuing to be monitored and those that can be screened out at this stage.

Table 10.1 High-level technology assessment summary and screening

Technology	Technology Readiness Level	Resource Quality	Near / medium-term Readiness	Recommendation / Priority Level	Note
Fixed OSW	7-9	High	High	High – Very High	High priority. Promote and pursue.
Floating OSW	6-8	High	High	High – Very High	High priority. Promote and pursue.
OTEC	3-6	High	Low	Low - Medium	Continue to monitor.
SWAC	5-7	High	Medium	Medium - High	Continue to monitor. Consider means of promotion of technology uptake.
Wave energy	3-6	Low - Medium	Medium	Low - Medium	Not priority but potentially of interest. Continue to monitor.
Tidal energy	5-7	Low	Low	Low	Unsuitable – screen out
Ocean current energy	1-4	Unknown	Low	Low	Unsuitable – screen out.

10.4 / CONCLUSION

In conclusion, both fixed and floating OSW have been identified as the priority focus technologies to enable large-scale decarbonisation of electricity supply in the near to medium term, noting the potential challenges of developing relatively small-scale projects at distance from the main centres of the industry. For OTEC, in contrast to both forms of OSW, economies of scale are unlikely to be a problem with proposed projects generally under 10MW. Technological risk and economic considerations (i.e. achieving an acceptable LCOE) are however much more uncertain and pose the main barriers to delivering a project in the region. Tapping into additional revenue streams by coupling with SWAC projects for example may provide a route to delivering additional value but this is not straightforward. Standalone SWAC projects also look promising, noting the highly site-specific nature of these projects necessitating detailed assessment of opportunities. Wave, tidal and ocean current energy offer limited potential for reasons discussed previously in this technical note.

In Barbados, a country which has been active in investigating ocean energy over recent years, the Ministry of Energy, Small Business and Entrepreneurship is considering installation of ocean energy technology within its

EEZ to contribute to the Barbados National Energy Policy target of 100 per cent renewable energy by 2030. As part of this work a suite of ocean energy studies have recently been completed with the aim of assessing the feasibility of ocean energy from a technical, environmental and logistical point of view as well as considering legal, supply chain capacity and tourism impact (Barbados Government, 2021).

Through this work, 16 possible ocean energy project scenarios were identified. Of that number, six were selected which included fixed OSW, floating OSW and OTEC, and ranked in order of priority. The outcome of this process was that fixed and floating OSW located off the north of the island were identified as the preferred options with strong viability from a cost perspective. This work also revealed that the wind resource in Barbados is on a par or of a higher quality than areas in northern Europe which are already host to large OSW projects. Further detail of this work is proprietary and is not in the public domain but its outcomes are directly relevant and are a strong indicator of what is possible and likely in terms of the viability of OSW and OTEC elsewhere in the region.

Whilst fixed OSW is considered to be preferred to floating OSW on technical and cost grounds at present, the 'gap' between the technologies is narrowing. When additional benefits of floating OSW in the Caribbean context are taken into consideration the gap narrows further. Examples of these benefits include compatibility with less advanced port infrastructure, reduced requirements in terms of supply chain capability and reduced visual impact with turbines located further from shore. Indeed, according to a recent study collating the views of experts around the globe, the median expert predicts that 11–25% of all new offshore projects globally will feature floating foundations by 2035 (Nature Energy, 2021).

Floating OSW will very soon emerge into a major sector in its own right and will need to be viewed separately to the more established fixed OSW. The importance of floating OSW and ratio or mix of fixed to floating OSW projects does seem like it will be higher in the Caribbean than many other markets. Therefore, given the predicted strong performance of floating OSW and the similarities between fixed and floating OSW, it is logical that both technologies are investigated and progressed in parallel in any future studies in the region.

For both fixed and floating OSW, achieving a scale of project substantial enough to deliver reasonable economies of scale will be a major consideration. A regional approach has been proposed to try and tackle this and ensure sufficient activity in the region to generate competition from manufacturers and the supply chain. If numerous smaller projects were being progressed in the region in a similar timeframe, it might be possible to benefit from improved buying power and economies of scale to deliver a better LCOE. An alternative, but perhaps more challenging approach may be to construct a single large project and look to connect in multiple countries through sub-sea transmission cables.

Additionally, as a note of caution, the Caribbean has a number of unique elements which make it difficult to draw direct comparison with other regions. Indeed, there are significant differences from country to country and island to island within the region itself. It is worth highlighting that are likely to be instances where there is a limit to which achievements, experiences and lessons learnt elsewhere around the globe are relevant and can be applied to the Caribbean. One such instance is the topic of LCOE's where, for reasons outlined above, it is unlikely that LCOE levels in the Caribbean will match those achieved elsewhere. Whilst this fact may be a critical consideration in other regions, it is not of particular relevance in a Caribbean context. Given the high and often fluctuating electricity prices in the region, the target LCOE for project viability in the Caribbean is not as low as elsewhere. Therefore, while a direct comparison can provide useful context, caution should be exercised when making comparisons with other markets.

Indeed, establishment of a regional approach to revenue support for new projects, such as through subsidy, revenue stabilisation, or long-term government backed power purchase agreements may also be a useful mechanism for encouraging activity. Given the existing cost of energy for many countries in the region this could be set at a level which could make smaller projects more attractive for developers. Another factor which could positively impact the prospects for project development in the Caribbean is the emergence of other new markets in the western hemisphere. This could alleviate some of the issues associated with being reliant on sourcing key supply chain elements such as equipment manufacture and supply, and installation vessels from markets in Europe and Asia. In North America, development is gathering pace with the emergence of a number of large-scale projects including the 800MW Vineyard Wind project approved in May 2021. Momentum does also seem to be building for deployment of offshore wind in Brazil, and particularly in the northeast of the country as a market with relatively close proximity to the southern Caribbean (IDB, 2019). There are a number of potential projects mooted with a variety of local and established international companies from across the global said to be involved. Details are however scarce and difficult to define.

It is also worth noting that the low carbon agenda drives further electrification of industry and transport (including shipping). It can therefore be expected that demand will increase from new or existing sectors for green electricity. In that vein there may be an opportunity for countries in the Caribbean to use ocean energy technologies to reduce the carbon footprint of its main industries – the offshore oil industry in Trinidad and Tobago for example.

Other future markets being explored for OSW include production of green hydrogen by connecting wind turbines to electrolysers. A project in Germany is looking to further combine this OSW powered green H_2 with captured CO_2 to create carbon neutral aviation fuel (Recharge, 2019). Other projects, such as HySeas III in Scotland, is looking to use green hydrogen to power shipping (HySeas III, 2019). In the medium to long term there could be an opportunity for the Caribbean to use green ocean energy to power new industries in the region, such as a hydrogen/ammonia bunkering and refuelling for low carbon cruise liners, the incentive being to unlock an indigenous clean energy resource with potential that far exceeds the current projected electricity demand of all of the focus countries in this technical note, and can play a pivotal role in moving away from the oil-based system which the region depends on at present.

10.5 / RECOMMENDATIONS FOR FOLLOW ON WORK

In addition to presenting a technology review of numerous relevant ocean energy technologies, this technical note has analysed available data on marine energy resource and other datasets to allow evidence-based discussion and recommendations to be made on the suitability of each technology for consideration for near term deployment. Results of Locational Guidance work for fixed OSW, floating OSW and OTEC have also been presented and discussed.

This technical note therefore provides a solid foundation on which to base future work to identify and assess locations of particular potential for future projects. Further work is required to identify promising areas for development to take account of the level of electrical demand, grid capacity, other sea users and other technical parameters.

The work carried out and methodology applied in this technical note has provided the following benefits:

- 'Screening' of viable technology types and narrowing of technology options - thus lending focus to future discussion and policy development.
- A much-improved understanding of potential siting of future offshore arrays, taking into account resource availability and other key considerations.
- Raising awareness of the potential that exists in the region – particularly for OSW – and highlighting the deliverability of this technology within a reasonable timeframe
- Understanding of possible additional benefits outside of MRE including contribution to the wider Blue Economy agenda.

Overall, this technical note has shown the extensive potential for ocean energy deployment in the Caribbean across numerous technologies in terms of matching resource potential, technical and commercial readiness and Locational Guidance work, therefore providing a solid founding on which to base further, more specific investigation of MRE technologies in the region.

10.6 / LINKS TO FURTHER INFORMATION

In production of this technical note every attempt has been made to fairly and accurately describe and evaluate the current status of the various technology sectors within the Ocean Energy industry. However, due to the breadth of activity underway and in the interest of brevity, it has been necessary to be selective in the information presented. Numerous industry specific reports are available which supplement the information in this technical note and which the reader should consult for further detail. To this end links are provided to a range of recent reports in Table 10.2.

Table 10.2 Reports of relevance to the selected marine energy technologies

Report title	Year	Source
CAF: Pre-feasibility Study for Deep Seawater Air Conditioning Systems in the Caribbean	2015	https://www.esmap.org/sites/esmap.org/files/Caribbean_SWAC_Final_Report_01-10_web.pdf
International Energy Agency: Renewables 2020: Analysis and forecast to 2025	2020	https://iea.blob.core.windows.net/assets/1a24f1fe-c971-4c25-964a-57d0f31eb97b/Renewables_2020-PDF.pdf
IEA-OES Annual Report: An Overview of Ocean Energy Activities in 2020	2021	https://www.ocean-energy-systems.org/documents/40962-oes-annual-report-2020.pdf/
IEA-OES: Ocean Energy in Islands and Remote Coastal Areas	2020	https://www.ocean-energy-systems.org/documents/85277-ocean-energy-in-islands-and-remote-coastal-areas.pdf/
IRENA: Fostering a Blue Economy- Offshore Renewable Energy	2020	https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Fostering_Blue_Economy_2020.pdf
IRENA: Innovation Outlook: Ocean Energy Technologies	2020	https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf
IRENA: Practical Insights on Green Hydrogen	2021	https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/May/IRENA_Coalition_Green_Hydrogen_2021.pdf
Ocean Energy Europe: Ocean Energy key trends and statistics 2020	2021	https://www.oceanenergy-europe.eu/wp-content/uploads/2021/02/OEE-Stats-Trends-2020.pdf
Ocean Energy Europe: 2030 Ocean Energy Vision	2020	https://www.oceanenergy-europe.eu/wp-content/uploads/2020/10/OEE_2030_Ocean_Energy_Vision.pdf
US Department of Energy: 2019 Offshore Wind technology data update.	2020	https://www.nrel.gov/docs/fy21osti/77411.pdf
Wind Europe: Offshore Wind in Europe, key trends and statistics 2020.	2021	https://windeurope.org/intelligence-platform/product/offshore-wind-in-europe-key-trends-and-statistics-2020/
World Bank Group: Going global – expanding offshore wind in emerging markets.	2019	http://documents.worldbank.org/curated/en/716891572457609829/pdf/Going-Global-Expanding-Offshore-Wind-To-Emerging-Markets.pdf

Photograph source: St. Vincent and the Grenadines

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