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Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

Grant agreement number: 213380

EquiMar

Deliverable D5.4
Site matching and interaction effects

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Site matching and interaction effects

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Summary

This report offers guidance for the matching of wave and tidal energy devices to marine energy sites and also for interaction between devices that make up an array. At the stage of writing this document arrays are in their infancy with most development focussing upon individual commercially viable devices tested in real sea conditions. There is however sufficient understanding and research to begin to offer generic guidance for the arrangement of devices within arrays. This information is collated herein to offer guidance for all aspects of the marine energy industry.

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1. INTRODUCTION

1.1 DRIVERS FOR DELIVERABLE

In the short to medium term wave and tidal energy devices will be installed in multiple numbers at a given site. Such installations are commonly known as farms or arrays. As with many other technologies it is expected that the scale of arrays will increase in time from a few MW initially to perhaps many hundreds of MW. A key driver for installation of an array of devices is to increase the production of energy whilst maintaining or decreasing the unit cost of energy when compared to a series of isolated devices. This is achieved with general economy of scale, the sharing of systems (such as electrical connections) and reduced installation/maintenance costs per device.

As arrays become larger in size (in terms of number of devices and energy extracted) interaction effects between devices are expected to increase in magnitude and complexity. With limited research work having been completed to date regarding array performance and interaction effects the need for guidance is clear.

1.2 STATUS OF MULTIPLE DEVICE ARRAYS

At the end of 2009 developers were at the preliminary stages of installing and operating devices within an array structure. Verdant Power tested six 35kW tidal turbines in the East river, New York, US. The project delivered power to the grid with the turbines operating on both ebb and flood tides. Pelamis Wave Power also saw devices installed within an array. Three 750kW floating devices were installed at Aguçadoura, Portugal and grid connected. In South Korea a 1MW installation of vertical axis tidal turbines was installed in the Uldolmok strait in 2009. Plans to expand the rated capacity at this and other potential tidal stream sites within the country are being pursued. In the short term (2010 onwards) there are a large number of developers that have plans to install arrays of wave and tidal energy devices.

1.3 CLASSIFICATION OF ARRAYS

It is likely that arrays will evolve in size and complexity as the technology develops. A useful concept that has arisen from this aspect of the Equimar protocols is the definition of the size of an array. A key driver for nearly all types of wave and tidal device will be the minimisation of negative interaction effects between devices whereby structural loading is increased and/or power production is reduced. Early arrays will most certainly be composed of a single row of devices aligned perpendicular to the incoming wave or tidal resource (where the resource has a low degree of directionality). Arrays can be expanded by including a second row where downstream or down wave devices are positioned in the spaces left between devices in the upstream/up wave row (see Figure 1). This is the limit of what we will refer to as 1st-generation arrays. This configuration has the following benefits.

a. It will minimise device interaction
b. Maintenance and access to devices is not restricted as both rows can be approached from outside the array
c. Arrays can potentially become quite large with this configuration depending upon location

Second generation arrays would be for multiple rows of devices (greater than 2) where interaction effects do occur. The benefits of a large number of devices at the same site outweigh the potential for increased device loading and/or reduced performance and access issues to some devices within the array. Figure 1.1 illustrates this issue as the furthest row downstream is most likely to encounter some form of negative interactive effects from the upstream rows whilst access to the middle row could be more difficult due to the bounding effect of the two adjacent rows.

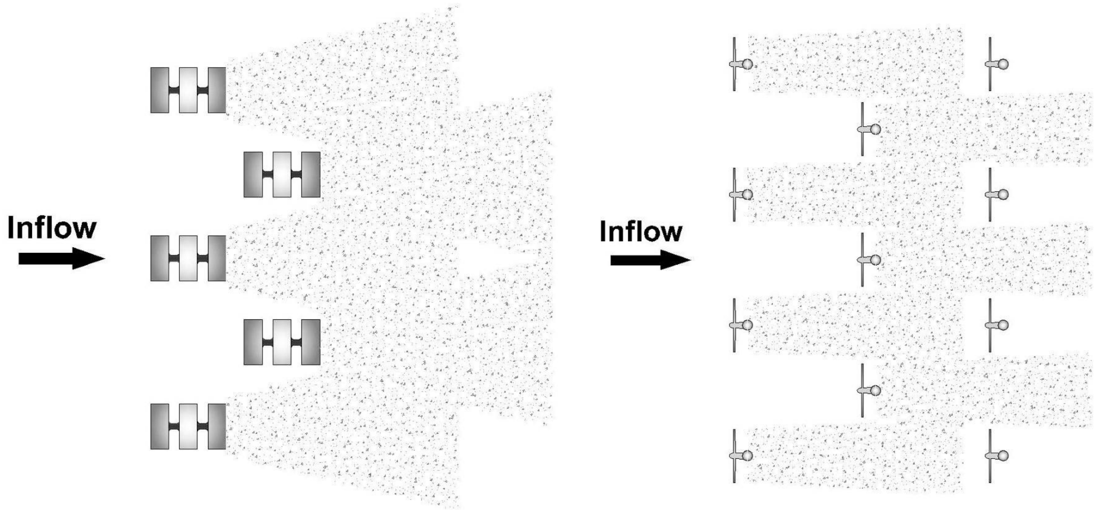

Figure 1.1 2-Row wave energy array (left) and 3-row tidal array (right)

The definition given above means that the rated power of an array is independent of this classification. Instead it is driven by the operational complexity of the array.

The classification of arrays in this manner is important as many of the device and performance metrics applied to arrays become more subjective for 2nd-generation arrays. Definition and comparisons between several 1st-generation arrays should, in theory, be easier.

1.4 TIMELINESS OF THIS DOCUMENT

It is expected that progress in array development will increase rapidly in order to reduce the cost/installed power capacity ratio. Thus there is significant possibility that publications regarding array design and performance will quickly become outdated. At the time of writing there has been a reasonable body of research conducted regarding wave and tidal device interactions both experimentally and numerically. However the work has opened up a host of new research areas. As arrays are scheduled for the short-medium term research work in this area is accelerating rapidly. Therefore this element of the EquiMar project will provide qualitative recommendations where there is any element of doubt as to the absolute measurement of an aspect of array design or performance.

The content of this document is based upon a number of key aspects pertaining to the manner in which wave and tidal energy arrays will develop:

1. Early arrays are likely to be composed of less than 10 devices aligned in a linear manner perpendicular to the incoming resource direction (if device performance is dependant upon resource direction) or possible a geometric pattern (if not directional). The size of arrays, the degree of interaction between devices and general complexity of arrays will increase over time.
2. The influence of a marine energy converter upon the local spatial flow field will vary between different types of devices and also with the nature of the incoming marine resource. Therefore array design and layout is expected to be device specific.
3. As technology improves and new equipment is developed the manner in which arrays are designed and operate will invariably change. It is possible that quantitative aspects of this protocol may then require amendment. Where possible, qualitative recommendations will be given to avoid this.
4. When a device is positioned within an array and is subjected to interaction effects the inflow of energy from the marine environment will differ to that of other devices within the array. Thus an 'available resource' will exist and is likely to be different for many of the devices that compose the entire array. Quantification of this 'available resource' in a potentially complex flow field is a key aspect of defining array performance.

2. RESOURCE QUANTIFICATION AND ASSESSMENT

2.1 OBJECTIVES OF RESOURCE ESTIMATION AND ASSESSMENT

Resource assessment is generally based on the most appropriate mix of physical metocean measurements and numerical modelling that is available. Different constraints apply to the different modes. For example, numerical modelling can provide arbitrary temporal and spatial resolution – but at computational and therefore economic cost. Crucially, the numerical models still need to be validated – and this requires real data from relevant instrumentation. These instruments in turn will vary in terms of capital and operating costs, accuracy, quality and spatial and temporal characteristics.

Spatial characteristics

Point measurement (surface wave buoy, rotary current meter)

Axial measurement (Acoustic Doppler Current Profiler)

Area measurement (radar, satellite systems)

Temporal characteristics

Frequency of measurement acquisition

Return period (scanning or dynamically moving systems such as satellites)

Length of measurement acquisition (intermittent or continuous over a period of time)

Once data is available it can be analysed and interpreted in order to estimate the resource. A common exercise is to interpolate between certain spatial and temporal characteristics based upon justified methods in order to provide a better estimate of resource. In some cases such as tidal prescribed methods can be used to extrapolate resource measurements over greater periods of time. An example is harmonic analysis that is based upon the predictable nature of the tidal resource at a particular location where a certain amount of resource data has already been acquired.

A great deal of the above is often performed numerically using software programs. These take measured data and extrapolate it (in terms of time and space) using physical or statistic principles. Specific models will not be addressed here but care should be taken to assess the quality and accuracy of such numerical tools.

It remains that there is often insufficient metocean data available at any specific site in order to quantify the resource to a good level of accuracy. Historically metocean data has been acquired for shipping and meteorological purposes and not generally at high density in areas with strong wave and tidal characteristics. As marine energy becomes more established this situation should change.

2.2 PHYSICAL METHODS OF QUANTIFYING THE MARINE ENERGY RESOURCE

2.2.1 Wave energy resource measurement acquisition equipment

A comprehensive review of methods to acquire wave data was recently presented by Kahma et al. (2005). The most relevant methods are buoys, satellite systems, pressure transducers, wave staff, ship-borne wave recorders and marine wave radar systems. Their most important features are compared in Table 1. Some systems specify the directional wave spectrum. This is not trivial task and no instrument exists that can measure all the data required to determine the directional spectrum without additional assumptions. The average wave direction is usually well defined and various instruments agree reasonably well. The variability in wave direction (spreading) is more ambiguous and conclusions from them should be drawn with caution (Kahma et al. 2005). The type in Table 1 indicates if the measurement equipment involves physical contact with the wave (direct) or not (indirect). The seven methods included in Table 1 are individually discussed below.

Table 1: Comparison of wave energy resource measurement acquisition equipment

Criteria	Buoys	Satellite: Radar altimeter RA (TOPEX/Poseidon, ERS-1/-2, Jason-1/-2, Envisat)	Satellite: Synthetic Aperture Radar SAR (ERS-1/-2, Envisat, TOPEX/Poseidon)	Pressure transducer	Wave staff	Ship-borne wave recorder	Marine wave radar system
Type	Direct	Indirect	Indirect	Indirect	Direct	Indirect	Indirect
Measured quantities	Wave height and period, mean direction, position, water temperature, wind speed, atmospheric pressure	Significant wave height, currents, water temperature	Significant wave height if waves large enough, wave directionality	Wave height and period, directionality with several transducers	Wave height and period	Wave height, wave period	Wave height and period, directionality
Measurement frequency	3.84Hz	1Hz, back at same position after: 9.9 days (TOPEX/Poseidon), 4.95 days (Jason-1/2 combined) and 35 days (Envisat)	Return period analogue RA	-	Up to 30Hz	1Hz	For 2 minutes every 5 minutes
Spatial coverage	Point measurement	Area of 2-10 km each 7 km along ground track, ground track separation between 315 km (Jason-1/2) and 80 km (Envisat)	100 × 100 km^2, track separation analogue RA	Point measurement	Point measurement	Point measurement	Area
Typical accuracy	Heave 0.5%-1%, ≈ 0.5º direction, 0.1ºC temperature	Altitude 3-4 cm, wave height better than 5%	Mean directionality well defined, variability in wave direction (spreading) more ambiguous	-	0.1%	10%	10%
Service live	Up to 3 years	Operation record 13 years (TOPEX/Poseidon)	Analogue RA	-	-	-	-

Buoy

The most common method of direct data acquisition is the surface buoy. Buoys have been used for measuring waves since the early 1960s. Compact units measuring all six degrees of freedom of the buoy are nowadays available, such as the Motion Reference Unit MRU (Kahma et al. 2005). The data from buoys are often used to calibrate and validate other methods. Buoys give a good estimate of the sea state from a 30 min sample, but may be too expensive for long term wave climate estimation, except at a small number of key reference sites. Long-term buoy wave measurement networks are therefore still relatively few and far between (Cruz 2008). Surface buoys can be elastic moored or free-floating; the former tend to be in shelf seas whilst free-floating buoys are often deployed in deep waters on the mid-Atlantic ocean.

Motion sensors – usually accelerometers – in 1 or 3 degrees of freedom are used to record time series from which spectra can be derived. The buoy motion can be processed to yield a spectrum at, typically, half-hourly intervals. If 3 degrees of freedom are used, together with a compass for absolute reference, then directional spectra can be derived. For convenience these can be further processed to spectral parameters such as significant wave height, energy period, principal wave heading and directional spreading. Kahma et al (2005) note that the average wave direction is usually well-defined, has a clear interpretation, and estimates from various instruments agree reasonably well. Directional spread is a much less stable parameter, and it depends both on the instrument and on the analysis method used. They recommend that for any directional property other than the mean direction a combination of different methods of measurement and analysis is needed. The half-hour spectra can be consolidated over longer intervals, e.g. 3 hours, in order to improve the spectral variability. The sea-state parameters or the spectra themselves can be used to determine the power in the waves, and hence the output from a wave energy converter of known power response.

A wave buoy can also incorporate GPS, compass and atmospheric instruments to measure temperature, atmospheric pressure, wind speed etc. as well as sensors for chemical and ocean biological observations. On board processing of the collected data and radio transmission via satellite or link are common features of modern buoys. A relatively new type is the GPS buoy which is completely free from its own sensors. Its six degrees of freedom are followed by the satellite Global Positioning System (GPS) (Kahma et al. 2005). The specifications in Table 1 are the details for the Directional Waverider MkIII, one of the most popular buoys (Datawell BV 2002).

Satellite radar

Examples of wave energy resource studies for WEC sites applying satellite data are included in Krogstad and Barstow (1999). The return period of a satellite to a specific location depends on the offset per orbit of the ground track distance: the larger it is, the shorter is the interval till a satellite flies again over a specific site. The satellite tracks for Europe of three satellites are shown in Figure 2.1. Radar techniques can also be employed from the coast, ships (see marine wave radar system) or airplanes covering a large area and having a high resolution (Kahma et al. 2005). Radar systems are best suited for long period waves (swells), allowing their tracking over very long distances. Two type of satellite radar are distinguished namely the satellite Radar Altimeter (RA, employed e.g. on ERS-2 or SEASAT) and the Synthetic Aperture Radar (SAR, employed e.g. again on ERS-2 or TOPEX/Poseidon).

a) RA: Satellite RA uses vertically pointing pulse radar to measure the range of the ocean surface with standard resolution of one estimate every second corresponding to measurements every 7 km along the track with a satellite speed of 7 km/s. The smallest achievable ground track separation at the equator is around 80 km (Table 1). The typical radar footprint diameter varies with the wave height from 2 to 10 km. The wave height is obtained exactly below the satellite from the distortion, in particular in the return pulse leading edge, with an accuracy of some centimetres. Further the wind speed is determined from the strength of the total backscatter. Ocean currents are indirect measured from the slope of the water surface and the water temperature from the height of the mean sea level which rises with increasing temperature (Krogstad and Barstow 1999). The RA has to be calibrated and validated, normally with buoy data, in order to remove altimeters-dependent biases on significant wave height (Cruz 2008). No wave data are returned, of course, when the satellite passes over land, and the resolution of the wave data in the vicinity of the coast is limited spatially by the radar footprint and temporally by the 1Hz sample rate. Consequently data are of lower quality or non-existent within about 10km of the coast as the satellite passes from sea to land. When the satellite passes from land to sea, which on average it does 50% of the time, the RA takes a few seconds to lock on to the sea surface, so the no or low-quality data region is 20-30km. This makes satellite measurements less useful for the near-shore region – which is where wave energy devices are expected to be deployed. However, they are useful for cross-comparisons with buoy data and for validating numerical models.

b) SAR: The directional wave spectra can be determined with a SAR producing images. The regular SAR image covers a square area 100×100 km^2 along the swath and consists of 5000×6300 pixels. This method provides not a true image of the surface but has to be transformed by an algorithm in wave information (Krogstad and Barstow 1999).

Satellite based radar systems for coastal applications were launched by the US space agency NASA (satellite SEASAT), the US Navy's (GEOSAT), the NASA in collaboration with the French space agency CNES (TOPEX/Poseidon, Jason-1, Jason-2) and the European space agency (Envisat, ERS-1, ERS-2 etc.).

The *SEASAT* launched in 1978 by NASA was the first Earth-orbiting satellite designed for remote sensing of the oceans and had on board the first spaceborne SAR. Specific objectives were to collect data on sea-surface winds, sea-surface temperatures, wave heights, internal waves, atmospheric water, sea ice features and ocean topography. The recordings ended after 105 days in 1978 when a massive short circuit in the satellite's electrical system ended the mission. The GEOSAT, launched by the US Navy, operated already for a longer period namely from February 1986 till 1989. However, a large part of is measurements were classified and not available for public use.

TOPEX/Poseidon was launched in 1992 as a joint satellite mission between NASA and CNES to map ocean surface topography (RA system). It measured 95% of the Earth's ice-free ocean surface with an accuracy of 3.3 cm. It provided data in more than 62,000 orbits over 13 years before it stopped working in October 2005. With its value of satellite ocean observations TOPEX/Poseidon helped to revolutionize oceanography.

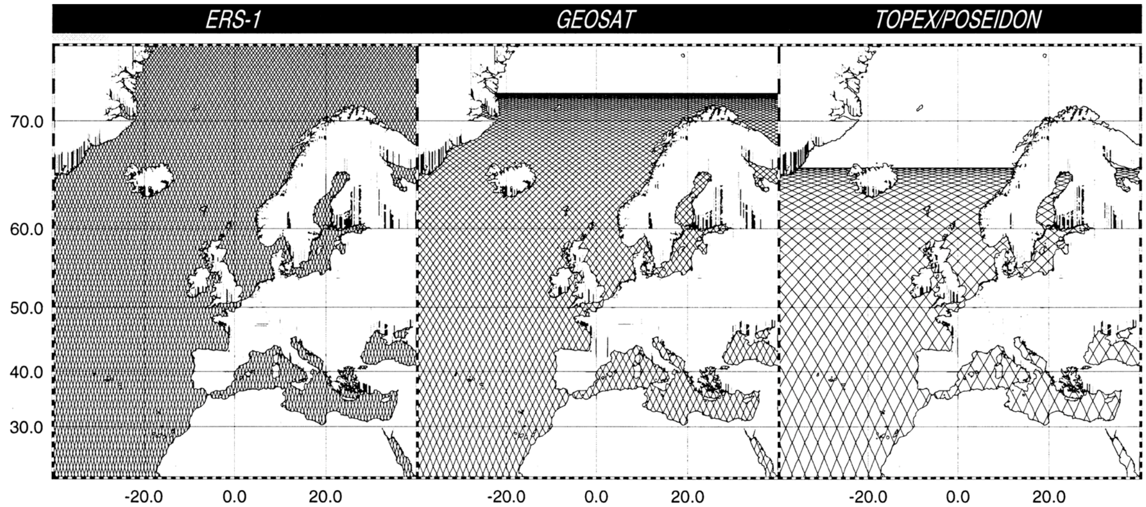

Figure 2.1 Satellite tracks of ERS-1 (80 km ground track separation), GEOSAT and TOPEX/Poseidon (315 km separation) for Europa. A dense grid implies longer time intervals for the satellite to return to a specific location (Krogstad and Barstow 1999)

Parallel to TOPEX/Poseidon the *Jason-1* satellite was launched in 2001 again by NASA and CNES and in 2008 *Jason-2* operated by the U.S. and French weather agencies. They monitor again 95% of the ice-free ocean every 10 days with 254 passes and from a height of 1336 km above the equator. During the first months Jason-1 shared an almost identical orbit to TOPEX/Poseidon, which allowed for cross calibration. At the end of this period, the older satellite was moved to a new orbit midway between each Jason-1 and Jason-2 ground track. Recent orbit maneuvers in 2009 put the Jason-1 satellite on the opposite side of Earth from the Jason-2 satellite. Jason-1 now flies over the same region of the ocean that Jason-2 flew over five days earlier. Its ground tracks fall mid-way between those of Jason-2. This interleaved tandem mission provides twice the number of measurements of the ocean's surface, bringing smaller features such as ocean eddies into view. The tandem mission also helps pave the way for the future ocean altimeter mission Jason-3 that will collect much more detailed data with its single instrument than the two other Jason satellites together and is planned to launch in 2013.

Another type of satellites is *Envisat* built by the European Space Agency Esa and launched in 2002 as successor of ERS-1 (launched in 1991) and ERS-2 (launched in 1995). Devoted to environmental studies, and climate change in particular, its mission is to observe Earth's atmosphere and surface. It is carrying ten complementary instruments for observing parameters ranging from the marine geoid to high-resolution gaseous emissions. Among these instruments are a RA, and a precise location system. Envisat's orbital period is 35 days, like for the older version *ERS-2* and for some of the phases of *ERS-1*. It is integrated in new international climate study programmes such as Goos and Godae. Envisat thus forms part of the coming operational era in oceanography, offering near-real-time data access. The European space agency characterises its altitude accuracy better than 2.4 cm, and the accuracy for the wave height better than 5% or 0.25 m.

Pressure transducer

Pressure transducers are usually located near or on the seabed and can monitor the pressure at a discrete location (Table 1). Since the pressure is proportional to the height of the water column above the instrument, sampling at a high frequency allows the passage of waves to be mapped. The strong signal depth attenuation with frequency severely limits the high frequency response, and surface elevation profiles, usually obtained by inverse filtering, are typically rather poor unless sophisticated non-linear methods are used (Kahma et al. 2005). Spatially extended arrays of pressure transducers were the earliest directional instruments, and these are still used for accurate detection of swell directional spectra. Pressure transducers can also be employed in combination with current meters in order that the effect of currents on wavenumber and hence attenuation can be calculated.

Wave staff

A wave staff is a large version of the resistance or capacity laboratory wave gauge consisting of metal wires aligned vertically in the water column. They are usually fixed to a rigid structure such as a pier or oilrig. The electrical properties of those wires change proportional with the wave covering a greater or lesser proportion of its length. A disadvantage is that the signal at a given water level may also change with the salinity or other particles changing the chemical properties of the water column. Measurements of high accuracy require therefore an in situ calibration which may be un-practical in some situations. Wave staffs are more and more replaced by laser or radar altimeters (Kahma et al. 2005). As an example, the accuracy of the Wave Staff III from Ocean sensor systems is 0.25% of full scale between 20% and 80% of the wire length. If greater accuracy is desired, the unit can be calibrated in situ and the data can be post-processed. Both techniques are for the advanced user and will result in better than 0.1% accuracy over the full range of the unit (Ocean sensor systems 2005).

Ship-borne wave recorder

The ship-borne wave recorder system was devised by Tucker (1956) and applied for many years for offshore wave measurement in the North-East Atlantic, for example on light-vessels and weather ships. Today, it is in continued routine use on a number of research ships world-wide. It is based on two pairs of accelerometers and pressure sensors which are mounted port and starboard on the ship's hull below the waterline. Data from the port and starboard instrument pairs are combined to eliminate the effects of ship roll both in accelerations and pressure. The pressure sensors provide a wave height signal additional to the heave and the two are combined to calculate in situ sea surface height variability. The sampling frequency is 1Hz and the system stores raw surface elevation data as well as spectral information and summary parameters such as the significant wave height (Table 1). The accelerometers and pressure sensors are regularly calibrated and are both robust and accurate to about 1%. Comparison with buoy showed reasonable agreements. However, the limitation on the accuracy of the ship-borne wave recorder data is uncertainty in assessing the response to the waves of the ship. The wave heights are in general rather underestimated if compared to buoys, typically in the order of 10% (Yellard et al. 2007).

Marine wave radar system

The system is mounted on a fixed location on the ship and uses a marine X-band radar operating in short pulse mode to map the sea surface in 2D. It uses those time series of images to produce a full 3D directional wave spectra. Wave slope can be extracted from the radar images and processed in order to obtain directional wave height spectra. Relatively few comparisons between marine wave radar systems and buoy data exist. An exception is the study of Dankert et al. (2005) who found that a marine wave radar system underestimated the significant wave height H_s by about 15 cm on average over 3 weeks in conditions where H_s was up to 6 m. Sometimes the radar system is calibrated with buoy data to deliver more reliable measurements (Yellard et al. 2007, Miros AS 2007). A specific type of a marine wave radar system is WAVEX Wave Monitoring System developed by Miros. It is recommended that the antenna is at least 15 m above sea level. The error specification for this system are 0.25 to 0.50 m for the significant wave height is $H_s < 5$ m and <10% for rougher sea conditions, 10% for the wave period and <20º for the wave direction. Other applications of radar can be from an airplane or from space (see section satellite radar).

2.2.2 European Union Wave Energy Data Sources

The vast majority of the wave energy in the EU is on the West-facing Atlantic coastline with estimated energy densities ranging from about 30 kW/m in shallow waters (< 40 m) increasing to 70 kW/m in deeper waters further offshore (Figure 2.9). Generally the energy per metre crest length increases with latitude. Inner sea areas are sheltered with the North Sea having the most energetic wave climate. Baltic and Mediterranean waters are tranquil in comparison and are far less attractive for economic exploitation of the wave energy resource. However, the wave power resource is not the only criteria to select a suitable site. Other factors such as the proximity to shore or grid as well as the ratio of extreme to mean significant wave height may also be relevant (Cruz 2008).

In a typical WEC project, long term predictions are made with numerical models and these are validated with a few months of in situ buoy measurements. Normally, data is required for a period of at least 10 years, to allow for seasonal, year-to-year and longer-term variability. For sites in depths of less than 100 m, specific consideration of local bathymetry is necessary, and various numerical shallow water models are available that can be used to calculate the nearshore wave climate, starting from the data from deep water reference site (Cruz 2008).
Besides numerical simulations and in situ measurements also satellite data become more and more attractive. The following gives an overview of available data sources for European waters classified into sources based on buoy, satellite and numerical data.

Sources based on buoy data

At any time there are approximately 3,000 wave measurement buoys operating in the water. This number varies constantly as the lifespan of each device varies and does not generally exceed 3 years. The most essential buoys can be expected to be replaced relatively quickly if they are lost, malfunction or reach the end of their lifespan. Buoy data reach a high accuracy and can provide a full wave characterization for WEC projects including directionality. However, long-term buoy wave measurement networks are still relatively few and far between (Cruz 2008). Whereas satellite or numerical data can be applied to nearly any site, buoy data, moored buoy data in particular, are connected to a specific location. The buoy locations are hereafter reviewed for specific countries or regions, therefore, after the introduction of some relevant international organizations. Most buoy data serve meteorological requirements and are therefore available from national Met Offices.

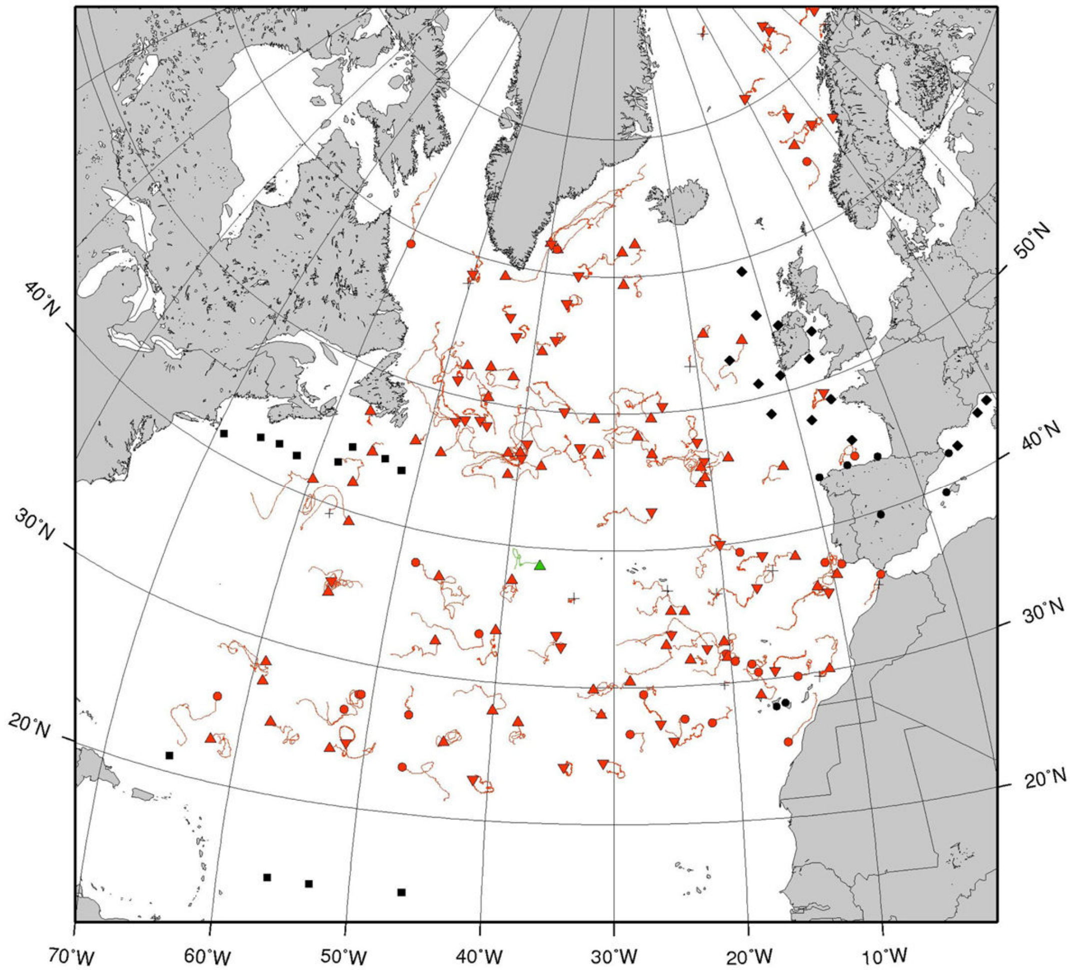

Figure 2.2 E-SURFMAR buoys network in March 2010 including drifting buoys with trajectories and moored buoys (E-SURFMAR 2010)

The Data Buoy Cooperation Panel DBCP

The DBCP, formed in 1985 as a joint body of the World Meteorological Organization and Intergovernmental Oceanographic Commission of UNESCO, is an international programme coordinating the use of autonomous data buoys over ocean areas where few other measurements are taken. Their webpage http://www.jcommops.org/dbcp/ encourages buoy holders to share their real-time and archive data for helping weather forecast, climate prediction or oceanographic research. Data buoys measure air pressure, sea surface temperature, ocean current velocity, air temperature, humidity, wave characteristics and wind velocity. The DBCP aims to increase the quantity, quality, global coverage and timeliness of atmospheric and oceanographic data. These observations are relayed by satellite and used immediately to improve forecasts and therefore increase marine safety. The DBCP launched in 2005 their 1250th drifting buoy. Most of the drifting buoys were deployed by commercial ships and research vessels (DBCP 2009). In March 2010 the network included world-wide 1548 drifting buoys (Europe: 74 from E-SURFMAR, 11 in France, 13 in Italy, 2 in Norway and 12 in the UK) and 399 moored buoys (Europe: 8 from E-SURFMAR, 16 in France, 1 in Italy, 5 in Ireland, 10 in Spain and 61 in the UK).

EU in general

E-SURFMAR is the Surface Marine observation programme of the Network of European Meteorological Services EUMETNET. E-SURFMAR is also the European member of DBCP. It was established during 2003 and was initially defined for duration of four years. However, the project is at the moment planned till 2011. It is supported by 15 countries under the responsibility of Météo-France. The E-SURFMAR design study (2003/04) aimed to improve the quality of numerical and general forecasts over Europe. It showed that the most suitable parameter required by the regional Numerical Weather Prediction (NWP), which cannot be provided by the space segment, is air pressure. It recommended using more drifting buoys and Voluntary Observing Ships (VOS) reporting hourly data from sensitive areas: in the North Atlantic (north of 35°N) and the Mediterranean Sea. The buoys network of E-SURFMAR in March 2010 is shown in Figure 2.2. The drifting buoys record mainly air pressure, sea surface temperature or wind speed but no wave characteristics. Most of the moored buoys do measure wave heights and periods and some of them the wave spectra as well (E-SURFMAR 2010). Most of the moored buoys are covered hereafter. No further buoys in the not shown part of the Mediterranean Sea are available in March 2010 from the E-SURFMAR network.

The ECMWF (European Centre for Medium-range Weather Forecast) provides in situ measurement data, after a registration procedure, for verification purposes of modelled data. However, ECMWF comes on their webpage http://www.ecmwf.int/ also to the conclusion that "the in situ wave data coverage is rather limited."

Baltic Sea
The Swedish Met Office SMHI uses the data of five buoys shown in Figure 2.3 namely one located in the Southern Bothnian Sea (Finngrundet), in the Northern Baltic Proper (Huvudskär Ost), in the Southern Baltic Proper (S. Östersjön), in Kattegat (Läsö Ost) and in Skagerak (Väderöarna). Available data for those five buoys include the significant wave height, wave period and directionality.

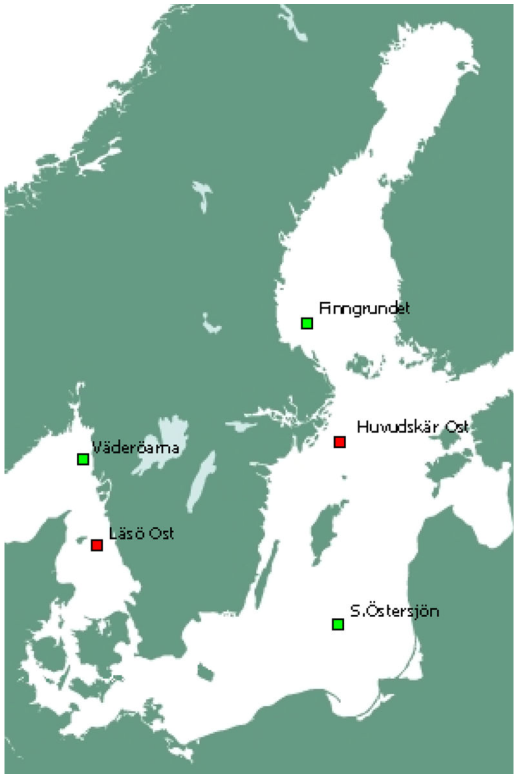

Figure 2.3 Buoys locations in the Baltic Sea used by the Swedish Met Office SMHI

UK and Ireland
The UK's Met Office provides data for 48 marine observation sites as shown in Figure 2.4(a) consisting of moored buoys, lightships and island systems. Recorded are parameters such as weather, sea and air temperature, humidity, atmospheric pressure, wave period and wave height. However, only 15 of the 48 sites record the wave characteristics. The latest hourly marine observation data can be viewed on their webpage http://www.metoffice.gov.uk/. The U.S. National Data Buoy Center (http://www.ndbc.noaa.gov/) provides in addition to the buoys of the Met Office also measurements of the private industry and oil platforms mainly in the North Sea as shown in Figure 2.4(b).

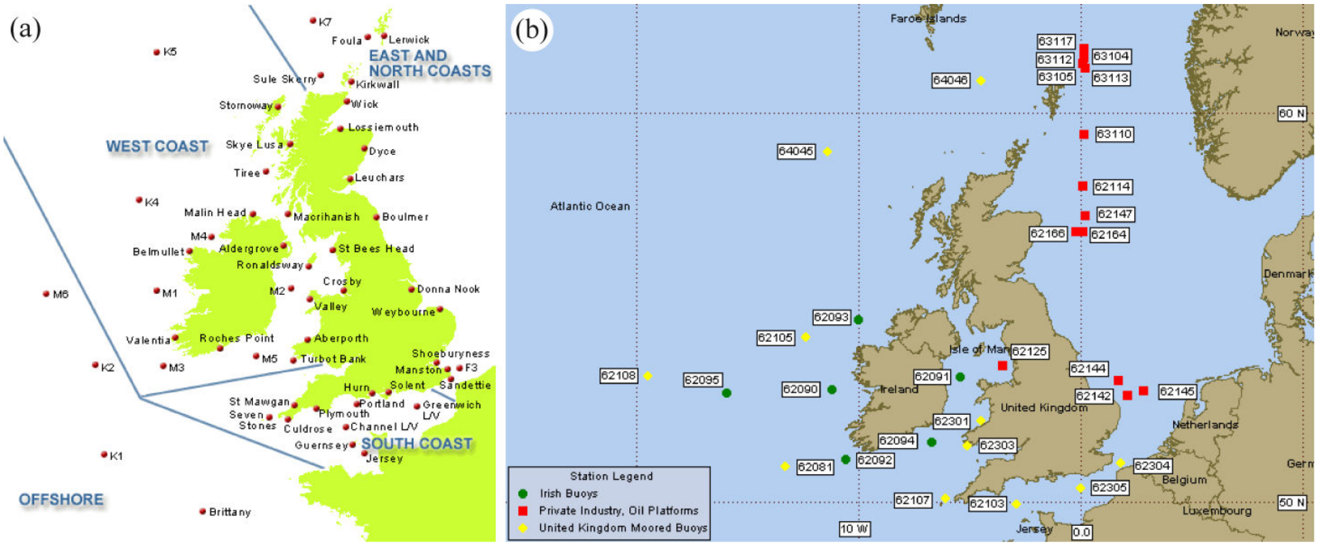

Figure 2.4 Marine observation sites (a) of the UK's Met Office (from http://www.metoffice.gov.uk/) and (b) of the U.S. National Data Buoy Center (from http://www.ndbc.noaa.gov/)

France
Coriolis (http://www.coriolis.eu.org/) is part of a larger system for operational oceanography in France which aims to monitor and forecast the ocean behaviour within three projects namely sea-surface observation using satellite sensors, in situ measurements from ships, moored or drifting autonomous systems and assimilation of in situ and satellite data in an ocean circulation model. Coriolis contributes to the in situ part of this system, with the objective of developing continuous, automatic and permanent observation networks. Coriolis includes the maintenance and calibration of equipment, data compression and real time transmission and data collection, quality control, archiving and distribution. In addition, the U.S. National Data Buoy Center (http://www.ndbc.noaa.gov/) provides data for the moored buoys around France as shown in Figure 2.5.

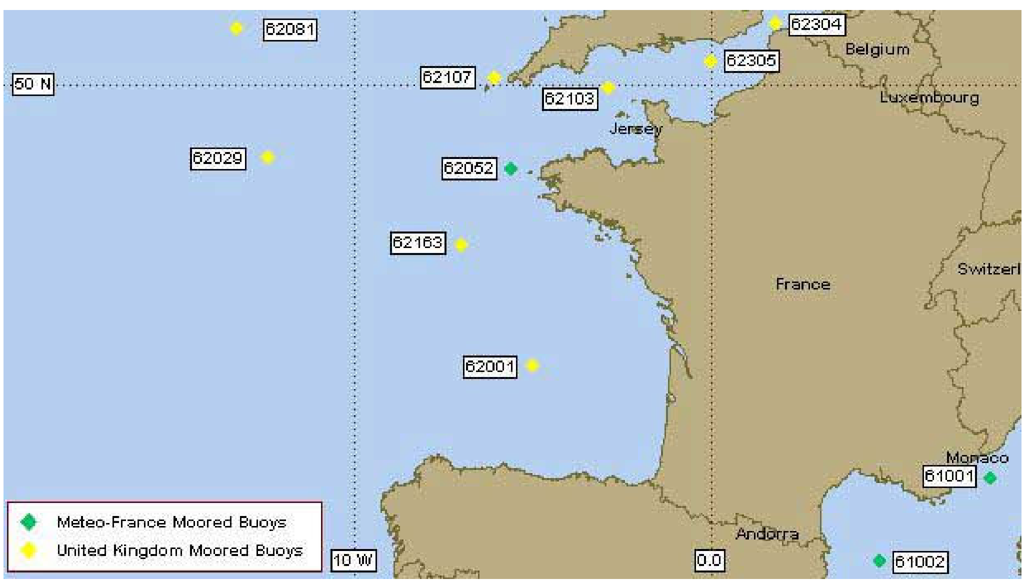

Figure2.5 Moored buoys of Météo-France and of South UK shown on the U.S. National Data Buoy Center webpage (from http://www.ndbc.noaa.gov/)

Spain
The Spanish National Ports & Harbours Authority (Puertos del Estados, http://www.puertos.es/en/index.html) owns a deep sea and coastal buoy network as shown in Figure 2.6. The deep sea network includes 13 SeaWatch and 3 Wavescan buoy stations which are located at points with depths between 200 and 800 m and measure hourly atmospheric and oceanographic parameters (Figure 2.6a). The coastal network is providing real time data at some specific points located in shallow waters. The main objective of the measurements is to complement those of the Deep Sea Network at those locations of special interest for the port operations or wave modelling validation. The buoys employed are scalar and directional Waverider and directional Triaxys

(Figure 2.6b). Iglesias and Carballo (2010) applied the data of three buoys shown in Figure 2.6(a) in combination with hindcast data and the numerical model SWAN to characterize the wave energy resource in the Estaca de Bares area.

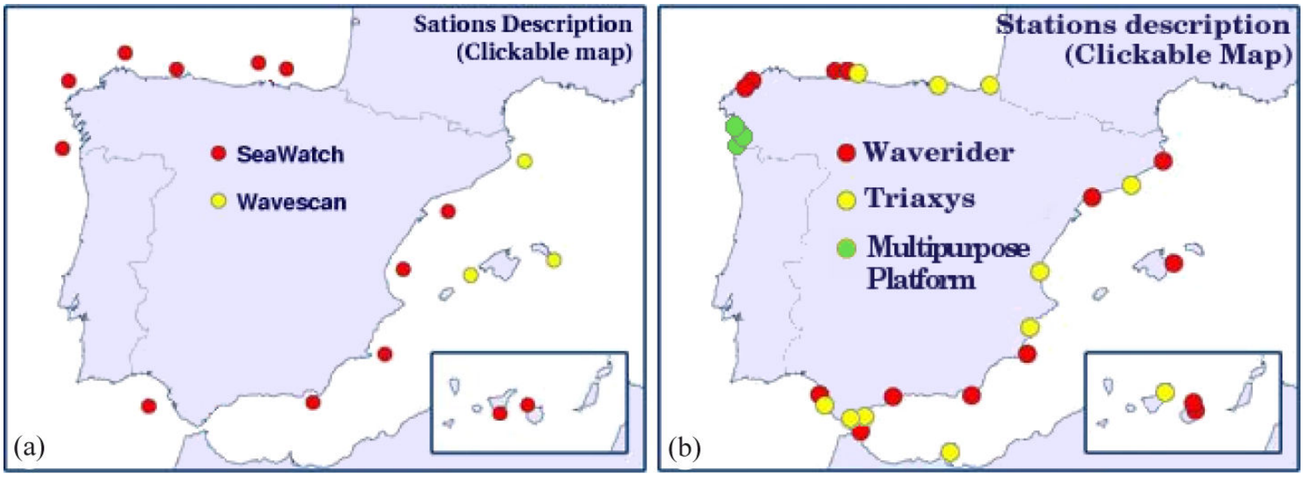

Figure 2.6 (a) Deep sea and (b) coastal networks of Spanish National Ports & Harbours Authority (from http://www.puertos.es/en/index.html)

Portugal

The Hydrographic Institute is the Portuguese Navy's Laboratory of Ocean Sciences and is the main responsible for the installation and maintenance of tide gauge stations as well as acquisition, processing, archiving and dissemination of sea level data. They operate 12 wave measurement stations as show in Figure 2.7. Measured data include the significant and maximum wave height, the mean and maximum wave period, mean direction and water temperature. Data of the four stations Leixões, Figueira da Foz, Sines and Faro where applied by Rusu and Soares (2009) to validate WAM and SWAN simulations.

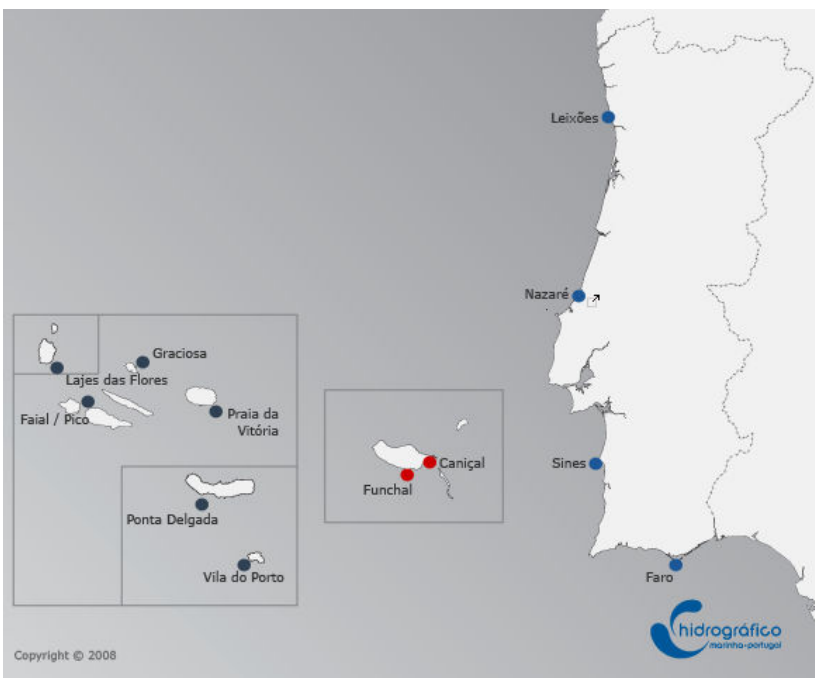

Figure 2.7 Wave measurement stations operated by the Portuguese Hydrographical Institute (from http://www.hidrografico.pt/boias-ondografo.php)

Italy

The Italian Institute for Environmental Protection and Research (ISPRA) - Telecom Italia and Envirtech are responsible for the deployment and maintenance of the Italian Data Buoy Network (also known as RON). The permanent Italian data buoy network is able to monitor meteorological data, directional waves and others sea motion, chemical and physical parameters. It is possible to get connected to their network on their online database under http://www.envirtech.org/ron.htm. Vicinanza et al. (2009) assessed the 15 offshore buoy locations shown in Figure 2.8(a) recording for up to 17.9 years. They got their data from the Italian

Wave Network (IWN). Vicinanza et al. (2009) found mean yearly power values of 1.4 - 4.1 kW/m except for one buoy at Sardinia with 13.1 kW/m.

Greece
The system POSEIDON from the Hellenic Centre for Marine Research HCMR (Table 2) is offering access to the most recent data recorded by the buoy network in the Aegean and Ionian Sea. The data are available either as time series graphs or as text based format for the latest transmission. The ten buoys, shown in Figure 2.8(b), are located SE of mount Athos, at Lesvos, Skyros, Saronikos, Mykonos, Santorini, Kalamata, Cretan Sea (E1M3A), Pylos and Zakynthos and provide surface temperature, significant and maximum wave height, mean wave direction, current speed and current direction.

Figure 2.8 Buoy network in (a) Italy (from Vicinanza et al. 2009) and (b) in the Aegean and Ionian Sea under the POSEIDON programme (from http://www.poseidon.hcmr.gr/)

Sources based on satellite data
A source of increasing importance for wave energy resource assessments are satellite radars which cover nearly the whole globe, but are limited in their timely and spatial resolutions (Table 1). The two main satellite measurement systems are the Radar Altimeter RA and the Synthetic Aperture Radar SAR which are described in Chapter 2.2.1. Table 2 summarises relevant activities involving satellite data. The most relevant projects for the WEC development may be EuroWaves, GlobWave, POSEIDON, WERATLAS, World Wave Atlas and World Waves which are described in more detail in this Section except for POSEIDON which is addressed in the Section *Sources based on buoy data* and WERATLAS and World Waves which are addressed in the Section *Sources based on numerical data*.

Table 2: Activities involving satellite wave data relevant for WEC (after http://www.globwave.org/)

Name	**Organisation**	**Run time**	**Provided features**	**Description**
ALTICORE (ALTImetry for COastal REgions)	6 teams funded by INTAS	2006-2008	Altimeter data	The project focused on improving the quality and availability of altimeter data along and near the coasts of European seas and investigated effective methods of reliable data exchange through dedicated web services and data management infrastructures.
Archimede	APAT	Since 2005	Wave data, sea levels, currents and meteorological measurements	The aim is of retrieving historical datasets of meteo-marine observations and to elaborate them and create a national database accessible for all activities related to the coastal-marine field.
AVISO	CLS	Since 1992	Altimeter data (ocean circulation, sea surface height, significant wave height etc.)	An archive of satellite altimeter data based on the TOPEX/Poseidon, Jason-1, ERS-1, ERS-2 and Envisat satellites.
CERSAT	ESA	Since 1991	Altimeter, buoy and numerical data	A processing and archiving facility centre hosting a database of collocated products including satellite altimeter, scatterometer, radiometer, buoy and satellite/model data available for the distribution to the scientific community world-wide.
DUACS (Data Unification and Altimeter Combination System)	SSALTO (Segment Sol multi-missions dALTimetrie)	Ongoing	Altimeter data (e.g. significant wave height)	A multi-mission altimeter data processing system processing data from all altimeter missions controlled by SSALTO to provide a consistent and homogeneous catalogue of products for varied applications. It serves in near-real time the main operational oceanography and climate forecasting centres world-wide and in delayed time hundreds of participators.
ECOOP	71 partners	Since 2007	Ecosystem models, harmful algal blooms warning systems, maritime ship routing applications etc.	Project aims to create a database based on satellite and in situ measurements offering the ability to detect environmental and climate changes and to improve forecasting of the behaviour of European seas. It will also combine those data with existing regional and coastal sea forecasting systems for forecasting models.
ENVIWave	8 European partners	Completed in 2002	High quality ocean wind and wave products	An initiative to use data from the altimeter and SAR instruments aboard the Envisat satellite in order to combine with numerical models (e.g. WAM). The aim was to improve the short term forecasting of the sea state in at least three European countries and one Asian country.
ESPEN	Coordinated by HCMR	2002-2007	Short term forecasting of the sea state and real time information	A pilot project designed to provide wave measurements and forecasting information with specific applications to Hellenic navigation based on buoy measurements.
EuroWaves	Coordinated by Fugro OCEANOR with EU partners	Developed 1997-2000	Wave data	A tool based on the model WAM/SWAN which can be used for the evaluation of wave conditions at any European coastal location calibrated by in situ and satellite altimeter measurements.

GAPS (Global Altimeter Processing Scheme)	NOCS	Ongoing	Altimeter data (e.g. mean sea surface height)	It contains global data from the ERS-1/-2 and TOPEX/Poseidon altimeters organized into files where each file contains a single orbit cycle of data for a given satellite and the mean and residual sea surface heights are calculated at each point of a reference grid for research purpose.
GHRSST HR-DDS	ESA, MERSEA, NCOF	Since 2002	Sea surface temperature	Tool for analysing and inter-comparing all forms of SST data whether from satellite, in situ, model or interpolated sources at 250 locations world-wide based on pre-analysed statistics from the input data.
GlobWave	Lead by Logica with 4 partners	2007-2010	Satellite wave data	The project will provide free access to satellite wave data and products in a common format, both historical and in near real time from various European and American satellites. It shall also provide comparisons with in situ measurements and interactive data analysis tools.
JCOMM WFVS (Wave Forecasting Verification Scheme)	ECMWF	Since 1995	Wave data	Currently 12 meteorological centres submit their modelled wave data to ECMWF which collocates them with the corresponding buoy data and provide the comparison back.
MaxWave	11 EU partners	2000-2003	Extreme waves forecasting and statistics	An EU funded project which aimed to investigate waves of extreme height or shape, in both deep and shallow water, which cause accidents at sea.
POSEIDON	HCMR	1997-2008	Wave height, wave period and wave direction	This is a planning tool aimed at the protection of the marine environment, supporting business activities as well as preventing disasters and saving lives in the Greek seas. It supports the collection of data from in situ buoys which are used in conjunction with forecasting models to produce reliable predictions.
RADS (Radar Altimeter Database System)	TU Delft	Ongoing	Altimeter data	A harmonised, validated and cross-calibrated sea level database of satellite altimeter data including GEOSAT, TOPEX/Poseidon, ERS-1/-2, Jason-1/-2, GFO-1 and Envisat.
WERATLAS (European Wave Energy Atlas)	7 EU partners lead by INETI	-	Wave climate and wave energy statistics	It uses model predictions and in situ measurements to characterise wave climate and wave energy statistics in European seas in the offshore region.
World Wave Atlas 2.0	Fugro OCEANOR	Since 1994	Significant wave height with 1 s resolution	A global satellite altimeter database and software package calibrated against buoy data with a monthly update and sorted globally in 10 × 10º areas.
WorldWaves	Fugro OCEANOR	Since 1994	Global offshore wave and wind time series database on 0.5 × 0.5º grid including directional wave spectra	Commercial product delivering world-wide offshore wave and wind time series based on the ECMWF database including modelling in shallow waters with SWAN and further tools establishing computational grids and editing bathymetric data.
WorldWideStatistics	Fugro OCEANOR	-	Significant wave height and mean wave period	Commercial product consisting of a set of ready to go bivariate wave statistic tables, available as annual, seasonal and directional statistics for 150 regions world-wide, based on 10-year WorldWaves time series data.

Abbreviations in Table 2 if not mentioned: APAT = Agency for environment Protection And Technical services, CLS = Collecte Localisation Satellite, ECMWF = European Centre for Medium-Range Weather Forecasts, ESA = European Space Agency, ESPEN = Enhanced operational System for wave monitoring and Prediction with Applications in Hellenic Navigation, EU = European Union, GHRSST = Group for High Resolution Sea Surface Temperature, HCMR = Hellenic Centre for Marine Research, INTAS = International Association for the promotion of co-operation with scientists from the New Independent States of the former Soviet Union, MERSEA = Marine Environment and Security for the European Area, NCOF = National Centre for Ocean Forecasting, NOCS = National Oceanographic Centre Southampton, SAR = Synthetic Aperture Radar, SWAN = Simulating WAves Nearshore, WAM = WAve Model.

EuroWaves

A European consortium has developed a software package capable of providing wave statistics practically anywhere in Europe in both deep and shallow waters. This EuroWaves project was supported under the EU's MAST III programme and run from November 1997 to October 2000. The package is based on a high quality European wide offshore wave data base, which derives from wave data from the last 20 years from the WAM (WAve Model) model run at the European Centre for Medium-Range Weather Forecasts (ECMWF) in the UK, quality controlled by satellite altimeter data. The programme is equipped with a European wide bathymetric and coastline data base and toolbox, an advanced statistical package and various shallow water wave models (http://www.oceanor.no/projects/Eurowaves/index.htm).

GlobWave

The GlobWave project http://www.globwave.org/ is an ongoing three year initiative mainly funded by the European Space Agency to service the needs of satellite wave product users across the globe. It is led by Logica UK, with support from 4 partners, and will provide free access to satellite wave data and products in a common format, both historical and in near real time from various European and American satellites. In addition to common format satellite data the project team shall provide comparisons with in situ measurements, interactive data analysis tools and an enhanced wave forecast verification scheme for operational forecast production centres. The project will be operational in early 2010, and will be directed through regular and structured consultation with the user community.

World Wave Atlas 2.0

Fugro OCEANOR provides commercially the World Wave Atlas (WWA, http://www.oceanor.com/products/wwa.htm) since 1994. WWA is the collective name for a series of comprehensive high resolution atlases capable of providing wind and wave climate statistics for any country or region world-wide. It is both sold as a complete package, providing global coverage as well as by region, by country and site-specific. The satellite altimeter wind and wave data is fully calibrated against buoy data and is provided with a resolution of 1 s on a 0.5 × 0.5º grid and the along-track data are sorted globally into 10 × 10º area files which is also the minimum area sold. The data is updated monthly and is available from a number of missions such as GEOSAT, Topex, Jason or Envisat (Chap. 2.1.1). Based on the WWA data, the developer Fugro OCEANOR is able to provide the following information at any location globally:

- Time series of wave heights, period and direction for up to 20 years for European waters (up to 12 years elsewhere) mainly for deep waters, but also modelled with SWAN for shallow waters on special request.
- Typical statistics such as exceedance probabilities for wave height, extreme significant wave height, maximum wave height and crest height estimates, duration statistics (downtime analysis), bivariate and trivariate statistics for wave heights, periods and directions (e.g. scatter diagrams of wave height and period).

WERATLAS

WERATLAS is a software running under WINDOWS which was developed by seven European institutions and described in Pontes (1998). It enables the user to browse through the statistical information of annual and seasonal wave-climate and wave-energy statistics for a set of points at the European coasts being delimited by 49°W - 45°E and 26.5° - 73°N. The majority of the selected data consists on results from WAM model. Measurements were used in areas were the accuracy of model results is questionable and high quality measurements are available. The parameters considered are the significant wave height, the mean (energy) period, the spectral peak period, the mean direction and the wave power of flux of energy per unit crest length. The following areas were considered (INETI 1997):

- North-eastern Atlantic - Directional spectra computed six-hourly by the global WAM model for the period 1987-1994.
- North Sea - Directional buoy data and Plessey radar data for the period 1981-1994.
- Norwegian Sea and Barents Sea - buoy data (mostly directional) for periods between two and eight years.
- Mediterranean Sea - Mean wave parameters computed six-hourly by the Mediterranean WAM model for the period July 1992 - December 1995.

The modelled data were verified with buoy and satellite altimeter data resulting in a very good agreement for the North Atlantic but an underestimation of the modelled wave power per unit crests length compared to measurements of up to 55% in the

Mediterranean Sea (INETI 1997). Figure 2.9 shows the wave power resource for Europe based on some of the sites included in the WERATLAS. The same concept as in the WERATLAS was also applied specific for the Portuguese coasts in the ONDATLAS project with focus on 85 points in 20 m water depths (Pontes et al. 2005).

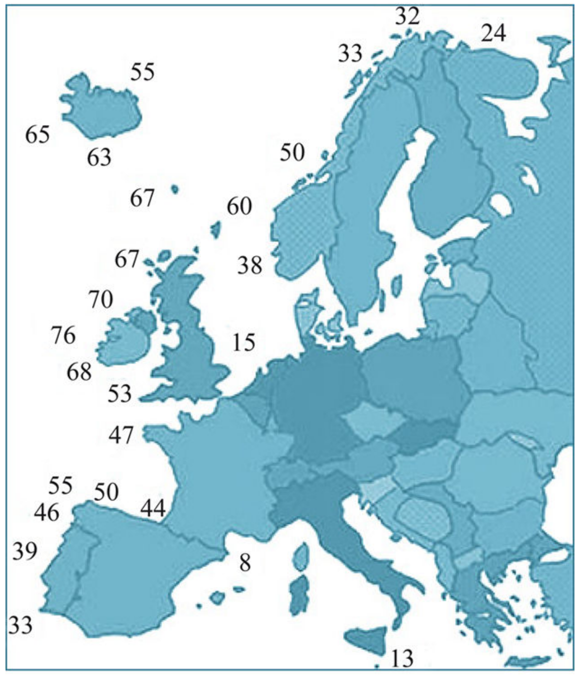

Figure 2.9 Time averaged wave power [kW/m] per unit crest length for Europe for some of the sites included in the WERATLAS

WorldWaves
A commercial product from Fugro OCEANOR delivering world-wide wave and wind time series at 10,000 offshore sites based on 10 years (and in most regions over 45 years) 6 hourly of the ECMWF WAM model archive data. They are calibrated against satellite and buoy data. The time series data are available for up to 40 years. Nearshore wave time series data and statistics are modelled with SWAN. Further tools establish computational grids and editing bathymetric data. Within minutes the WorldWaves package provides the following data (http://www.oceanor.com/products/worldwaves.htm):

- Offshore or nearshore wave statistic, directional spectra and time series data in a timely, cost-effective manner
- Reconstructions of wave conditions for particular time periods anywhere globally
- Tailor-made Worldwaves systems for any country or region world-wide

2.2.3 Tidal energy resource measurement acquisition equipment

Tidal current measurements have been acquired over a long period of history predominantly for navigation and shipping purposes. The predictable nature of the tidal flows at a particular location also means that much tidal data is very old and potentially has been gathered using old equipment. This means that resource assessment estimates could be relying upon antiquated and inaccurate data; with the thrust and power of a tidal energy device dependant upon the square and cube of velocity respectively this has obvious implications.

The most relevant methods of quantifying the tidal energy resource are acoustic Doppler system with or without surface tracking capabilities (for wave data). These and other forms of measurement equipment are summarised in Table 3 below.

Table 3: Comparison of tidal energy resource measurement acquisition equipment

Criteria	Acoustic current profilers	Log-pole (staff)	Rotary current meter	Electromagnetic flow meter	Radar systems
Type	Direct	Direct	Direct	Direct	Indirect
Measured quantities	Tidal speed and direction. Enhanced surface tracking can quantify wave direction, period and amplitude	Surface current velocity and direction	Tidal speed in direction of probe	Tidal speed in direction of probe	Surface tidal speed and direction over large surface area
Measurement frequency	Up to 1Hz. Sample averaging used to gain accuracy (typically several minutes)	Continuous.	Continuous. User defined sample time	Continuous. User defined sample time	Minimum approx. 10 minutes
Spatial coverage	Vertical column. Generally up to 40 cells throughout depth	Single point	Single point, generally close to surface if deployed from vessel.	Single point, generally close to surface if deployed from vessel.	300m to 15km
Typical accuracy	±1% of measured velocity	unknown	Unknown. Depends upon calibration, time of deployment and alignment.	Unknown. Depends upon calibration, time of deployment and alignment.	RMS error approx 7cm/s. Directional error up to ±7°
Service live	Battery powered sea bed mounted typically 1-month deployment	-	-	-	Continuous. Radar stations generally land-based.

Acoustic Doppler Current Profiler (ADCP)

Current profilers measure current speed and direction in multiple layers throughout the water column. Units can be mounted on the seabed in an up-looking configuration or down-looking from either a vessel or surface buoy. Acoustic beams diverge from the ADCP unit to for a conical volume. Average velocity and direction is measured at discrete distances from the ADCP such that the cone is divided into layers. The number of these layers (often referred to as 'bins') is dependant upon the instrument setup. Generally for fixed position resource assessment ADCPs are mounted on the seabed and operate autonomously. Sealed battery packs power the instrument, generally for a full spring-neap tidal cycle of 28 days. Underwater modems can be employed to transmit data to shore although generally data is stored in the ADCP unit itself and accessed upon retrieval. Dynamic surveys can be achieved by mounting the ADCP upon a moving vessel and sweeping across an area correcting for vessel speed and heading. The benefit of larger area coverage is tempered by the transient nature of the data acquired at any particular point. Generally a dynamic sweep passes over at least one active and static ADCP in order to correlate data sets.

ADCPs often incorporate a vertical beam to quantify the wave resource. Whilst not as functional as a dedicated wave measurement device this does allow the general nature of the wave climate to be defined at a particular tidal site. As the instrument function is not compromised by the inclusion of an additional beam this option is generally taken especially if a reasonable wave climate exists.

Log-pole

Log pole measurements were historically used by the UK admiralty for many tidal velocity measurements. A long, neutrally-buoyant pole is placed in the water with a length protruding above the waterline. At zero tidal velocity the pole is orientated with its longitudinal axis vertical. The weight distribution of the pole is such that in a tidal current the pole tilts from vertical. Calibration data is used to determine the flow speed for any given angle. Obvious errors in measurement magnitude include the presence of waves and determining the pole angle to a good degree of accuracy. Only surface tidal velocity can be measured and historically harmonic analysis was used to expand spring and neap tide measurements measured using log poles.

A similar piece of equipment is the drifting log ship. These devices are simple to use and still used today with GPS tracking. A Neutrally buoyant pole sits vertically in the water with approximately 300-500mm protruding above the water line. At the water surface there is a hole to which a graduated line is attached. The pole is set to drift from a moored vessel and once clear of the vessel wake the pole advancement is timed. Clearly only single measurements of velocity are able to be acquired hence spring peak and neap tides. More advanced versions might employ an electromagnetic line arrangement with a higher sample frequency but even then in a 3m/s tide a 100m line would only last 30 seconds.

Electromagnetic flow meter

Electromagnetic (EM) flow meters are robust but can be highly sensitive to noise. This methodology is generally used for measuring volumetric flow through pipes.

Rotary current meter

Rotary current meters are another device used historically for measuring tidal velocity. A small calibrated drag-force impeller is rotated by the current. Such devices offer point measurements of tidal speed and if a directional vane linked to a potentiometer is employed then point tidal velocity measurements can be attained. Rotary current meters are often prone to bio-fouling. Measurements are usually made from above the water line using a pole or line to position the flow meter thus measurement are generally limited to the near-surface region.

Radar systems

Radar systems are an area-coverage method of measuring velocity. Fixed radar stations, generally located on land, can map surface currents and direction. Velocity accuracy is generally better than direction. If sea bed properties are known then a specific vertical velocity profile can be approximated in order to correlate the surface velocity down through the water column. Systems are generally costly but the large spatial areas that can be covered compensate for this.

2.2.4 European Union Tidal Energy Data Sources

As previously discussed tidal stream measurements have not been acquired in suitable spatial or temporal density in order to inform array design. Most measurements were acquired in order to inform shipping and thus only peak flow speeds (generally mid channel) were taken. Other research has been dedicated to quantifying rates of sediment transport and thus in close vicinity of the sea bed, an area where tidal devices are unlikely to operate.

Resource assessments conducted in 1993, 1996 and 2004-5 (ETSU, European Commission, Black and Veatch Consulting Ltd) indicate that the overwhelming majority of tidal energy is situated around the British Isles. The historical importance of shipping to the UK has also meant that most of the tidal velocity measurements reside with the UK Hydrographic Office (UKHO). Spring and neap tidal stream data has been acquired at many locations in UK waters and extrapolated using tidal harmonic analysis to provide 30-minute continuous data of both velocity and direction. This data whilst of great use is limited in 2 ways:

1. Inaccuracy in measured spring/neap tidal data will be offset using harmonic extrapolation ensuring a constant error.
2. Due to the large area coverage of UK admiralty flow measurement campaigns tidal stream data points have low spatial resolution.

As the thrust force and available power vary with the square and cube of flow speed respectively historical measurements should be used with caution.

More recently ADCP devices have been used to quantify the magnitude of the tidal resource in a number of locations. The purpose of such studies is not always for tidal stream energy extraction; ADCPs can be used for more general studies combined with sea bed composition and bathymetric mapping. In most cases this data is gathered for commissioned work but may still be available for purchase.

The European Marine Energy Centre (EMEC) has conducted a number of ADCP campaigns around Orkney in northern Scotland. Similarly tidal energy industry stakeholders are encouraged to approach national meteorological offices and shipping authorities in order to ascertain if relevant tidal stream measurements have been acquired in specific locations.

2.3 Written Literature

2.3.1 Literature regarding the quantification of the Wave Energy Resource

With a larger number of wave measurement devices deployed and the need for data to validate meteorological office numerical models the status of wave energy data sources is arguably more comprehensive than tidal. Much of the European resource is located on West-facing coasts with an uninterrupted fetch from the Atlantic Ocean. Therefore the UK, Scotland, Ireland, France, Spain and Portugal enjoy the highest energy wave climates. The European Wave Energy Atlas documents this data as discussed in section 2.1.3. Other European studies have been conducted [Pontes et. al 1993, Pontes et. al 1996, Pontes 1998]. National studies have been conducted for a number of EU countries.

For the UK, a project commissioned by BERR in 2007 further developed the existing UK Marine Renewable Energy Resources Atlas, with enhanced definition of the primary resource variables, including wind, wave and tidal energy, and improved accessibility though a webGIS interface. More details can be found online http://www.renewables-atlas.info/ [Renewables Atlas].

Another example is that published by the Sustainable Energy Authority of Ireland in 2005, available online [SEAI] detailing the methodology used which is similar to the array method employed by tidal energy. Power capture from an example device was considered with a estimated array device packing density. Exclusion areas were considered and sites in excess of 100km from the coastline were discounted. The resultant extractable power estimate was 21TWh, sufficient to supply 75% of ROI's 2006 electricity requirement. There are a number of other studies published specific to individual members of the EU. Stakeholders are encouraged to seek out such reports and to contact their own national marine energy centres, for example those in the UK, Portugal and Denmark (links given in the references).

Various regional studies have assessed the wave energy resources throughout Europe. For example, a wave prediction system was developed for the Madeira Archipelago and the Portuguese continental coastline (Rusu et al., 2008) based on a general WAM model covering almost the entire North Atlantic basin and a more detailed SWAN propagation used in the coastal environment. These Studies targeted both the most energetic seas as well as average sea conditions, and were calibrated using operating wave data buoys. Similar studies have been undertaken for the Swedish West coast (Waters et al., 2008), the Spanish regions of Galicia, Asturias and South-East Bay of Biscay (Iglesias, Lopez et al., 2009-2010) as well as for various coastal regions of the North Sea (Beels et al., 2007).

Another local study was undertaken at the European Marine Energy Centre (Folley et al., 2009). The wave energy resource was derived from the wind and wave records offshore to the West of Orkney from the European Centre for Medium Range Weather Forecast's (ECMWF) European Waters Wave Model. Subsequently a Mike21 Nearshore Spectral Wave model was developed to investigate nearshore wave propagation. This study highlights some important characteristics to take into consideration as the reduction in directional distribution in shallower water, the over-accounts for highly energetic sea-states in the mean energetic values in offshore water. Taking these factors into consideration have shown that the reduction in the wave power density between the "deep water" sites and the "nearshore" sites is generally approximately 10% for the most commonly occurring sea-states.

Site-specific studies also exist and one such example is for the proposed Wave Hub off the South West coast of the UK. This is a sub-sea electrical connection hub provided for developers in order that they may installed a number of devices to generate meaningful quantities of power of rhte electrical grid. A number of studies have already been conducted for the Wavehub project including comparative work (Halcrow 2006 [1,2]) investigating the output from Meteorological Office European and UK wave climate modelling plus measured wave data from a location off the South West coast. Some work has also been conducted to assess the reduction in wave energy resource downwave of the wavehub [Miller et al] as the south west coast of the UK is a popular recreational area for surfers.

Finally, Mackay et al. detail the uncertainty in the estimation of the energy extraction from a wave energy converter (WEC). First, the study deals with the accuracy of the historic data Indeed both the calibration of model data and estimation of confidence bounds are made difficult by the complex structure of errors in model data. Then, a second article considers the uncertainty which arises from variability in the wave climate, dealing with the high levels of inter-annual variability and longer-term decadal changes in wave climate.

2.3.2 Literature regarding the quantification of the tidal Energy Resource

Historically tidal stream measurements have been gathered for shipping and other related offshore industries hence peak values are of most importance and generally low spatial density is a common characteristic. Therefore resource estimates to date contain many assumptions and in reality are only approximations of the tidal energy resource potential. In terms of the UK most resource estimates to date have been based on admiralty tidal flow data (Bryden, 2006) that has a limited spatial resolution even with interpolation (Bahaj, 2008) and has no consideration for the vertical velocity profile that can vary for differing locations and levels of sea bed roughness. For tidal energy and in particular arrays there is a requirement for high density depth-profiled velocity measurements at each potential site (Bahaj, 2008), this is starting to happen (albeit at low spatial density) but is an ongoing process but is currently not economically feasible on a large scale (Iyer et al., 2009). Another potential solution is methods that map velocity over larger areas such as radar systems as addressed in section 2.1.3 (Wyatt, 2009).

The majority of resource estimates performed to date concern the UK resource although there are a limited number covering the European and Global resource. These are acknowledged as having a much higher degree of uncertainty (Black and Veatch Consulting Ltd, 2004). There have been a number of reviews of such resource assessments (Blunden and Bahaj, 2007) , (Blunden, 2009) (Couch and Bryden, 2006). It is not the purpose to offer critical analysis of any one particular method. Full validation for any resource estimation will only occur when spatially dense flow measurements can be gathered and arrays installed at any particular location. There are three main methods of resource assessments which are detailed in (Black and Veatch Consulting Ltd, 2004, Hardisty, 2007, Bahaj, 2008, Bryden, 2006):

1. **Computational methods:** Based upon fundamental fluid mechanics equations such models vary in complexity. They require validation which is either obtained from small-scale experiments or full-scale tidal stream measurements although the latter can be spatially diffuse in nature. Energy extraction can be modelled by increasing the impedance of a region. Generally this is done uniformly over an area using methods such as increasing the sea bed roughness or reducing momentum (sink) of the fluid.
2. **Flux method**: The Flux method considers the energy that enters the tidal site and provides a percentage of this energy that can be captured. It is independent of array layout and device type. (Bryden et al., 2007, Blunden, 2009, Hardisty, 2007, Garrett and Cummins) .
3. **Analytical method:** this method uses numerical modelling to characterise tidal flows at specific tidal sites. A high resolution picture can be developed by combining sparse tidal data with known characteristics of the flow around tidal turbines (Bahaj, 2008). In this way an array can be arranged and the total energy extracted can be estimated. It does not consider the wider environment such as flow behaviour around the array of any impedance effects of the region. An Analytical estimate was also conducted by (Myers and Bahaj, 2005) for the Alderney Race, Channel Islands.

UK Resource

Early studies by (Fraenkel and Musgrove, 1979) and (Wyman and Peachey, 1979) based on Admiralty chart data and basic analysis of estimated kinetic energy estimated the UK resource to be 14.7-18.7 GW respectively. During the 1990s two seminal reports were published. (ETSU, 1993) estimated the UK resource to be 6.9 GW and selected sites based on the following two requirements; spring peak tidal stream velocities greater than 2m/s and depths of greater than 20m. This report used an array method and 33 sites in total were identified around the UK based on velocities taken from tidal stream diamonds and tidal stream atlases. The later European Commission report (European Commission, 1996) estimated the UK resource to be 3.9 GW and again used a similar array method where peak flow velocities of greater than 1.5 m/s were considered exploitable.

Recent resource assessments by (Black and Veatch Consulting Ltd, 2004 & 2005) were based on the flux method. The authors conducted a review of previous work including (ETSU, 1993) and (European Commission, 1996) and concluded that these array methods significantly over estimated the UK resource potential because they failed to consider the effects of energy extraction on the flow. In response the revised UK resource estimate was made at 2.5 GW. Based on work presented in (Bryden and Couch, 2006) and (Bryden et al., 2007) it was estimated that 20% of the available kinetic energy could be exploited. This factor was later revised in Black and Vetch's Phase II report to account for the variation in flow regimes at different tidal sites. The resulting UK resource estimate reduced to 2.1 GW.

Recent work (Salter and Taylor, 2007) postulates that the Pentland Firth has a much higher resource potential than estimates such as (Black and Veatch Consulting Ltd, 2005) suggest because of the channel's low impedance hence increasing the number of tidal turbines will have little effect on reducing flow velocities. The author calculates the energy dissipated due to bed friction alone is huge and leads onto the much smaller value of extractable power of up to 17 GW which is significantly greater than the all previous estimates of the entire UK tidal energy resource. The authors acknowledged that the model used was simplified using a highly subjective bottom friction coefficient. In summary the differences in all resource assessments are based upon:

1. Changing understanding of the available and extractable energy
2. Variations in number of locations considered
3. Difference in assumptions at each considered location such as turbine packing density

European Resource

Resource estimations for Europe are limited but the (European Commission, 1996) report extends it estimates to 57 European sites using the same method that they employed for estimating the UK potential and the total non-UK European resource was stated as 16.7 TWh/y. The (European Commission, 1996) consider their value to be a reasonable first approximation even though the Figure is considerably less than the predicted UK resource. It is postulated that this is partly because much of the European resource is located in Mediterranean regions where tidal ranges and flows are limited. To validate this estimate further work is required.

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3. MATCHING DEVICES TO THE MARINE ENVIRONMENT

This section of the protocol investigates which device and site parameters are critical for the matching of a particular wave or tidal energy device to a specific site. Guidance is offered on which parameters should be considered and how device/site matching could be rationalised.

The most common tool utilised for device/site matching is Graphical Information System (GIS) software. Graphical information for an area under consideration can be overlaid (such as bathymetry, wave climate, currents, electrical gird routes) in a graphical software package. Layers can be assigned a value of importance and thus summation over the wider area can yield sub-areas that offer the most beneficial location for wave or tidal energy devices. This is a simplified definition of GIS, there are other functions that make it a powerful tool but its effectiveness and the end result is ultimately governed by the following parameters:

- Availability of data
- Accuracy / spatial extent of layer information and resolution
- User-defined weighting assigned to specific layers

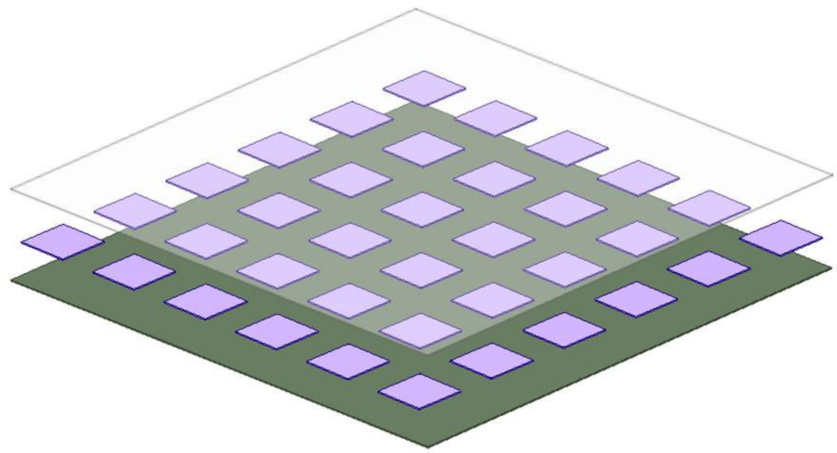


Figure 3.1. Diagrammatic representation of GIS layer analysis.

In addition to wave or tidal resource, there is a large number of general characteristics which define suitability of an marine energy converter array to a specific site:

- **Physical Characteristics**
    - Sheltering or focusing by the local coastline
    - Seabed surface conditions (sedimentological and bed form features);
    - Bathymetry;
    - Current velocity and direction.
- **Environmental Constraints**
    - Proximity to statutory and voluntary nature conservation areas (e.g. both existing and planned Special Areas of Conservation, Special Protection Areas, SSSI, Marine Consultation Areas etc), sensitivities and concerns etc;
    - Benthic habitats/marine ecology (including electro-sensitive species);
    - Intertidal habitats;
    - Fish and aquaculture areas;
    - Marine mammals (e.g. including cetaceans, seals, otter etc);
    - Birds;
    - Coastal processes;
    - Marine archaeology;
    - Aesthetic impacts and seascape;
    - Location of any noise sensitive receptors;
    - Cumulative impacts.
- **Other Users of the site**
    - Nature conservation;
    - Marine aggregate/maintenance dredging and any dredged material /spoil disposal sites;
    - Pipelines and cabling;
    - Navigation;
    - Military;

- Shipping routes, anchorages and port approaches;
- Commercial and recreational fisheries;
- Recreational sailing;
- Tourism;
- Archaeological and cultural heritage.

In addition to this are key installation and operational characteristics:

- Proximity to available grid capacity
- Proximity to suitable port / harbour for staging installation and decommissioning
- Proximity to suitable long-term O&M base
- Proximity to potential cable landfall

This protocol will:

Identify parameters applicable for device/site matching and relate them to various scenarios that might occur for device/site matching exercises.

This protocol will not:

Perform GIS (or any other) analysis in order to match wave/tidal devices to sites. It follows that the weighting of information layers are user-defined and can vary between potential sites.

Separate and highlight issues that pertain to farms or arrays of devices. Wider spatial consideration will alter the decision-making process regarding the potential location of wave/tidal energy device arrays.

3.1 BARRIERS TO DEVICE/SITE MATCHING

Some considerations prevent the installation of arrays of devices even before any device/site matching process is undertaken, for example

- Military use of area – Submarine, surface vessel exercise areas, ammunition dumps
- Scientific / Environmental – protected species of flora/fauna
- Commercial – fishing, aggregate dredging, shipping lanes

These can be termed “Showstoppers” – an event, action or inherent characteristic that prevents any further development. Other issues/parameters defined below are not quite so absolute in terms of precluding array design.

3.2 METOCEAN PARAMETERS APPLICABLE TO DEVICE/SITE MATCHING

Nearly all metocean parameters will be both site and device specific thus quantifying any such metrics for the EU wave/tidal resource would be an enormous undertaking. As discussed in section 3 any analysis based upon device-specific parmaters is not within the scope of this protocol due to the fact that:

a) The output of GIS-type analysis is dependant upon user-defined weighting of parameters
b) There have been and will continue to be a myriad of such resource assessments for EU waters

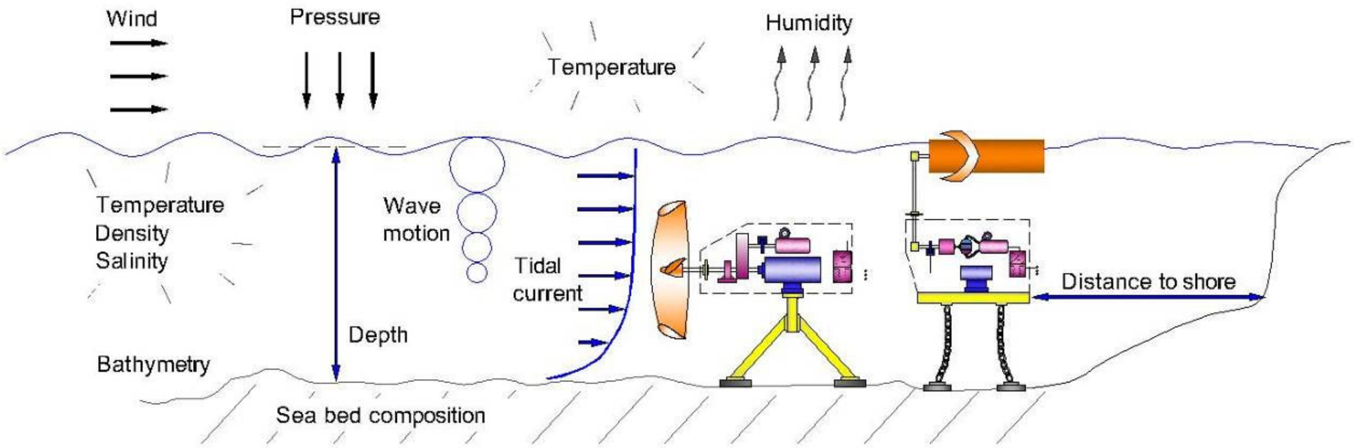


Figure 3.2 - Diagram of typical Metocean variables affecting wave and tidal energy arrays

Metocean variables can vary both in a spatial and temporal sense for an array location. Figure 3.2 illustrates some of the most pertinent metocean parameters. The most important spatial variable is likely to be the incoming wave/tidal resource in terms of available energy to an array site. This will vary in a spatial sense depending upon the depth and bathymetry across the array site. For large arrays it is unlikely that the depth will be uniform across the site. The tidal velocity will be greater for shallower depth regions within an array and this can be observed to good effect at the Race of Alderney between the UK Channel Islands and the Cap de la Hague, France. The Eastern part of the race has significantly higher flow speeds compared to the deeper more tranquil West region. For wave energy reducing depth will increase wave height and decrease wave length. Clearly there are 2 issues of importance here:

1) The magnitude of the variation in depth/ bathymetric profile
2) The measureable effect this has at the devices within the array

Deliverable 5.3 stresses the importance of quantifying array metocean conditions around 1st-generation arrays if expansion is planned. If the depth/bathymetry conditions do vary appreciably across the site it is advisable to quantify the wave/tidal resource to a good spatial density across the site. Metocean data such as wave and tidal characteristics should be gathered following guidance from the resource assessment section of the Equimar protocols.

Distance to shore is an important aspect of site selection and matching devices to specific sites. At the present stage of development there already exists 'shallow' tidal and wave energy devices; the former hope to harness faster flowing estuarine environments and tidal flows where depths are generally less than 20m whilst the wave energy devices are suited to shallow shoreline locations and thus have a limiting working water depth.

The length of underwater transmission cables to shore will influence site selection. It must be considered that linear distance to the nearest shore or electrical grid connection point may not be an option for a number of reasons. A number of obstacles may exist between the array and the shore such as dredging sites, steep changes in bathymetry or ammunition dumps. Thus the true cable length to shore may be greater.

3.3 DEVICE PARAMETERS APPLICABLE TO DEVICE/SITE MATCHING

Whereas the previous section was perhaps more relevant for device/site matching for a specific device guidance given here could be said to be for selecting the most suitable device for a specific site. There is no agreed method on how to best perform site matching; as discussed earlier in section 3 the weighting of parameters is highly subjective and dependant upon the person(s) conducting a matching exercise.

From layer 2 of the device classification template the rated operational conditions in terms of tidal velocity and wave climate characteristics are specified. It is important that the rated conditions are not exceeded (at least not frequently) and to this end the ability of any device to perform at a specified site may require a number of devices to be compared and matched to a specific array site. This will ensure optimal operation and power production.

Layer 3 of the device classification template describes a number of device parameters that will be important for device-site matching.

The basic form of device foundation is dependant upon the water depth and sea bed composition. The working water depth will influence device-site matching depending upon the range that can be accommodated by a device. Some devices will be far more sensitive to changes in depth than others where a wider operation depth range will decrease the sensitivity of this parameter when conducting a site matching exercise.

The method of alignment that the device employs in order to minimise structural loading whilst maximising energy capture will be a factor when matching devices to potential sites. Some tidal energy devices do not employ a yaw mechanism (similar in function to those on wind turbines) assuming that the tidal flow is exactly or very close to being bi-directional. This may preclude them from being deployed at sites where there is a large amount of 'swing' in the tidal direction between ebb and flood tides. Wave energy devices in deep water can enjoy wave climates where changes in wave direction are slow to occur and thus the ability to align a device rapidly is not generally a problem. Similarly near shore devices operate in an environment with low wave directionality and in some cases can omit an alignment mechanism.

3.4 Infrastructure parameters applicable to device/site matching

As far as Wave and Tidal Energy Converters are concerned, the main issues to be considered are the installation stage and maintenance throughout the life of the device. The device being offshore, accessibility is limited by many factors. The proximity of the site to a harbour is a good option for quick and relatively cheap operations. Onshore transport and communication links are also important especially with the remote nature of some potential marine energy sites.

An important factor that must not be overlooked is the competition between marine energy and offshore wind infrastructure. For the installation of the turbine, the seabed drilling is performed by the same ships, the same types of vessel are required for maintenance and the problem arises again where similar equipment is used for the grid connection. Therefore, a very important factor for any technology is its capacity to be deployed in large-scale farms in very short period, taking into account all the accessibility issues. In the coming years, the significant development of offshore wind farms is expected and there is a serious threat that this might interfere with the marine energy sector.

All marine energy converters will require station-keeping systems or foundations in order to maintain their position. Particularly, floating devices would probably adopt moorings with several anchors placed at a determined distance from the device and imposing a certain "footprint". If those devices were to be deployed and moored independently, the size of the "footprint" might impose an important constraint on the inter-device distance. A possible alternative would be constituted by a globally shared mooring arrangements for arrays in such a way that several converters might be moored and interconnected together. This would save infrastructures (in terms of anchors and chains) and might even prove to be beneficial for wave energy converters .

Another factor influencing the arrays configuration is represented by the electrical connection infrastructure. The rated power of the whole farm influences the choice of the connection and imposes requirements in terms of infrastructure and cabling It is likely that future marine energy farms will host floating or submerged substations to allow elevation of the voltage for efficient transmission and their positioning will have to be defined accordingly to a feasible device configuration (Figure 3.3).

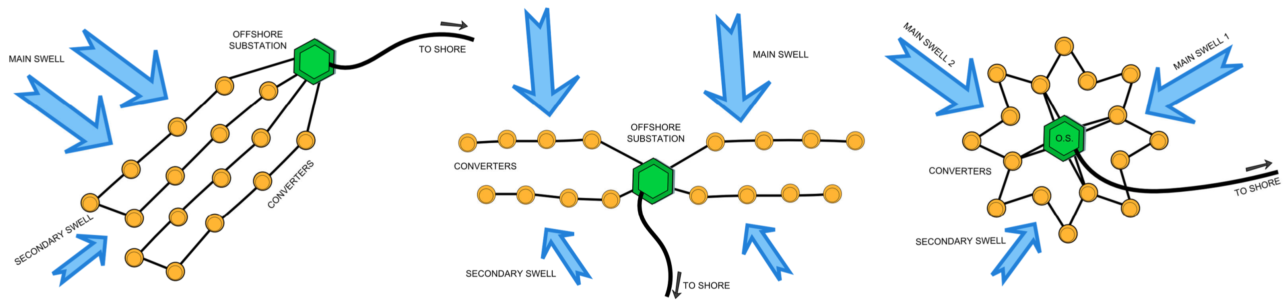


Figure 3.3 - Possible alternatives for a wave energy converters array electrical connection configuration

Also, in some cases marine energy arrays will have to be electrically inter-connected before being linked to the general hub or substations. In such cases, the inter-device distance should be chosen according to the requirements defined by the umbilical cables design and the need to avoid extreme mechanical loads on one hand and excessive power losses on the other. Finally, as mentioned before, another very important constraint on inter-device distance will arise from the need for vessels and their equipment to operate at ease on the single devices for maintenance and repairs. This requirement will be often device- and site-specific making it difficult to define guidelines to deal with it.

Marine energy farms, like other renewable energy sources, will probably be connected to distribution grids. But one different aspect of marine energy is that it will only has access to the grid placed near the shore, which makes that the site of the farm becomes more important regarding grid connection issues. So, when a marine farm is planned, there are aspects like grid strength that have a greater consideration. The grid strength has influence in the ability of the farm to control the voltage level. Other important aspect to be taken into account is the ratio between the resistance and the impedance of the grid (X/R).

When a point of the grid is fed with a current, this causes an increase or decrease of the voltage in said point. The extent of this voltage variation depends on the grid impedance; when the grid has a high short-circuit power the voltage change caused is small due to the small impedance of the grid, that is, the fed current does not cause a significant voltage increase. On the contrary, in the case of a weak grid, its impedance is very large, so the feed current can cause important variations on voltage level. Therefore, when a marine energy farm is connected to a weak grid, high variations of voltage level can be produced. A typical case of a connection to a weak grid is the case of a farm connected at the end of a transmission line.

4. GUIDANCE FOR INTERACTION EFFECTS BETWEEN DEVICES IN AN ARRAY

This section addresses the manner in which devices can interact within an array and the parameters that can facilitate such interaction. Marine energy devices will convert some of the energy from the metocean environment (waves or tides) into a useful work. This can taker a number of process paths but the end output is most likely to be the generation of electricity. Removing energy from the marine environment at a local point (the device) will lead to a reduction in energy in the far field surrounding the device but generally this reduction is conveyed downstream or downwave. The temporal and spatial characteristics of this reduced-energy region will vary with metocean and device characteristics but it is commonly referred to as a wake. This is the principle mechanism for device interactions within an array. Ideally we wish to ensure that all devices are presented with equal inflow of energy. However, due to spatial constraints and other issues thus may not be possible to completely avoid device interactions. The wave and tidal energy industry should strive to understand interaction effects (principally the wave or stream field) in order to achieve the following:

To minimise interaction effects for a given type or design of array

To allow interaction effects to be incorporated in to design, planning and operation

The above statement implies that interaction effects are not desirable but there is incidental evident that some interaction effects are beneficial. Most common and perhaps held in the highest regard is an increase in incident energy to another device within the array.

This protocol will:

Identify parameters that influence device interaction within an array structure. Give qualitative guidance as to the degree of influence such parameters might have based upon:

Related literature

Physical modelling

Numerical modelling (assuming model is suitably robust)

This protocol will not:

Be able to give quantitative guidance upon many device specific issues where literature or previous modelling has not been conducted.

4.1 LITERATURE REGARDING MARINE ENERGY DEVICE INTERACTION

It is apparent that for wave and tidal technologies nearly all of the investigative/research effort regarding device interaction studies has been conducted either at small-scale or using numerical simulation tools that have been validated (or not) using experimental studies. There are clear deficiencies in the work completed to date; the most common experimental parameters are scale effects and the inability to accurately replicate full-scale met-ocean conditions. Numerical modelling suffers from a lack of experimental validation at all scales. Increased effort in this area is most important as measurements from wind farms (perhaps the most closely related application to wave and tidal arrays) show a significant reduction in power associated with interaction effects between adjacent turbines. This section does not provide an exhaustive list and review of all relevant literature. Instead it offers an overview of the type of research that has been conducted to date in order that all actors within the wave and tidal energy industry can make informed decisions regarding device interaction and also the need for further quantification of specific issues.

4.1.1 Wind farm interaction effects

Wind turbines offer a reasonable comparison with wave and tidal energy devices. Wind farms are composed of a number of devices in close proximity extracting energy from the surrounding environment. It can be argued that they have a very good similarity with tidal energy with the common features of extraction of kinetic energy from a moving fluid. Tidal differs most significantly with the constrained nature of the flow field and turbulence structures in water and air are also quite different. However, whilst quantitative results from wind turbine trials cannot be used for tidal energy the methods and approaches used can serve as a platform for understanding. Some of the qualitative issues arising from wind farm device interaction can also be of interest to wave energy arrays.

Early work was conducted to quantify the intensity of wind turbine wakes with respect to down wind distance. Many smaller-scale experiments were conducted in large wind tunnels whilst full-scale measurements were gathered at sites such as Goodnoe Hills in the U.S.A [Baker 1984]. Kite anemometry measurements at 9 rotor diameters downstream yielded flow speed reductions of between 10 and 15% depending upon ambient turbulence intensity. This translated into reduction in available power of up to 40%. Work has been published regarding the power losses at the Middlegrund offshore wind farm [Barthelmie 2007]. At the latter site average power of the farm is approximately 90% of rated power. Peak power is as low as 40% of the rated wind farm output although this is for a narrow and infrequent wind direction and owes much to the single line of closely spaced devices which is not a typical wind farm configuration.

From the above work numerical models were developed [Gomez-Elvira 2005]. Barthelmie (2008) compared 5 numerical models to predict losses at the Horns Rev and Nysted offshore wind farms. Normalised power for turbines downwind of the first row averaged approximately 0.8. As perhaps expected it was stated that existing models coped well with small wind farms but under-predicted losses due to wake interaction for larger multi-row wind farms. It is expected that a similar case will exist for wave and tidal arrays; the increase in complexity arising from the transition from 1st to 2nd generation arrays as described in deliverable 5.3. A further paper suggested that power decay in downstream rows or turbines was greater and could reduce overall power output in the range of 60% to 80% depending upon wind direction [Méchali 2006]. A number of modelling numerical approaches have been considered for analysis of flow effects around wind farms [Migoya 2007]. These include full Computational Fluid Dynamics (CFD) Navier-stokes solutions, mass-conservation and stochastic models [Sorensen 2007]. From the work referenced above the following is clear:

1. Power losses due to interaction effects are large in multiple row wind farms
2. Numerical and analytical models increasing under-predict power losses as the number of rows increase
3. These serious issues are more relevant to 2nd-generation wave and tidal arrays. 1st-generation arrays should not suffer due to the lack of device interaction.

4.1.2 Experimental studies

At the present state of technological development for wave and tidal energy most experimental effort has been focused upon performance quantification of single devices. There has been little experimental effort made regarding quantification of the flow field around devices or indeed any interaction effects that might occur between devices. Almost all the existing published work regarding interaction effects has been conducted at small scale. No doubt some wave and tidal energy device developers have conducted scale trials to measure wake and radiated wave fields but with the emphasis upon testing of single devices to demonstrate commercial viability and the need to protect intellectual property much of this information (if it exists) is not in the public domain. There has been some scale studies performed for tidal energy devices investigating wake effects and interaction [Myers 2009,2010, Maganga 2010]. Laboratory studies offer controlled conditions albeit with a different ambient turbulence structure to that of a full-scale tidal site.

Wave energy studies have focused upon point-absorbing devices due to the discovery that close inter-device spacing can enhance energy capture due to resonant effects caused by the radiated wave fields [Stallard 2008, Weller 2009].

4.1.3 Numerical and analytical studies

Numerical studies are now being published for both wave and tidal energy studying effects of wake flow fields and device interaction. For wave energy devices most effort has focused upon point-absorbing devices [Backer 2009, G. Thomas 1981, S. Thomas 2008, Pedro 2009, Child 2009, Babarit 2009]. In monochromatic wave fields it has been found that positive interaction effects occur whereby array power production increases due to resource amplification generated by the wave-fields radiated from individual devices. However, it should be noticed that positive constructive interference of the diffracted and radiated wave fields (which might enhance power absorption) occur only at determined frequencies whereas it can even turn into negative interaction effects at some other frequency ranges. Some device-specific literature is now being published for wave energy devices [Beels 2009]. Whilst most tidal energy numerical/analytical work has focused upon singular large energy extraction from tidal currents (see section 2) there are some emerging numerical studies regarding device interaction [O'Doherty 2009].

4.2 ENERGY CAPTURE PERFORMANCE OF SPECIFIC DEVICES

The energy extraction performance of devices within an array will affect the magnitude of any interaction effects, both positive and negative. There has been some experimental work to quantify this but it is generally accepted and understood that for increased device energy extraction the downstream or downwave resource will be increasingly diminished. However, the nature of this is not absolute and varies from individual devices to cases where multiple-devices extracting energy from can lead to more severe effects. Figure 4.1 shows the downstream flow field (vertical plane) of 3 porous disks often used to simulate horizontal axis turbines such as wind and tidal devices [Myers 2010]. Each of the 3 disks shown exerts a differing amount of thrust upon the incoming flow which serves to simulate varying device energy extraction. It can be seen that in the near wake region close to the disks there is a difference in the magnitude of the flow velocity. However, further downstream in the region where subsequent devices might be placed within an array there is little if any difference. This is due to the ambient flow dissipating the wake generated from the device. However, for multiple devices within an array this may not be the case as has been demonstrated with energy losses in wind farms. Thus it is important not to make strong generalisations, or carry over results from similar technologies or other device types.

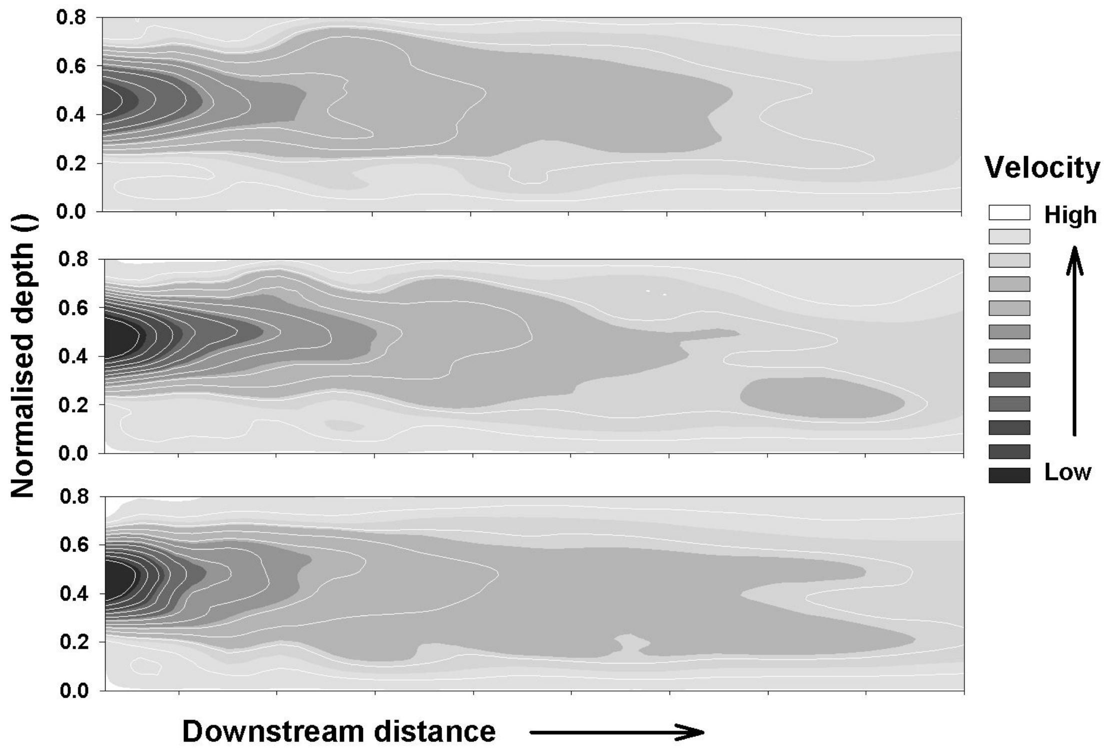


Figure 4.1 – downstream flow field of 3 actuator disks; lowest exerted thrust (top) and highest (bottom)

4.3 METOCEAN PARAMETERS

4.3.1 Directionality of the resource

An influential metocean parameter is the directionality of the wave or tidal resource. This can not only have a considerable influence upon single device performance but also upon the interaction of devices within an array as has been demonstrated for wind farms [Barthelmie 2007, 2008, Méchali 2006]

The region of lower energy down stream or downwave of a device will be wider when the directionality of the incoming resource increases. This was encountered in the wind energy industry and is known as "wake meandering". This effect is illustrated in Figure 4.2. It follows that if the directionality of the resource is not well understood and the array is not designed for such metocean conditions the degree of device interaction is likely to increase. This will undoubtedly have a negative effect as loading increases and energy capture decreases for devices operating in the wake or energy capture zone of an upstream/upwave device.

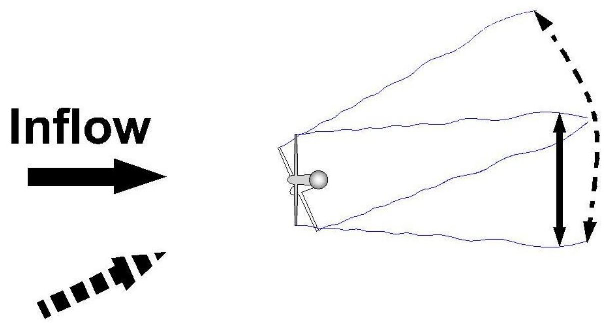


Figure 4.2 Increase in spatial extent of downstream wake (dashed lines) for increasing directional inflow

Both wave and tidal energy benefit somewhat from relatively low directionality. Most wave sites tend to have a strong prevailing wave direction thus wave field direction changes very slow; in the order of several hours. One such tidal energy site where a high degree of resource directionality is already known is Portland Bill [Blunden 2006] on the south coast of the UK. Tidal sites often have a bi-directional resource that reverses close to 180˚ between flood and ebb tides. However, at the Portland site flow detachment occurs around the headland causes a reverse in flow direction that it is far from bi-directional. If the nature of resource directionality is known and quantified in advance of installation such effects can be incorporated into the design of the array.

4.3.2 Bathymetry

Bathymetry may affect device interaction within an array. Continuity of depth within and surrounding array area is an important issue. This may lead to changes in direction of waves/tidal currents that could affect the magnitude of device interaction. It is likely that for wave energy arrays such sites would be avoided due to wave refraction. If the changes in depth are not too severe or immediate then this may have a lesser effect for tidal energy. Continuity will ensure that shallower areas of an array site would have higher flow velocities whereas deeper areas would receive a more tranquil flow regime. This may require different sizes of devices in order to effectively capture energy from the site. Changes of bathymetry over short distances would be detrimental to both wave and tidal. For the latter technology strong turbulent structures could be shed at such bathymetric transitions that could negatively impact upon device power production and structural loading.

Significant changes in bed roughness characteristics would lead to increased turbulence in the water column. This could change wake lengths downstream of tidal turbines [Myers 2010]. Increasing bed roughness would also reduce the magnitude of the wave energy resource.

Plans for early tidal arrays have demonstrated the importance of bathymetry at a particular site. One planned tidal array is proposed for the sound of Islay in northwest Scotland. This is a narrow passage almost triangular in cross section. Therefore installation of a 1st-generation type array (see section 1.3) does not seem possible due to the restricted width and therefore devices must be installed axially downstream of each other. It is expected that for early arrays such a separation distance might be overly-cautious to minimise negative interaction effects. A second tidal energy array is proposed at Paimpol Brehaut in Brittany, France. Early indications show a device layout not consistent with that suggested in this report but rather driven by the bathymetry at the site and the need for device placement in a narrow range of depths. Therefore bathymetry may prove to be a key driver in the arrangement of tidal energy devices within arrays.

4.3.3 Short-term unsteady events

Such effects include storm surges and freak waves. Often these are infrequent and would not affect device interaction within and array as it is most likely that devices would be in survival mode. Thus the fraction of incoming resource harnessed (if any) is smaller than for rated conditions so interaction less likely.

4.4 SPATIAL INFLUENCE OF ENERGY CAPTURE FROM INDIVIDUAL DEVICES

Despite the lack of knowledge of how wave and tidal devices might interact it is possible to make qualitative assessments of many situations.

4.4.1 TIDAL ENERGY

The tidal energy resource at most sites generally has a low degree of directionality. Most common is that the angle between the flood and ebb tides is usually close to 180 degrees. A value to exactly 180 degrees is referred to as a bi-directional. In most cases this is not the case and there is an amount of 'swing' as the direction of the flood and ebb tides is not exactly reversed. Despite this the predictability of the tidal resource (both in terms of tidal stream velocity and direction is high.

From section 4.3.1 it is evident that in most cases tidal flows are close to being bi-directional. The degree of 'swing' between flood and ebb tides is generally site-specific and thus we can make a number of qualitative observations based upon existing knowledge regarding wake flows from energy extraction devices and experimental work.

It is most likely that 1st-generation tidal arrays will be of a single row configuration arranged perpendicular to the predominant direction of tidal flow (Figure 4.3). Here the region of flow influenced by the devices (wake) is shown as a shaded region propagating downstream. The principle device interaction parameter is the distance A laterally between the devices. It is assumed that this arrangement will be beneficial for a number of reasons:

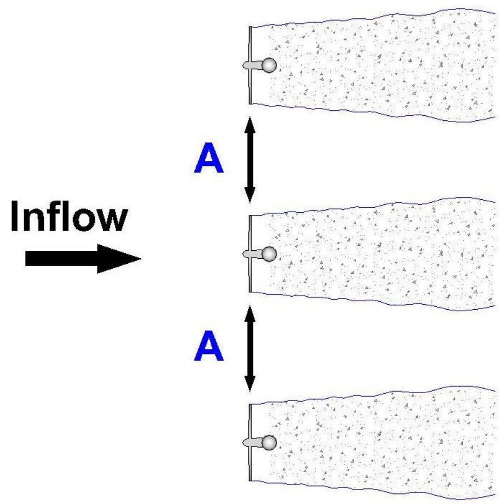


Figure 4.3 Single row 1st-generation tidal array

- Turbines will not operated in flow region A
- Distance A probably will need to be small for interaction effects to occur
- Initial arrays are likely to be composed of up to 10 devices thus lateral coverage at most tidal sites will be small
- Access for installation/maintenance craft is good

Early artist's impressions of tidal energy device manufacturer's arrays supports this reasoning.

It is expected that as the size of tidal arrays increases a dual row arrangement will need to be considered. Scale model testing supports the offset row arrangement as shown in Figure 4.4.

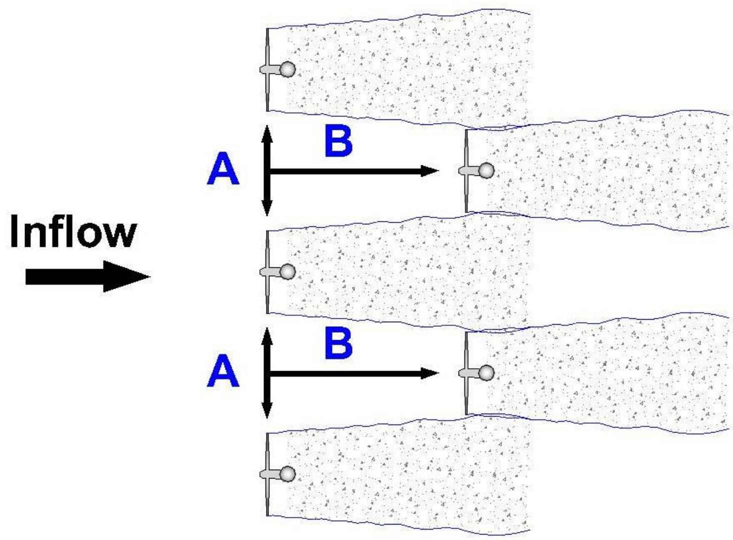


Figure 4.4 Dual row 1st-generation tidal array

It is intuitive that if distance *A* is large then the tidal field moving through the gap between 2 devices will remain relatively unchanged towards the centre of the gap. As distance *A* is reduced the amount of undisturbed tidal flow will also reduce. At some small value of *A* adjacent devices will affect each other and this is likely to be a negative interaction. It also now follows that there must be an optimal value of A where adjacent device spacing is acceptably small but also where enough of the wave/tidal resource can pass through the gap. Now we have the ideal scenario for an expanded 1st-generation array with 2 rows. Distance B will be optimised where the downstream/wave row is operating in flow conditions similar to that of the first row. As the tidal device wake will tend to diverge this further supports the theory that there is an optimal value of B depending upon device type, operation and met-ocean conditions. Whilst we cannot give definitive values for A and B we can inform device developers in a generic manner to empower the industry to acquire data to optimise inter-device spacing. Device developers are encouraged to forward plan single row arrays to incorporate installation of a second row at a later date by measuring tidal resource downstream of a single row array (see D5.3). 2-row arrays will hold a number of benefits:

- Turbines can experience the same inflow characteristics
- Distance B probably will need to be small for interaction effects to occur
- Almost double power output over single row array for similar array lateral width
- Installation/maintenance craft can attain clear access to all devices from upstream and downstream side

Once arrays reach sizes whereby the offset 2-row arrangement occupies a disproportionately large lateral distance of a tidal channel then devices will need to be arranged in larger numbers with additional rows of devices (Figure 4.5). Here the 2-row offset pattern is repeated with subsequent rows. We now have a 2nd-generation array as defined in section 1.3 of this document.

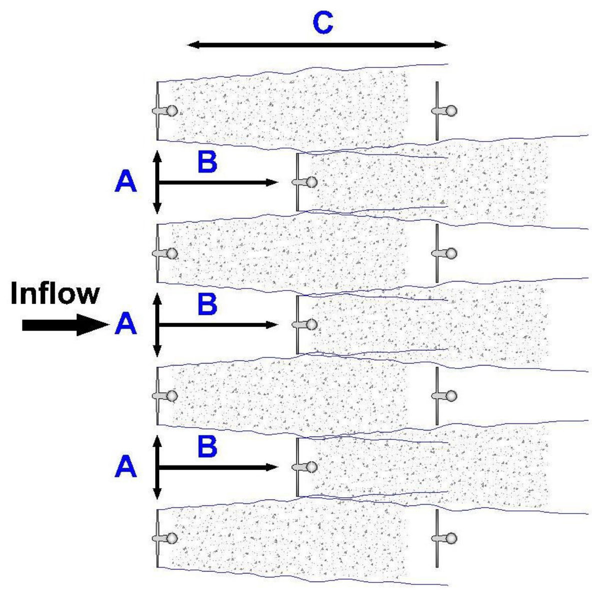


Figure 4.5 2^{nd}-generation tidal array

Distance C refers to a distance directly downstream between two devices as shown in Figure 4.6.

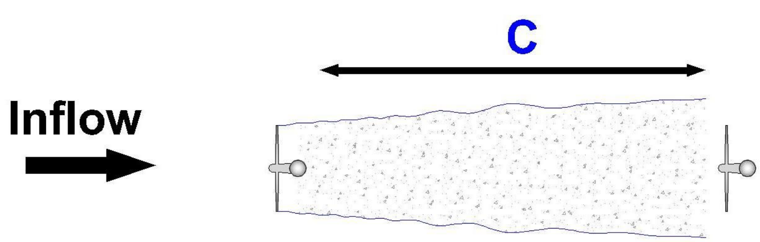


Figure 4.6 Tidal device operating in the wake flow of a device located directly upstream

Increasing the distance C will reduce the degree of interaction which is negative i.e. the downstream device will generate less power than the upstream device. With tidal energy sites being of a finite size arrangements with zero device interaction are probably unrealistic. Thus C will be determined on a site by site basis with a natural trade off between limiting negative interaction effects whilst maximising energy capture from the array as a whole. The optimal value of C will vary with the parameters discussed in section 4.3. At this time there is no quantitative guidance that can be given for this. Reference is made to earlier sections of this document specifically literature covering power losses in wind farms. Once again device developers and operators of 2-row arrays are encouraged to quantify downstream flow conditions in order to inform existing array expansion or layout of new 2^{nd}- generation arrays.

4.4.2 Wave energy

With the large range of device concepts the process of identifying interaction effects within a wave energy device array is more involved than for tidal energy. The wake or radiated wave field will vary with the principal motion of the hydrodynamic subsystem of the device. Figure 4.7 taken from the 'device classification template' illustrates the type of radiated field and wave regime for a heaving and pitching device.

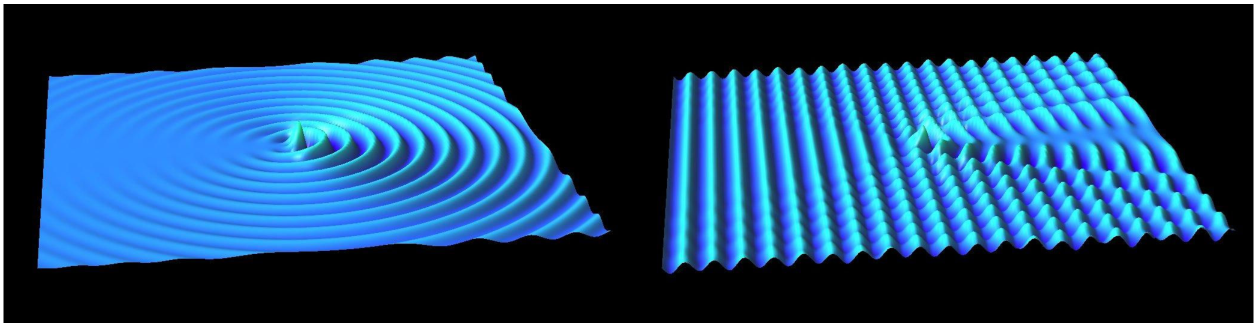


Figure 4.7 Heaving and surging (or heaving and pitching) mode radiation pattern (left) and with incident wave (right)

Thus we have a range of lateral spacing advice for single row 1st-generation wave energy arrays.

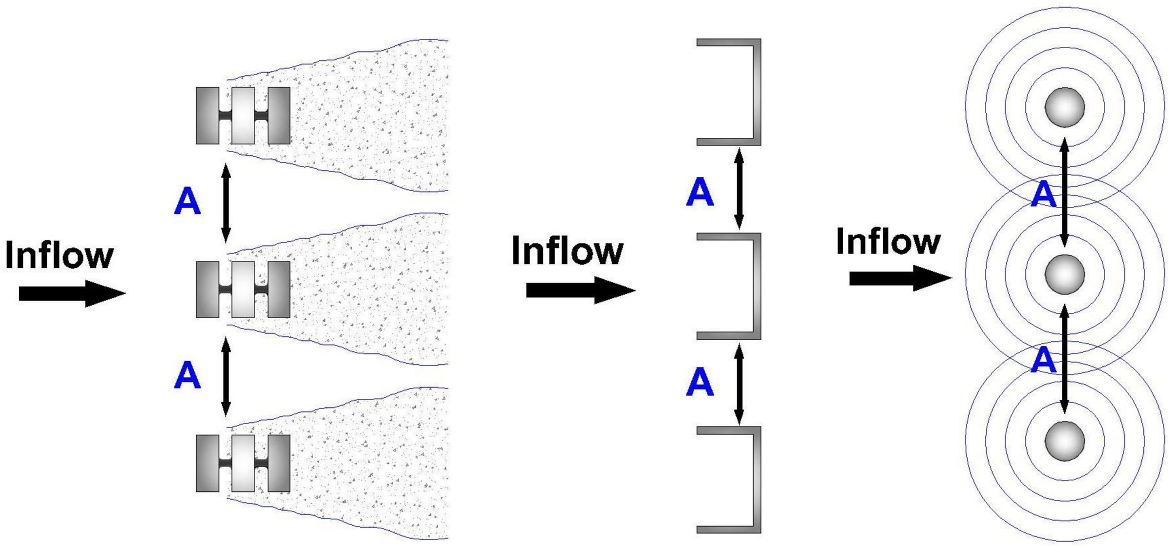


Figure 4.8 Single row 1st-generation wave arrays (line absorber (left), terminator (centre) and point absorbers (right)

In general the down wave radiated wake will be wider than for tidal energy devices. However, with the range of wave energy device motion paths and subsequent influence upon the surrounding wave field specific quantitative guidance is not possible. Device developers are encouraged to conduct trials where the lateral separation distance A is optimised. This is assumed to be defined as:

- Whereby A is as small as possible to minimise array size but large enough to avoid negative interaction, inter-device physical contact and to allow easy access to all devices

Or

- Distance A is such that the radiated wave field enhances adjacent device performance whilst avoiding inter-device physical contact and allowing easy access to all devices

Single-row wave energy arrays have the potential to occupy a greater lateral width (of wave crest) than tidal arrays as the latter could be constrained by adjacent landmasses and the need to minimise channel blockage. Wave energy sites (especially deep water locations) are often away from land and human infrastructure meaning that lateral width is most likely to be constrained by continuity of resource (arising from changes in bathymetry) and cost of electrical connection of a very wide array.

2-row 1st generation arrays for deep water wave energy devices are likely to have similar guidance and characteristics to tidal energy (see section 4.4.1). Once again wave energy arrays could be much wider than tidal due to site characteristics meaning that installed power capacity is much larger and 2nd-generation arrays are installed at a later date.

For generic advice regarding 2nd-generation wave energy devices where negative interaction effects are expected the reader is referred to the previous section addressing tidal energy arrays. The principal difference lies with certain heaving point-absorber devices where positive interaction has been shown (see section 4.1). In this case dimension C is not relevant and a 2nd-generatin array might have a very uniform geometric layout (Figure 4.9). Wave energy stakeholders are encouraged to understand any interaction effects pertaining to 2nd-generation arrays in advance of planning and installation.

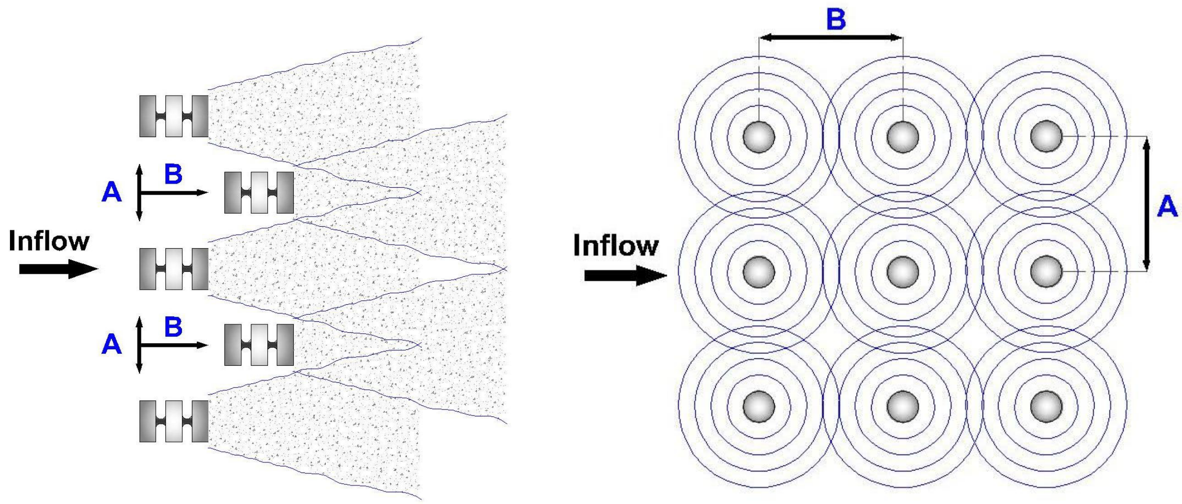


Figure 4.9 Dual row 1st-generation wave array (left) and 2nd-generation of heaving point absorbers (right)

4.5 ELECTRICAL INTERACTION EFFECTS

Connecting individually to shore every device of the marine energy farm would enable a very flexible and reliable operation of the generator units. Nevertheless, in most cases this solution might lead to excessive cabling (and laying operations) costs even for small farms close to shore.

In addition, the number of devices connected in one circuit is limited as electrical barriers exist as a result of both the capacity of the collection cables and the voltage drop along their length. The maximum number of devices per circuit is therefore a function of the generators rated capacity and the adequate spacing between the different units of the farm. Therefore, generating units are grouped into medium-voltage electrical collection subsystems within the marine farm. Those arrangements, so-called clusters, are then integrated together via offshore platforms from where the transmission to shore is initiated.

Types of clustering

Following types of clustering methods are considered in this work:

String clustering without redundancy: the devices are connected in parallel along a single collection cable (C1 and C3).

Star clustering: the devices are connected independently to a cluster nodal platform (C2).

String clustering with redundancy: the devices are connected in parallel along a closed loop collection cable and a switch controlling the power flow in the cluster (C4). Many other redundancy design might be implemented.

DC-series clustering: the devices are series-connected in various branches. This configuration is only used in DC clusters technologies

(C5).

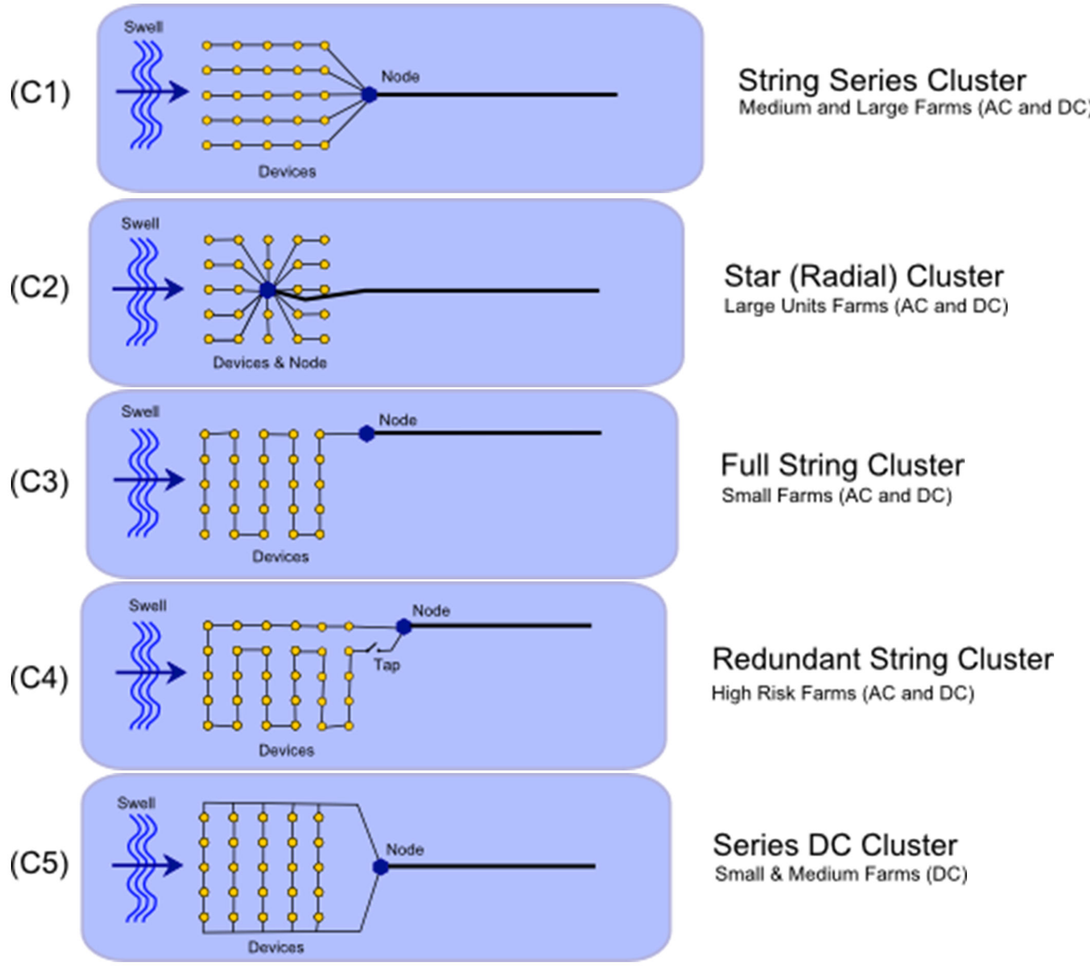


Figure 4.10: Main types of clustering for marine energy farms.

Number of clusters per farm

The number of clusters somehow determines the number of devices per cluster as the total installed power of the system is usually fixed. Different numbers of clusters cause different network topologies and, thus, result in different costs, power losses and reliability.

When the distance to onshore connection point (PCC) is short enough and the draught power reasonable low, considering independent transmission cables for each cluster can avoid the implementation of a complex offshore substation

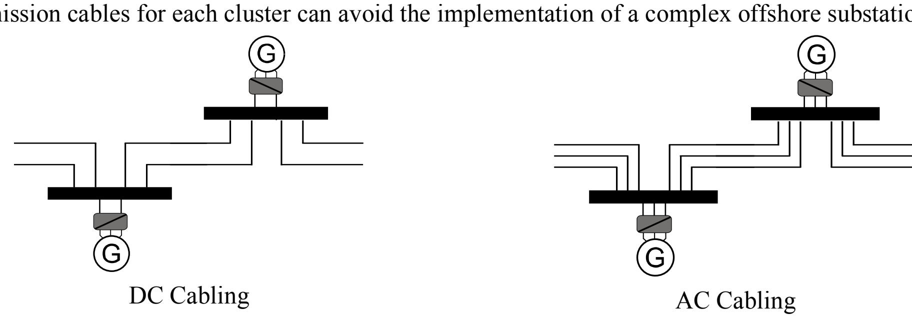


Figure 4.11: Interconnecting cables routes for AC and DC technology.

Whether the distribution technology is AC or DC doesn't affect the cluster configuration since the interconnecting cables routes are similar , except in DC-series clusters as the devices are series-connected in order to raise the DC output voltage up at the node.

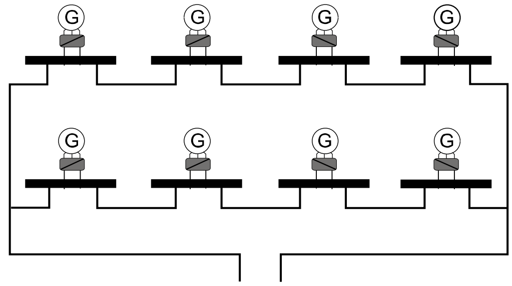


Figure 4.12: DC Series Cabling.

Cluster arrangements rest on the availability and fault ride through capacities of wave farms. Indeed, in a full linear cluster or string cluster, the main cable is the same for all devices, reason why the availability of the generation appears far better in star cluster configurations for example. In compensation, each radial cluster often requires a nodal connection platform.

Integration Architectures

The voltage level of the transmission system could be MV or HV, which determines whether the offshore platform is required or not. If offshore platforms with transformers or converters (for AC/DC integrated network s) are required, there are various ways of integrating the generators together and connecting them to the transmission system.

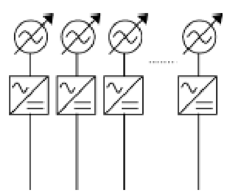
The following options are considered in terms of integration topologies:

Option a: The devices are directly connected to shore.

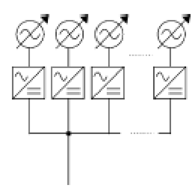
Option b: The farm consists on a single cluster connected to shore by a unique power cable.

Option c: The farm is constituted by several clusters independently connected to shore.

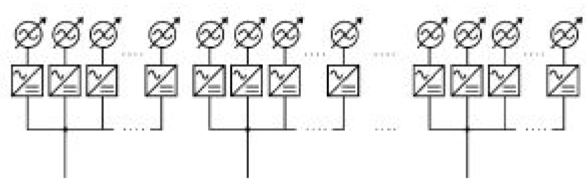
Option d: The different clusters of the farm are coupled together and share the same transmission cable to shore.



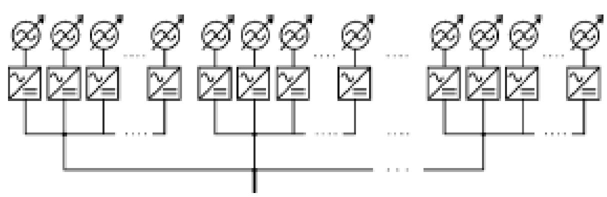
a) Individual transmission



b) Single clustered farm transmission



c) Clusters independent transmission



d) Multi-clustered farm single cable transmission [Thorburn]

Figure 4.13: Electrical integration configurations

A combination of these architectures is possible, since for availability requirements the introduction of redundant components has to be envisaged. When an offshore platform is required, appropriate switchgears can enable the optimization of the farm supply continuity. A comparison of the different considered integration configurations is shown in the table below:

Table 4: Comparison of the different integration configurations

Concept	Scheme a	Scheme b	Scheme c	Scheme d
Pros	Very high availability Low losses	Very low installation cost Simple maintenance	High availability	Low installation cost
Cons	High installation costs Connections onshore neccesary	Low availability May imply high losses	Connections onshore necessary	Difficult to find faults Complex system
Possible installation interval	Very small farms close to grid	Small farms with low risk	Large farms with high risk	Large farms with low risk

4.6 Installation and Maintenance Issues

A key issue that will be encountered when 2nd-generation arrays are installed will be access to the devices at the centre of the array. In this region it is likely that adjacent devices might bock access to those in the centre. It is also likely that by the time 2nd-generation arrays are installed due consideration will have been given to this issue and appropriate solutions will have been implemented. In the short term for all generations of arrays industry stakeholders should be mindful of the following that may drive array layout over and above those issues discussed in section 4.4.

Manoeuvrability of installation craft

This will vary depending upon:

- type of vessel
- physical size
- position, number and power of thrusters
- Station-keeping ability in wave and tidal climates

Station keeping of devices

Wave and tidal devices will be either rigidly fixed in position or employ slack moorings which will allow the device to move to a varying degree. If the latter is the case then this range of motion must be planned for when spacing devices within an array.

Safety factors for vessel/device proximity

Combining all the above factors a safety factor should then be applied to account for human operating ability, mechanical failure etc.

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5. CONCLUSIONS AND RECOMMENDATIONS

Wave and tidal energy arrays offer a means to harness and produce significant quantities of energy from the marine environment for human use. In the short to medium term it is most likely that arrays will be composed of up to 2 rows arranged perpendicular to the prevailing wave or tidal direction. For single row arrays lateral device spacing has the potential to be optimised but will depend upon a number of variables including device design and metocean parameters. It is recommended as part of Equimar that early arrays are used to inform later designs. This can be achieved by monitoring device performance parameters and acquiring additional metocean measurements such as downstream tidal or down wave climates.

Second generation arrays, as defined in this work not appear for a number of years due both the level of understanding required to minimise negative interaction effects and also the reasonable installed capacity that 1st-generation arrays can achieve. It is clear that certain generic lessons can be learnt from the wind energy industry such as the levels of device interaction within a multi-row array and the deficiencies of numerical simulation tools in predicting wind farm power output. Whilst there is little quantitative guidance that can be given for wave and tidal arrays it is certain that efforts to study device interaction effects will soon accelerate. Key areas of guidance are summarized below:

1. Deployment of arrays will be incremental so initial small-scale deployment should not compromise the final large-scale array. This forward planning should be considered from the first stage of array design.
2. Investigation into device interaction should be minimal for single row arrays with some exceptions (point-absorbing wave devices).
3. 2-row 1st-generation arrays will require investigation of 2 key device separation lengths. Device operation in radiated wake region can and should be avoided.
4. The principal exception to point 3 is point-absorber wave energy devices. Here positive interaction under certain wave conditions may promote operation in device-radiated wave fields.
5. 2nd-generation arrays will undoubted involve device operation in radiated flow fields from upstream/upwave devices. Device spacing should be optimised based upon cost/benefit principles.
6. Other issues such as device installation, accessibility and metocean conditions may drive elements of 2nd-generation device spacing.
7. Device developers and relevant industry stakeholders are encouraged to explore such issues to ensure that arrays develop in a progressive and logical manner leading to optimized installations producing the maximum amount of energy from the marine environment.