



Siting and selection for marine renewable projects

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This paper looks at the issues to be addressed when determining optimum locations for the deployment of marine renewables. As the public perception of global warming and carbon emissions heightens, governments and authorities are forced to insert renewables into their overall generation mix. Clearly, reducing emissions is a good thing for the planet as a whole, but it also has the added advantage of increasing power-grid resilience through distributed sources of generation. Although constantly improving, in general, renewables are still economically marginal investments, so great care must be taken to select and site these devices so as to maximize their return on investment (ROI). We will discuss the three primary areas of marine renewable devices: Wind, Wave and Tidal stream, and present the most important issues to be addressed when reviewing each. Particular attention is paid to wave energy devices as it is felt that these devices are currently in a particularly interesting, and relevant, phase of development. A selection of examples of each of the most significant and currently viable technologies is introduced for each of the areas, and for each of these devices, specific siting constraints are identified and discussed.

Keywords: site selection, wind, tidal and wave energy, constraints, renewables

Este artículo trata sobre los aspectos a ser considerados para determinar las ubicaciones óptimas para la instalación de equipos marinos de energía renovable. Debido a que la percepción pública se hace más sensible al calentamiento global y la emisión de CO₂, los gobiernos y las autoridades se ven forzadas a incorporar equipos de generación de electricidad que usen fuentes de energía renovable. Claramente, la reducción de emisiones es positivo para el planeta, pero también tiene la ventaja de incrementar la estabilidad de la red por medio de fuentes de generación distribuidas. A pesar del mejoramiento constante, en general, la generación usando fuentes renovables de energía representa todavía un porcentaje marginal de inversión. Por ello es necesario tener mucho cuidado en la selección y ubicación de los equipos de manera de maximizar la recuperación de la inversión. Se discuten tres áreas principales de los equipos marinos: viento, olas y mareas. Se enfatiza en los equipos de oleaje debido a que se encuentran en una etapa de desarrollo con grandes proyecciones. Se presentan ejemplos de las tecnologías más importantes y viables en cada área. Se identifican y discuten restricciones específicas de ubicación.

Palabras clave: ubicación, energía eólica, maremotriz y de oleaje, restricciones y equipos

INTRODUCTION

Renewable energy generation is undergoing substantial growth world wide, with various governmental schemes being employed to aid device development and encourage new installations. This subsidization will be a key enabler if global CO₂ emissions targets are to be met. The marine environment can provide a significant energy source to exploit for this purpose.

It is clear that there is significant energy present in the marine environment. Waves, winds, currents and tides are all sources of energy that under normal circumstances are avoided or mitigated. With the appropriate technology, however, these sources of

energy can be turned into exploitable resources.

There are a number of discrete energy sources present in the marine environment, some of which are more accessible than others. These include: wave energy, tidal energy, ocean currents, ocean thermal energy OTEC [1] and salinity gradient power [2].

Wave and tidal energy are likely to be the primary sources of marine energy in the near future, although there is growing interest in other, more esoteric forms that may also offer high potential resources if the technology is developed. Ocean currents contain a great deal of kinetic energy, unfortunately the velocities involved are low and efficient capture is difficult.

Ocean thermal energy exploits the temperature difference between a solar heated ocean surface and cooler deeper water. The temperature difference is normally in the region of 5-10°C meaning that it is difficult and expensive to efficiently transfer this temperature differential into useable power. This is a proven technology, although it has only been demonstrated at a relatively small scale (50 kW).

A more esoteric method uses the salinity differential between salt water and fresh water. There are a number of ways of turning this salinity differential into useable power. One such method uses a semi-permeable osmotic membrane to generating a hydrostatic head difference. Also "Reverse Electrodialysis", produces electricity through differences in ion concentration. These methods show promise and have been demonstrated in a small scale, however they still need to demonstrate that they can operate feasibly at a commercial scale.

Conspicuous by its absence, offshore wind energy was excluded from the above list as it is not strictly a marine resource and can in many cases be exploited better as an on-shore utility. Nevertheless, wind turbines are now moving offshore in an attempt to side-step many of the on-shore problems and also to attempt to capture higher wind resources. As a result of this, offshore wind energy can be considered as a growing marine sector.

The main reason for interest in the marine environment is the very high energies present and it is this which results in one of the largest challenges. Developers are attempting to design devices that operate flawlessly, capturing very high powers in environments that would otherwise be considered completely hostile. Therefore in order to develop a particular resource there is a trade-off between engineering and cost which is subject to the law of diminishing returns. This paper concentrates on what are likely to be the three main types of marine resource exploited in the near future, Wind, Tidal and Wave.

PRIMARY TECHNOLOGIES

Offshore Wind Energy

Wind power is a proven technology with a total global installed capacity of almost 100 GW; of this, currently 1% is installed offshore [3, 4]. There have been technological and cost barriers to an earlier adoption of offshore wind which are only now being addressed.

Of course, offshore wind is an expensive proposition, and although there are somewhat stronger winds offshore, it only really becomes an option when political or local issues prevent on-shore exploitation. The economic case for offshore wind is generally besieged with additional planning and logistic costs, coupled with the additional capital costs of sub-sea grid connections and foundation structures. Of course, subsidies and imaginative project financing can often offset these additional costs.



Figure 1: RePower 5 MW offshore wind turbine in around 25 m water [7]

Wind turbines have evolved into a proven design and work is currently concentrating on refinements to effectively improve efficiency whilst reducing costs and hence kWh costs. Larger turbines are seen as one way to reduce the overall cost per kWh by requiring less installed units and so theoretically reducing overall installation costs. The largest devices currently on the market are by manufacturers Enercon and RePower who offer turbines in the 5 to 6 MW range (Figure 1). These units have a rotor diameter above 120 m and a hub height generally over 100 m [5, 6].

Tidal energy

The total energy dissipated from tides globally is approximately 3000 GW with 1000 GW in readily



accessible shallow water. Tidal energy is seen to be very attractive as it does not suffer from the inherent irregularities of other renewable sources. The resource is regular, predictable and reliable. Energy can be produced through either tidal current or tidal range. There are currently three different methods for harvesting tidal energy; tidal turbines, tidal barrages and tidal lagoons.

Tidal turbines, as shown in Figure 2, are the sub-sea analogue of wind turbines. The high density medium means that for the same power the turbine can sweep a much smaller area. Tidal barrages operate by developing a hydrostatic head across an estuary, for example, and generate power using low head turbines in a similar manner to a standard hydroelectric plant. They are efficient schemes but require a particular geographic arrangement, such as an estuary that can be dammed, although there are opportunities in other similar geographic areas such as open mouth bays (Figure 3).

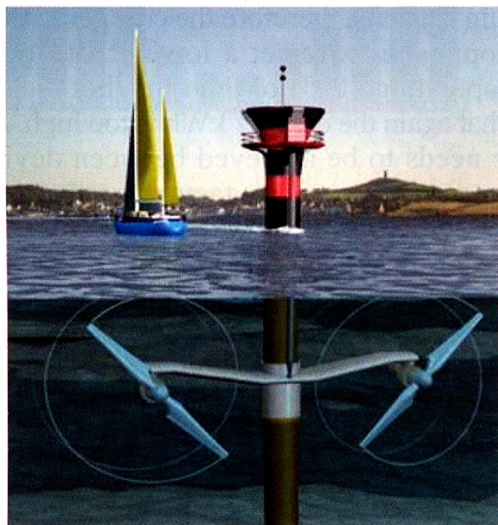


Figure 2: MCT tidal current turbine



Figure 3: La Rance tidal barrage, France, capacity of 240 MW

These schemes have been developed for many years and the UK is currently developing a scheme to install an 8 GW barrage across the Severn Estuary.

Tidal lagoons are isolated caisson-type structures located in an area of high tidal range. Power is generated by maintaining a hydrostatic head difference between the external water level and the internal water level. Again, this method uses low head hydroelectric devices to extract the potential energy.

Currently tidal turbines are at the pre-commercialization stage and gathering a considerable amount of interest, with one device being demonstrated at full scale. Marine Current Turbines (MCT) is probably the most advanced company in the development and demonstration of this technology with an operating grid-connected plant in Ireland, see Figure 2. It appears that even though this is an immature technology, it is very much on the brink of the mainstream with a number of schemes in the planning stages. Tidal barrages are a proven technology, La Rance have been operating since 1966 (Figure 3). If sited correctly they have the potential for very large power outputs through the use of proven hydropower technology. It is interesting to note that generally for a barrage scheme, power is generated only on a single phase of the tide. Whilst it is possible for two-way generation, the benefits do not always outweigh the additional costs. Tidal lagoons operate on the same basic principle as the tidal barrage, except that the barrage forms a circular lagoon which can be located anywhere with a large tidal range. For these schemes to be efficient they need to be very big, with the enclosed area in the order of a few km² and therefore they will provide a significant impact upon navigation, the environment and will cause serious changes in coastal processes. In addition, the power output from these devices will be much lower per unit length than a standard barrage and hence the cost per kWh will be significantly higher.

Wave energy

Certainly the most visible of the marine resources, wave energy extraction has been suggested for over 100 years. Feasible schemes have been put forward since 1970 and although development has been slow, commercial devices are now starting to emerge. One of the main reasons for slow development are the difficulties faced when designing devices that will capture the energy present whilst being inherently reliable and survivable in extreme conditions.

Power in kW per meter of crest length is expressed in terms of wave height H and period T , for easy reference, in deep water this can be approximated to:

$$J \approx H^2 T \quad (1)$$

where J is the energy in kW/m of wave crest, H is the wave height in meters and T is the wave period in seconds. The typical wave distribution for a typical high energy site chosen specifically for wave energy application is shown in Figure 4. This shows a year of recorded data which illustrates how the power in the resource is distributed. Whilst the average annual energy for this particular site in Figure 4 is only 22 kW/m, there is a significant proportion of the energy which is higher than 200 kW/m. Extreme loads are substantially higher still as this site features a 1:100 year design case with an energy of over 3 MW/m.

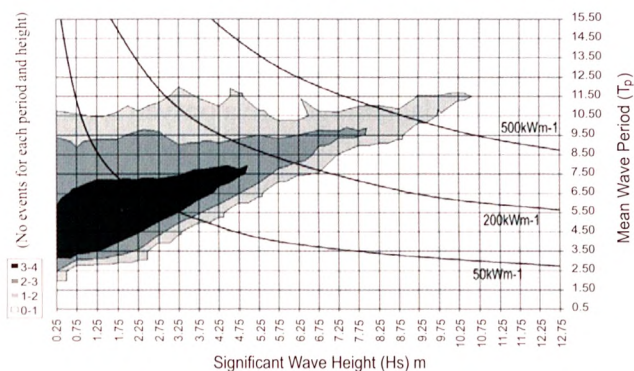


Figure 4: Historical distribution of wave height against period for the EMEC site in Orkney, UK [8]. A higher frequency of a particular sea state is determined by the darker shading. The curved lines indicate the resource power per meter of wave crest.

Another typical example of this is shown in Figure 5. This shows a time series of incident energy taken from a location off the Chilean coast. The sharply variable nature of the resource is clearly shown with the incident energy varying from less than 40 kW/m to 120 kW/m in the space of a few hours.

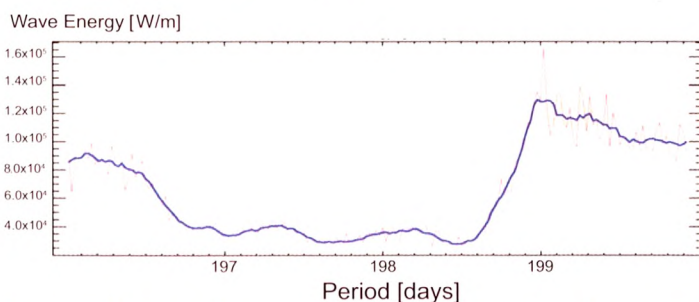


Figure 5: Measured time series of wave energy for a location 50 km of the Chilean coast for a period of four days.

Given the highly variable nature of the resource environmental conditions, wave energy devices need to be designed to do two things:

- Produce maximum output for as much of the time as possible
- Handle large peaks in incident wave energy without damage to the device and with minimal disruption to the device output (be inherently power limiting for larger, higher energy conditions)

The survival of any marine energy device is of paramount importance. In general, due to the stochastic nature of the water surface elevation, a large single wave may occur in a sea state with a much lower energy. If a device is already operating at rated capacity, it would need to be inherently survivable for these peak (generating) events. Of course, in highly extreme sea states, it is reasonable to expect the device to switch to a non-generating 'survival' condition, however a viable device needs to have the ability to "power limit" during operation to ensure the device is fully robust.

The sizing of a device to a particular site is also extremely important. At one extreme; a high-output, high-cost generator operating only occasionally at maximum capacity, therefore the cost per kWh is high. At the opposite extreme; a lower cost, low-output device operating 100% of the time, but the output is so low that again the cost per kWh is too high. A careful balance needs to be achieved between device rated power and device capacity factor in order to find the most cost effective device for a particular location. Figure 6 illustrates a typical power matrix for a Pelamis device. For a certain period, normally a year, the ratio of the total power developed by a device over the power developed if that device was operating at maximum capacity for the whole period is known as the "Capacity Factor". This is an important metric to consider and a personal rule of thumb is that this should be higher than 0.25 for an acceptable economics.

		Power period (T _{pow} , s)																	
		5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	
Significant wave height (H _s , m)	0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	
	1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle	
	1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33	
	2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59	
	2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92	
	3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132	
	3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180	
	4.0	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213	
	4.5	-	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	
	5.0	-	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	
	5.5	-	-	-	-	-	750	750	750	750	737	687	658	586	530	496	446	395	
	6.0	-	-	-	-	-	-	750	750	750	750	750	711	633	619	558	512	470	
6.5	-	-	-	-	-	-	-	750	750	750	750	750	743	658	621	579	512		
7.0	-	-	-	-	-	-	-	-	750	750	750	750	750	750	676	613	584		
7.5	-	-	-	-	-	-	-	-	-	750	750	750	750	750	750	686	622		
8.0	-	-	-	-	-	-	-	-	-	-	750	750	750	750	750	750	690		

Figure 6: Output power of the Pelamis P750 device given as a matrix of periods and wave heights [9]



The disadvantage with renewables such as wind and wave is their inherent variability and seasonality which means that the highest wave conditions only occur for a certain percentage of the year. This can be troublesome from an utility grid perspective. Fortunately the worst wave conditions generally tend to coincide with a higher demand for electricity. Figure 7 illustrates a full year wave resource against electricity demand.

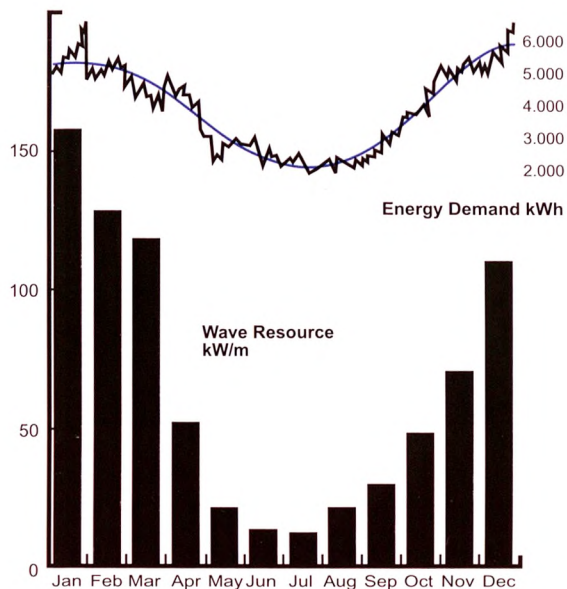


Figure 7: Annual seasonal wave variation for an area just off the Hebrides, Scotland [10]. The upper line illustrates the annual energy demand in kW for the Scottish town Lochgillhead [11]

WAVE ENERGY DEVICES

Wave energy devices have not yet tended towards any common design and this is certainly an indication of how immature this sector is. Nevertheless, there are certain developers that are very close to producing fully commercial devices [12].

Oscillating Water Column (OWC)

The oscillating water column device works as shown in Figure 8. The action of the waves within the cavity creates air pressure that drives a single direction turbine (wells with flow direction independent). Figure 8 illustrates the shoreline Limpet Device [13] which has been operating and grid-connected for a number of years, although primarily as a research installation. There are a number of devices which operate upon this principle and are aimed at commercial installation, some of which are fixed and others which are floating such as those by companies Float Inc and Wavestar.

Fixed, shoreline based OWC's are a relatively established and straightforward technology, with at least two full-scale installations in place, however, floating OWC technology is still to be proven, although the technology has shown promise at scale tests and is currently under extensive development.

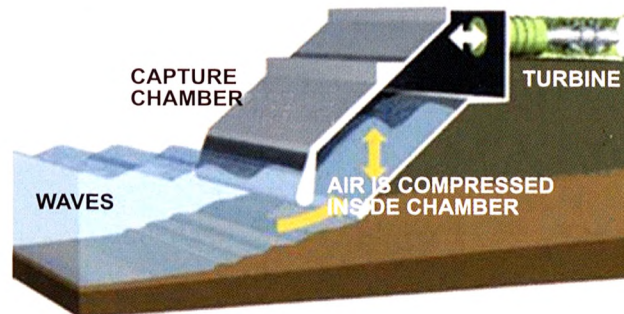


Figure 8: Operating principle of OWC. Limpet Device [14]

Pelamis Wave Power

The Pelamis is a segmental semi-submerged device that operates by generating energy through the relative motion of its individual segments. Rated at 750 kW per device, the design is inherently power limiting to the largest waves and based upon standard off-the shelf components. Currently the only wave energy device to have been demonstrated at a commercial level, the Pelamis has undergone extensive R&D since 1998 with full scale testing and sea trials being commenced in 2002. PWP now has the world's first commercial installation of wave power with three devices deployed off the Portuguese coast, thus PWP holds a significant developmental lead in the wave energy sector. Pelamis P 750 wave energy devices is shown in Figure 9.



Figure 9: Pelamis P750 device [9]

AWS Ocean

AWS Ocean is developing the Archimedes Wave Swing device, which is a submerged, bottom-connected device that generates power by the hydrostatic pressure

imposed upon the device as the wave passes over the top (Figure 10). The technology behind the device was verified at full scale with a 2 MW demonstrator in 2004 and significant development has since taken place, with a revised and improved pre-commercial prototype imminent.

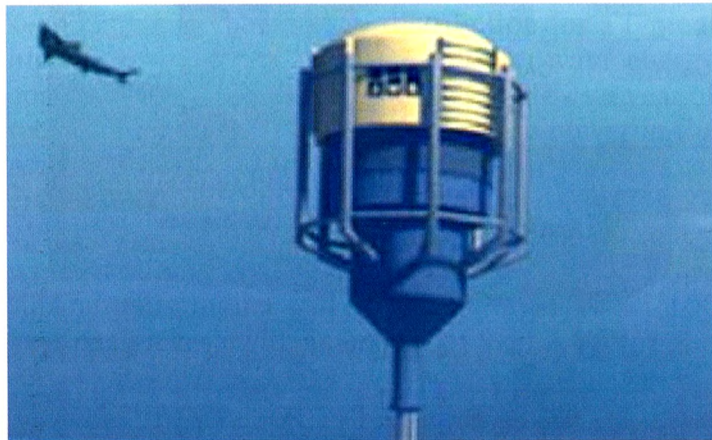


Figure 10: AWS device (taken from www.AWSOcean.com)

Wave dragon

The Wave Dragon device operates using the overtopping principle. Incident waves are channelled to overtop the device and fill a reservoir which is then discharged back to the sea using a low-head turbine. The Wave Dragon device is shown in Figure 11.

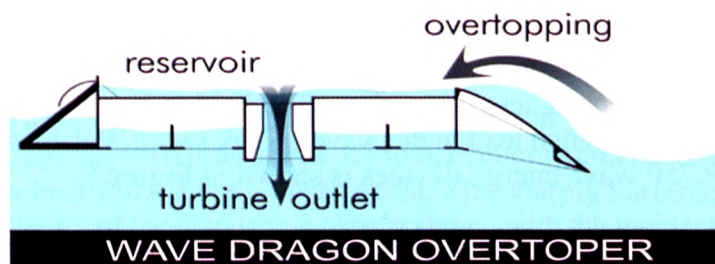


Figure 11: Wave Dragon Overtopping device

The Wave Dragon is another proven technology, with extensive sea-trial experience and is currently in the process of being installed as a 5 MW pre-commercial device off the west coast of Wales.

Point absorber

Utilizing the most basic principles, the point absorber is a device that generates power through the relative motion of a floating "Buoy" section and a submerged reaction structure. This motion is converted into power in a number of different ways, depending upon the

manufacturer. In particular, Fineveras AquaBuoy, and Ocean Power Technologies PowerBuoy both have full scale prototypes and appear to be fairly advanced.

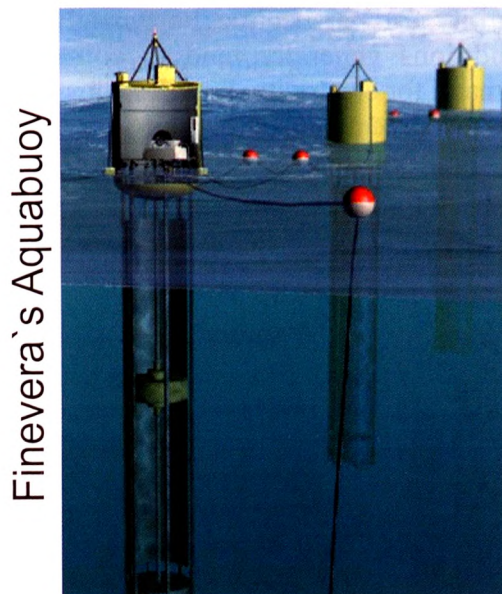


Figure 12: Point absorber

GENERIC SITING CONCERNS

Whilst the different technologies for marine power extraction presented thus far use quite different operating modes and environments, the criteria and processes for site selection can initially follow a similar process.

Firstly, it is important to understand that in the current global climate, the outcome of any marine renewable installation will be watched very closely. The performance of any effective scheme can have very good public relations effects for the parties involved. It is also important to consider, as early as possible, all the significant issues that may need to be resolved and to consult respectable, experienced professionals when dealing with the planning and selection phases. Any problems arising will ultimately have a disproportionately negative effect upon not only the project and its shareholders, but also upon others trying to promote the uptake of marine renewables and clean energy. The key should be to produce installations that are cost effective, but above all safe and reliable.

Ultimately the key ingredient in a successful renewable plant is successful siting. If the site is correctly chosen, costs can be minimized. An iterative selection process should be undertaken that ultimately balances the variables and fixes the critical control factors producing the lowest cost solution:



- a) Roughly identify overall area with suitable resource
- b) Eliminate NO-GO areas
- c) Identify suitable local infrastructure
- d) Determine provisional siting locations (roughly) if any
- e) Undertake detailed analysis of each location and identify any specific issues:
 - Determine survival conditions at site
 - Moorings and subsurface
 - Other pertinent issues
- f) Revise opinion of each site and determine either elimination or a more precise location

It must also be understood that while this macroscopic level of siting will go a long way to choosing a site, detailed analysis must also be undertaken to determine additional factors that may impact upon the economics. The challenge is to find a balance between resource, grid and infrastructure.

Resource modelling

Probably the most important issues to be addressed are accurate identification of the resource through remote sensing and numerical models, which can provide invaluable information to identify areas of interest. Once a rough location is selected, numerical models should again be used to analyze the location in depth, this is especially critical in tidal generation schemes. Detailed analysis is critical not only to fine tune the device and its economics but also to look at the extreme conditions and survivability.

Local grid infrastructure

The complexities and costs associated with connecting the device to the local grid must not be overlooked and should be taken into account at the earliest opportunity. The following questions should be asked:

- a) What power transmission capacity is required?
- b) Does the local grid have available capacity for current and future generation capacity?
- c) Can the local network support the irregular nature of the resource?
- d) Where is the most suitable tie-in point to the local grid?
- e) What is the most efficient routing of the sub-sea cable?
- f) What is the cost and feasibility to install or bolster local grid capacity?

Whilst it should not be the case, it is common that the power grid is often overlooked when considering marine renewable schemes. Any offshore marine scheme will require a sub-sea cable to provide the connection to the power grid. Consideration to the routing of this cable must be given to locate the most ideal tie-in location and for avoidance of either environmental or mechanical hazards. Thought must be given to the type of wave or current environment that the cable must pass through, in addition to the environmental impact any sub sea cable would have. For example, cable landfalls need to avoid sensitive habitats and if any trenching operations are required, then the release of suspended sediments should be considered.

The cost of the sub-sea connection can form a significant percentage of the installation cost, for example, a rough estimate of a 250 MW capacity sub-sea cable is US\$2 Million/km. Much of this cost is for installation mobilisation, so while lower capacity cables will be cheaper, they are not proportionally so.

Local infrastructure

It will be important during the life of a marine renewable project to achieve the following tasks as cost effectively as possible.

- a) Device construction and/or assembly
- b) Device installation
- c) Regular maintenance
- d) Resource (contractors / staff / equipment) availability

Inherently the best sites for renewables tend to be far from population causing somewhat of a problem, therefore, a carefully chosen location in proximity to a population centre will reduce many of the costs associated with installation and maintenance.

In summary, the three critical factors to optimize for a scheme are: resource, local infrastructure and electricity grid connection.

DEVICE SELECTION AND SPECIFIC SITING ISSUES

Offshore wind energy

Whilst any offshore wind turbine needs to be specifically designed to deal with offshore conditions, it also needs to be sized appropriately. High installation and maintenance costs (compared to land-based



devices) mean that the economics of smaller turbines sited offshore become marginal at best. For this reason, turbines upwards of 2-3 MW are typically suitable for offshore installations.

Survivability

Historical wind measurements taken on-site, coupled with solid data to produce a clear picture of the predicted wind-speeds at hub height are critical to produce expected performance estimate. Expected wind extremes, including storm conditions should also be considered at an appropriate return period. The hydraulic environment is also a critical element, and an accurate picture of the design-case waves and currents should be known with careful attention paid to selecting the extreme (design) conditions at appropriate return periods, as this will affect the design at elevation of the foundation structures.

Location

Large turbines are generally located at least 10 km offshore to reduce the visual impact to an acceptable level and take advantage of higher winds. Offshore turbines also require installation in relatively shallow depths, commonly being mounted in up to 30 m water depth. Larger turbines have been mounted in depths of around 45 m using jacket structures, although as the depth increases, the cost for foundation structures increases disproportionately, effectively limiting locations to a maximum of 50 m water depth. Therefore a primary requirement for offshore wind is a shallow coastal shelf that extends out quite some distance from shore.

Military

Wind turbine blades act as very effective radar reflectors, and so can have a significant impact upon military radar systems, especially as these are large devices that can be over 190 m high. These reflective effects can be reduced by some newly designed turbine blades, although it is unlikely that they will be eliminated altogether and so certain areas of the coast used by the military will be unavailable.

Vessel navigation

Shipping can form a significant risk when choosing a site and so exclusion zones around any offshore

installation will need to be implemented. The exclusion zone and site location needs to take into account the risk of vessel collision through several factors such as human error, mechanical failure and steering failure. These factors will combine with the prevalent environmental conditions and will determine the required distances from shipping zones [15].

Environmental

Erosion of the subsurface around any foundation structure and any sub-sea tie-in needs to be fully considered. Local wave effects and possibly longshore currents can cause significant problems if not addressed and mitigated at an early stage, either through the design of the foundation structures or through careful placement of the turbines.

One of the primary environmental problems is the turbine's effect upon birds and the possible displacement of indigenous local species. It should also be understood, however, that these structures can also have a significant beneficial effect with the foundation structures acting as an artificial reef, encouraging a proliferation of marine wildlife and the implementation of a vessel exclusion zone providing a no-fishing safe-haven, helping to increase fish stocks.

Tidal energy

The first step in identifying a suitable location is to find areas with a high tidal range, in excess of 6 m, or high tidal current flows with peak spring tides in excess of 2 m/s. Each tidal estuary will have its own particular 'tidal profile' and this should be analyzed to determine the average flow conditions at the site.

Tidal current profile

For good performance of a tidal turbine a high flow rate is essential. Care should be taken when interpreting site data as peak tidal flows can be deceptive if used as the only metric of potential performance. In general, tidal devices will not generate when the flows are less than 1 m/s, so the tidal profile needs to be correctly analyzed to determine the amount of expected operation.

Turbulence and flow inequality

The flow regime must be considered as tidal turbines can be sensitive to turbulence and non-laminar flow



must be avoided; therefore the proposed device location in the tidal flow needs to be analyzed. Ultimately this laminar flow requirement can have significant effects upon the number of turbines that can be located at any one site. For example, turbines should not be sited near to the channel edges and the wake from adjacent devices should also be minimized.

In addition to ensuring that the flow is laminar around the devices, it must be remembered that tidal flow is bi-directional in nature and both directions of the flow need to be considered as the structure of the channel could cause problems when the flow is reversed. Numerical modelling should be completed for any proposed installation. Figure 13 illustrates a typical output from a numerical flow model. Due to their nature, barrage or lagoon type systems do not suffer from the same turbulent flow issues, although the flow around any lagoon structure would need to be considered to confirm structural forces.

Navigation

Tidal turbines can cause a hazard to shipping and care should be taken to locate any device away from surface traffic. Turbine diameters are between 15 and 20 m and are placed in the middle of the water column; therefore the maximum under-kill clearance for any surface vessel will be directly related to the installation depth. Barrages will need to be designed to allow marine traffic to pass through, using lock-type structures. The delays and costs associated with introducing locks in areas of high traffic could be problematic.

Wave effects

Depending upon the location, there could at times be large surface waves travelling over a tidal turbine. In these areas it can be considered likely that these surface waves will have a noticeable oscillatory motion extending down to 20 m or 30 m. The wave effect at depth is dependant upon wave period, height and bathymetry.

Power connection

In areas of high-flow, the high current can have damaging effects upon anything exposed to the flow, such as power or instrumentation cables. In particular, vortex induced vibration (VIV) is a serious condition that can lead to premature failure.

Environmental

It is generally accepted that tidal barrages will have a significant environmental impact which should be addressed thoroughly and accurately. There will be an impact upon migrating fish species and other marine life, plus changes to the tidal flow patterns and water levels in the estuary which will have effects upon the coastline.

Whilst tidal lagoons have been advocated as devices with minimal environmental impact, it is fairly certain that this is untrue. The installation of such a large structure ($\approx 5 \text{ km}^2$) will invariably have significant coastal and environmental impacts.

Tidal turbines, as they are sited as isolated units and in areas of high current, are seen as having minimal environmental impact. Erosion will not be an issue as the sub surface is normally scoured clean. The turbine blades rotate slowly at approximately 15 rpm and so provide a minimal hazard for marine life. There is some concern, however, over larger marine creatures such as whales, which may be attracted to such devices and would not be agile enough to avoid the blades.

Wave energy

Wave energy devices can be divided into two groups for the purposes of siting, shoreline OWC devices, and floating offshore types. Floating devices share many, if not all siting concerns.

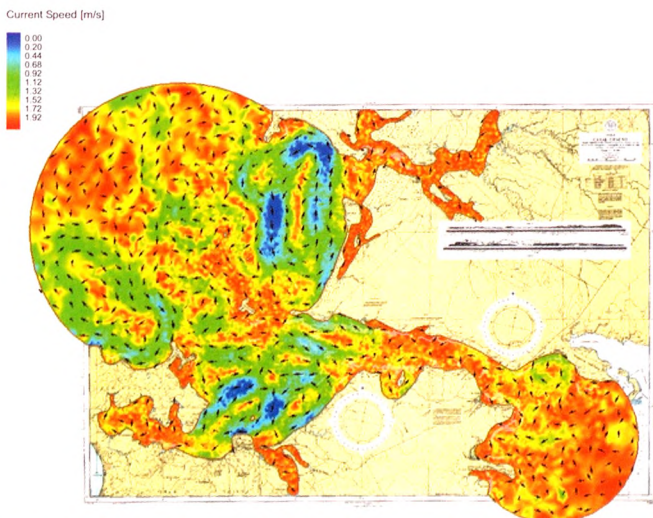


Figure 13: Typical numerical tidal flow analysis indicating areas of high flow during a peak flood tide condition (Chacao Channel, Chile).

Wave resource

It can be seen in [16] that the majority of the global wave resource is available at depths of 100 m or greater, with significant power still available at depths greater than 40 m. Commercially viable wave devices, as discussed earlier, are designed to operate effectively at depths up to 100 m. Figure 14 shows the Chilean wave resource.

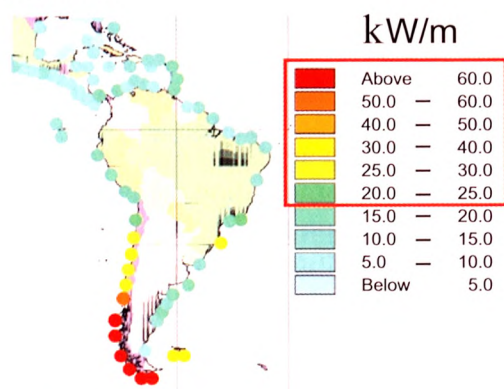


Figure 14: South America wave resource, showing quantities of incident wave energy off the Chilean coast

For commercially viable power it is estimated that the resource needs to be at least in the region of 20 kW/m average annual wave power [17]. In addition the period of the waves should also be considered when looking at an area of high resource. An area with consistent long period swells may actually have a high energy, but commonly devices will not be able to capture this long period energy. Capture is commonly optimized in the 8-12 second period range, outside of which the efficiency is reduced. As a result the distribution of the wave periods should be carefully considered when looking at the wave resource.

The natural variability in wave height at the site should be analyzed by calculating wave exceedance values that can be used to select the correct capacity device in order to optimize the project economics. These values illustrate the percentage of time the sea is above certain threshold wave heights and periods.

Grid connection

Connection to the main power distribution network can be the largest siting problem with wave devices. As the largest exploitable energies are found in depths of between up 40 and 100 m, grid-connection and sub-sea cable costs can be reduced by selecting a deep water site close to shore as possible. It is likely that

even in the most optimum siting the device will require a long and expensive sub-sea cable.

Survivability and moorings

In conjunction with siting devices in high seas, the extreme conditions at the site must also be carefully considered. This will affect not only the device, but also its mooring system. For the EMEC site with a 22 kW/m annual wave climate (Figure 4), the 1:100 year extreme condition is a 15.2 m Hs and, 18.4 s period. Whilst the device manufacturer will be able to confirm the device's survival characteristics in these extreme waves, the mooring method will need to be designed accordingly to prevent breakages.

Serviceability

Device access and maintenance will rely upon a local port to operate from. Floating devices may require recovery and or towing to a local port/facility for maintenance and the distance will be directly related to the cost of the operation.

Navigation and fishing

As with all marine devices discussed, careful placement away from shipping lanes and appropriate risk assessment for vessel collision should be completed. As these devices will probably operate further from shore and ideally in a grid/farm arrangement, exclusion zones, as with Wind Farms, will need to be arranged to prevent local marine traffic and fishing operations. These exclusion zones will need to take in account any self-orientation or weathervaning of the devices.

Environmental impact

It is unlikely that there will be any shoreline impact from the attenuation of wave energy by offshore devices. Studies have shown that even with wildly conservative approaches the reduction in energy reaching the shore is only in the order of a few percent [18]. More accurate studies conclude that any attenuation would be unnoticeable at a distance of greater than 2 km from the device [19].

SUMMARY

For marine renewables to contribute towards a significant part of our future energy there must



ultimately be an economic case for their installation. Currently such installations are subsidized by increased renewables tariffs and forced renewable purchase agreements, however, this will not last forever and so devices need to be developed to take advantage of economies of scale. The result is that from a siting perspective, devices need to be located in areas that will allow maximum power to be generated with minimum full life-cycle cost. When looking at marine renewables, the following points should be prioritized:

- a) NO-GO areas
- b) Local grid connection
- c) Local support infrastructure
- d) Annual resource at the site including extreme survival conditions
- e) Appropriate selection of device capacity to match resource

The order is significant as these schemes need to be considered not from a resource-first viewpoint, but from an infrastructure-first viewpoint. It is significant that the areas where the highest marine resources are found are always going to be the areas with the least infrastructure; the goal is finding the economical middle ground.

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