Resource Mapping of Wave Energy Production in Europe

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Abstract **In this paper a European resource assessment study, carried out under the project "The Strategic Initiative for Ocean Energy" (SI OCEAN) is presented. This paper discusses the outcome of the work and draw conclusions for the possible application.**

Keywords *SI Ocean, Resource mapping, GIS constraints, metocean data, wave energy device, marine energy, site selection.*

I. INTRODUCTION

The Strategic Initiative for Ocean Energy (SI OCEAN), supported by the EU Intelligent Energy Europe Program has been successfully completed. The SI Ocean project was established by a group of partners to document and analyse the barriers for the development of wave and tidal energy in Europe and to give recommendations on how the barriers can be minimized.

The two year (2012-2014) SI Ocean project was carried out by Ocean Energy Europe, The University of Edinburgh, Carbon Trust, WaveEC, RenewableUK and DHI.

As an essential part of this project a detailed resource assessment study was carried out, developing a comprehensive pan-European wave and tidal power resource on-line data portal. This paper will present the work and draw conclusions for the possible application of the results. The focus in this paper will be on the wave energy resource mapping. As some arguments and conclusions hold true for both wave and tidal energy production there are also many differences and trying to encompass both technologies in one paper may be too much.

The aim of the paper is to evaluate the results of the resource mapping carried out under SI Ocean. However, this was done on the basis of the major outcomes from SI Ocean [1], and [2]. The two main reports were named "*Wave and Tidal Energy Strategic Technology Agenda*" (STA) [1] and "*Wave and Tidal Energy Market Deployment Strategy for Europe*" (MDS) [2]. These reports renders the current status of the technology and identifies barriers for moving the technology forward and gives insight into non-technical barriers such as legislative and financial barriers. The barriers for ocean energy comes down to price of the energy (LCOE). The STA report [1] puts the LCOE cost for early arrays of commercial devices (i.e. not the prototypes) to 34-63c€/kWh for WEC's where in comparison currently LCOE for offshore wind is 12-19c€/kWh [3].

Given the outcome in the for-mentioned reports, where should we place wave energy converters (WEC) from a wave energy resource point of view?

If the only criteria for seeking out a good spot for a WEC was technical then it is still a hard job to match a specific WEC with a suitable location. But in reality a range of other parameters play a role

- Public capital funding linked to job creation in a certain area
- Guaranteed price for delivered electricity (feed-in tariff)
- Area for which you can get environmental consent and approval for placing it
- Distance from the company headquarters and access to skilled employees
- Conflicting commercial interest for the marine area (fishing, oil and gas, offshore wind)

Looking at Europe it seems that the climate under which the wave energy industry have been operating has favoured placing prototype sized devices in UK waters which must be attributed not only to technical choices but also some of the reasons above.

The history of the development and deployment of wave energy devices shows that the desire for some nations within EU to get ahead to a certain extend drives the location of WEC deployment rather than pure technological reasons. But in an EU perspective it may e.g be best to develop the technology in Ireland, build the machines in Spain and deploy them in France, and maybe not.

The strongpoint of the SI Ocean project was to look at the issues related to developing the wave energy industry on a European level. The project was based on looking at nations with a superior level of wave energy resource, named the Atlantic Arc. They included Denmark, France, Spain, Portugal, Ireland and United Kingdom. Common for these nations is that they have western faced coastlines exposed to large waves. The idea was to come to some collective conclusions on how to advance wave energy for the European Union. The focus on the Atlantic Arc proved to be less constrictive as one may think as almost all European countries contributes to the industry though delivering technology and parts for the WECs.

Within SI Ocean the resource mapping fed into the basis for writing the MDS [2] but this report does not present details of the resource mapping. This paper tries to put some of the report's conclusions in perspective by presenting results from the resource mapping.

II. THE SI OCEAN PROJECT

The SI ocean project was carried out with two major work paths, one looking at the status of the technology and the other at barriers towards market deployment.

The technology has advanced. Twenty years ago inventors of wave energy converters would arrive at the hydraulics laboratory carrying contraptions including bicycle wheels, odd looking floating devices all connected in imaginative ways. When a machine was able to light up a bicycle lamp there was

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a huge cheer in the laboratory. Now, 20 years on the industry has come a long way. In the laboratories and as prototypes we see well-functioning machines being optimized in all possible ways.

The WEC technology can be associated with a series of main components [4]:

- Structure & Prime Mover
- Foundations & Moorings
- Power Take Off
- Control
- Installation
- Connection
- Operations & Maintenance

A. Extreme Loads and Failure Types

In regards to structure and foundations the report divides WECs into categories based on water depth and suggests that the WECs moored in deep water is likely the most relevant as they can be placed where the waves contains the most energy on average. But as described this also poses the challenge to design a cost effective machine that can survive the extreme wave conditions. Even in the relatively sheltered Danish part of the North Sea extreme breaking waves up to a maximum height of 30m can occur. This corresponds to six story high building coming towards you at maybe 80km/hr and your WEC needs to be able to survive. Especially structures offshore cannot be expected to be towed to a safe harbour each time the weather forecast indicated a major storm. The survivability poses a huge challenge for WEC developers as both structure and moorings needs to cope.

The offshore industry (oil and gas and offshore wind) tries to overcome this by exposing only a small cross section in the form of platform legs or turbine foundations to the waves and makes the structure as rigid as possible. The problem is that for WECs you really want to make a structure that reacts very much to the impact of waves enabling you to generate energy out of this force and motion – you just do not want the really large waves. As argued later in this paper there may be solutions to part of this problem based on the choice of location for the WEC.

Another problem with the WEC itself is of course that most concepts relies on major movements of steel based structures with hydraulic component generators etc. Being able to withstand extreme conditions for these components are also very difficult.

For foundations you can sometimes hear the argument that the wave energy industry cannot use the standards and requirements for moorings that are applied within the oil and gas industry to keep their floating structures in place. They are overdesigned and way too expensive. As the status is now it is unlikely to find an investor that would like to compromise mooring safety based on the above notion. On the other hand smaller sized vessels like most WECs may be able to be moored in a more optimal way designed just for the type of structure and its behaviour under extreme conditions. Seeing this potential research projects are under way to see if there is support for lighter and cheaper moorings.

As very few full scale devices have been tested at sea for considerable amount of time the operation and maintenance cost for WECs are hard to estimate. Therefore, it may very well be better to design very durable components for the machines rather than maybe getting the optimal performance. During the last decade one of the main risk factors for the wind industry has been to manage the failure risk of wind turbines against preventive maintenance. The everyday durability combined with maintenance requirements for WECs will be a major driver for each projects financial viability. Failure of a underwater cable connector, a mooring line, a hydraulic cylinder will often be assigned to being “one of” case due to faulty design and as soon as the error has been rectified it will never happen again. However, there are no perfect designs, so each WEC project needs to allow for a number of failures of smaller or larger extent during the lifetime of the project.

Connection is also a challenge. The key to success is to get ones WEC hooked up on the grid and deliver some electricity to the consumer. However, placing sea cables – especially to deep water offshore is very expensive and the existing cabled cannot easily be used. The solution to this problem for now is to stay closer to shore and make use of testing sites such as EMEC, WaveHub and others.

There is a large number of concepts for WEC devices including attenuators, point absorbers, run-up, oscillating water columns, etc. The large number of concepts indicates that the winning technology has not been found yet or that different site conditions will suggest different WEC concepts.

B. Cost

On a European level there is a need for a unified approach to the technical challenges. The question is if the EU are able to provide incentives for developers to work together battling the common problems or if EU should consider to drive the research needed directly. The entire exercise is to reduce the capital costs of the devices (CAPEX) and the operational and maintenance costs (OPEX).

The SI Ocean project points at two main needs [1]:

- Technology development addressing the need to develop reliable, robust and efficient technology
- Risk reduction through successful device deployments at locations provided with grid infrastructure

The project sees joint research as one vehicle to drive down the levelised cost of energy (LCOE) for the WEC technology among other things. A proof that this can be done can be seen within the solar power industry where the price of solar panels have been falling over the last years from a level comparable with wave energy to being in competition with the price of offshore wind generated electricity. This also pinpoint another challenge for the wave energy industry as it will need to compete with other renewable energy sources that has a more progressed technology today such as wind and solar power.

But will it be feasible to drive down cost quickly enough to compete with other energy sources. Luckily the SI Ocean project did not attempt to answer that impossible question, but provides sound suggestions for which actions can assist positively in the process. An intensive consultation process was carried out with the stakeholders in Europe and among these many WEC developers. It could have been valuable to get performance data, maintenance records etc. from all developers with devices in real seawater. Understandably, the limited number of companies with such information at hand did not wish to part with it for a number of good reasons. This in change does implicate that a number of assumptions were needed when working with the resource assessment.

C. Technical Barriers

As described there are still major technical barriers for the development of wave energy converters but at the same time companies are facing barriers with regards to financing, environmental issues, legislation, grid connection, etc.

The strategic technology agenda report from SI Ocean [1] lists the following risks that needs to be addressed to mitigate the overall risk of stalling the wave energy development:

- Financial risk
- Technology risk
- Project consenting risk
- Grid-related risk

Some of these points have been mentioned above. The financial risk, i.e. lack of willingness for upfront capital investment, is deemed to be due to unclear revenue from the technology. In the long term it is difficult to know what revenue support will be in place and as there are no examples of arrays of WECs installed there is no experience on how well the technology performs over longer time. SI Ocean identified an increased volume of R&D capital as a part of the solution.

D. Consenting

Another issue is the project consenting. Getting environmental approval to place machines at sea containing hydraulic fluids etc. is a long and hard process. Partnering up with some of the established test sites alleviates some of that risk. There are often also a time window associated with a given consent meaning that you will need to deploy your WEC before time runs out. This means that developers do not want to start the consenting process too early at the risk that they will not be ready before the license runs out.

E. Grid

The grid connection issue is not only a problem of getting access to the grid through a sea cable. It is also a question of the grids ability to manage the increased amount of less stable electricity sources that wave energy form part of together with other renewable energy forms. That is why the word smart grid is heard around. Finally, the grid needs to be able to transport the amount of energy that the devices deliver and in remote areas this could become a factor. On a higher level it is of course difficult to argue that e.g. The Orkney Islands in Scotland has the potential producing a large amount of renewable energy of its coast and then ignore a grid problem that there is no major cable to main Scotland to distribute the power. Due to the limited size of wave energy it is inevitable that the technology will need to simply comply and use whatever grid there may be in place due based on conventional technology.

F. Resource Mapping

But where does all the wave resource mapping fit in? The idea has been that in order to argue that wave energy is a great idea there have been a need of proof that there is indeed a huge energy source out there that just need tapping into. A range of projects have delivered that proof either on national or international level [5], [6] and [7]. SI Ocean also contributed to this analysis [8] by including wave energy density maps for Europe. In order to align expectations between various stakeholders, it is important to encourage an understanding of how many WECs are needed to yield a certain amount of annual electricity given a range of assumptions. The resource mapping part of SI Ocean provides this perspective [8]. From this perspective it is easily deduced that wave energy will not become a major contributor to the electricity production in Europe in the foreseeable future. However, it can become an important contributor to the energy mix of renewable energy and as such potentially worth investigating.

Before planning optimal locations for placing wave energy converters (WEC) robust and efficient technology is needed. The STA report identifies a need for the industry to prove their technology and the need to reach at least a 25% efficiency and an uptime of the devices of more than 75%. Most of the WEC technologies has much higher theoretical efficiency than 25% but in reality when taking into account the loss through PTO system and delivery to the grid, etc. that target may be difficult to reach. The uptime is closely related to the survivability of the device. Unfortunately, locations with high wave energy density also experiences very extreme wave conditions. Few or none of the prototypes deployed in Europe have had enough time in the sea to prove their reliability. The wave resource study rendered in this paper will accentuate that issue.

Some of the factors that may ensure the progress of the technology is to keep and consolidate test and demonstration facilities in Europe. From a technical point of view Europe may benefit from focussing on 1-3 sites like e.g. the European Marine Energy centre (EMEC). A consistent public funding of RDI&D programmes are crucial for the WEC's possibility to mature into commercially viable energy converters. The SI Ocean STA report lists a range of good ideas to help the progression of the technology, some of which is already well under way.

III. METHODOLOGY

Most people think the ocean is vast with plenty of space for wave energy devices. However, there is little space not already claimed (by shipping routes, fishing grounds, offshore activities and so forth) that is also suitable for present wave energy extraction technologies. An important building block in identifying where energy is available close to the coast with no or few constraints is resource mapping. In collaboration with several of the SI Ocean partners, a GIS-based web client the SI OCEAN Data Portal, was developed (http://si-ocean.dhigroup.com/map). Here data can be freely viewed.

A large dataset was collected within SI Ocean. The data comprised GIS data identifying constraints for the placement of wave energy devices or tidal devices. These data were among others: Seabed bathymetry, environmentally sensitive areas, shipping lanes, distance to ports, distance to the power grid, offshore wind farms, distance to shore and offshore cables. The data is suitable for studying the effect of e.g. allocated Natura 2000 areas effect on the potential wave energy production on a European level. Zooming in one quickly realises that some data has limited resolutions and exhibits some errors. Thus the sites data cannot be used as basis for detailed local studies. However, that data functions well for the purpose of this paper giving perspective to the wave energy resource potential for Europe.

A. Data layers

The data is comprised of the following layers:

- Constraints: Telecom cables, Coastlines, Economic Zones, Natura 2000, Heritage sites, Offshore installations, Wind farms and Shipping lanes
- Placement criteria: water depth, distance to the shore, grid power stations and service ports
- Wave energy criteria: wave power, extreme wave height (for survivability assessment)
- Metocean data: wave data (scatter tables, omni directional)

To study the impact of the various features on the resource potential buffers were added to data, e.g. 200-500m to offshore oil installations. Data was post processed and reduced in complexity to enable use of the data through a web client. E.g. the distance to shore is simply given as a set of isolines along the coast as seen in Fig. 1 where distances were divided into 13 separate zones.

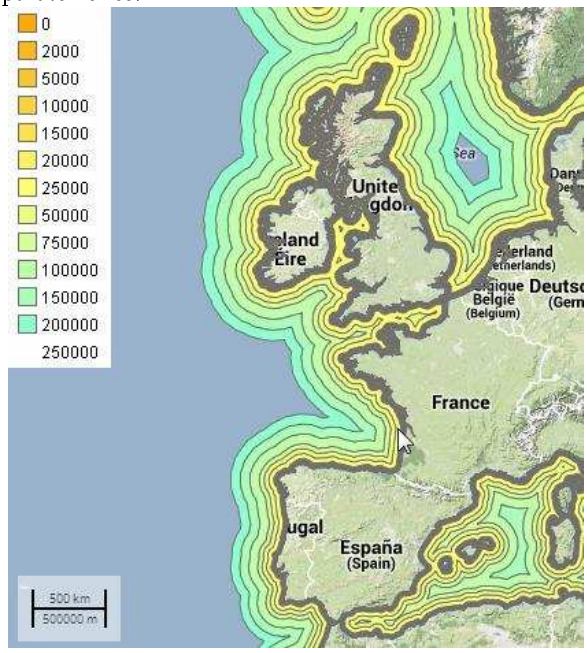

Fig. 1. Illustration of the “Distance to shore” data layer

As one may quickly realise some constraints are missing and here are oil and gas pipelines as well as high yield fishing grounds some of the important ones. It was not feasible to collect all data within the SI Ocean project.

The layers can be placed on top of each other and the remaining available space can be found.

B. Wave Power

Wave data from DHI’s global hindcast database were adopted for a period of 20 years (1993-2012). The data were established through numerical modelling using MIKE 21 Spectral Wave model by DHI. The wave model is forced by wind from the Climate Forecast System Reanalysis (CFSR) atmospheric model, established by the National Center for Environmental Prediction (NCEP). The special resolution is varying in the domain in the order of 100-200km.

The model has been validated against a range of observation data. The bias is generally smaller than ±15cm. The peak event values are also captured well, with a general peak-ratio in the order of 0.95-1.05. However, in more confined areas e.g. the North Sea, the special resolution is too coarse, leading to overestimation of the extreme events. The scatter index is generally in the order of 0.2.

The wave power is computed directly in the MIKE 21 Spectral Wave model by DHI. The power map presents the mean wave power over the full 20-year period. The wave energy was derived in kW/m width. The omnidirectional wave energy power was computed by the following expression:

$$P_{wave} = \rho \, g \int_{0}^{2\pi}\int_{0}^{\infty} c_g(f,\theta)E(f,\theta)\, df d\theta$$

where E is the energy density and c_g is the group velocity, both dependent on the wave frequency f and wave direction θ, ρ is the density of water and g is the acceleration of gravity. This resulted in the wave power map shown in Fig. 2. Results were very similar to those from other studies, although some variations occur as it can be expected when different models and different forcings are applied.

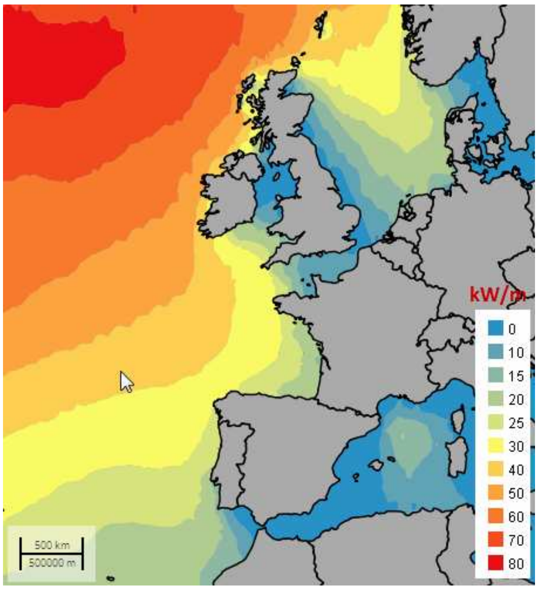

Fig. 2. Wave power map based on DHI's spectral wave model.

From the hindcast model wave scatter tables covering locations in the Atlantic arc region were also extracted to be used for the resource calculation shown later in this paper.

These data were saved as omnidirectional data averaged over one year. An example of such a scatter table can be seen in Fig. 3. Of course seasonal, directional data would become interesting as soon as detailed feasibility studies are carried out, but the omnidirectional approach was deemed sufficient in this case.

Wave Point
Element:21069 (6.63, 56.23) **Mean Wave Direction:**239

	Peak Wave Period Tp (s)															
Hm0 (s)	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	Sum
0.25																0.0
0.50				0.4	0.6	0.3										1.3
0.75				1.0	2.7	1.8	0.8	0.2								6.5
1.00				0.2	3.2	3.7	2.2	0.9	0.3	0.1						10.6
1.25					2.1	4.3	2.6	1.4	0.6	0.2						11.2
1.50					0.6	4.3	2.9	1.8	0.9	0.4	0.2					11.1
1.75						3.2	3.1	1.8	0.9	0.6	0.2	0.1				9.9
2.00						1.6	3.0	1.8	1.0	0.6	0.2	0.1				8.3
2.25						0.6	2.8	1.8	0.9	0.6	0.2	0.1				7.0
2.50						0.1	2.2	1.8	0.9	0.5	0.2					5.7
2.75							1.4	1.8	0.8	0.5	0.2	0.1				4.8
3.00							0.7	1.6	0.9	0.4	0.2					3.8
3.25							0.3	1.4	0.9	0.4	0.2					3.2
3.50								1.0	0.9	0.4	0.2	0.1				2.6
3.75								0.7	0.8	0.4	0.2	0.1				2.2
4.00								0.4	0.8	0.4	0.2					1.8
4.25								0.2	0.7	0.4	0.2					1.5
4.50									0.5	0.4	0.2					1.1
4.75									0.3	0.4	0.2					0.9
5.00									0.2	0.4	0.2					0.8
5.25										0.3	0.2					0.5
5.50										0.2	0.2					0.4
5.75										0.1	0.2					0.3
6.00										0.1	0.2					0.3
6.25											0.2					0.2
6.50											0.1					0.1
6.75																
7.00																

Fig. 3. Scatter table showing the percentage of time on an average year a certain combination of significant wave height and peak wave period occur.

When knowing the wave conditions in a location the annual production capacity for a WEC given 100% uptime can be calculated by combining the wave conditions with the power matrix for the WEC (see Fig. 4.). This makes it possible in the SI Ocean data portal to place individual devices and calculate the annual energy production by

$$Energy = \int_{i=1}^{NoOfSeastates} Seastate(i) \cdot power(i)$$

		Wave Period Tp (s)									
		4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0
Hm0 (m)		5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
0	0.25										
0.25	0.50										
0.50	0.75		13.6	17.4	17.8	16.5	13.6	10.6			
0.75	1.00		29.0	37.0	38.0	35.0	29.0	23.0			
1.00	1.25		45.7	58.3	60.3	54.9	45.6	36.9	19.0	14.9	
1.25	1.50		65.0	83.0	86.0	78.0	65.0	53.0	42.0	33.0	
1.50	1.75		88.2	113.2	116.6	105.8	88.7	71.6	58.0	46.0	
1.75	2.00		115.0	148.0	152.0	138.0	116.0	93.0	74.0	59.0	
2.00	2.25		145.6	187.3	193.3	176.0	148.0	118.0	93.8	74.6	
2.25	2.50		180.0	231.0	238.0	216.0	181.0	146.0	116.0	92.0	
2.50	2.75		218.2	280.1	284.6	253.6	209.2	178.2	141.1	111.1	
2.75	3.00		260.0	332.0	332.0	292.0	240.0	210.0	167.0	132.0	
3.00	3.25		305.3	384.9	377.3	333.1	283.1	234.1	191.5	156.4	
3.25	3.50		354.0	438.0	424.0	377.0	326.0	260.0	216.0	180.0	
3.50	3.75		408.8	489.3	476.6	425.9	354.8	299.9	240.1	196.2	
3.75	4.00		462.0	540.0	530.0	475.0	384.0	339.0	267.0	213.0	
4.00	4.25		543.8	592.1	580.7	517.9	426.9	359.8	303.8	237.7	
4.25	4.50		544.0	642.0	628.0	562.0	473.0	382.0	338.0	266.0	
4.50	4.75			688.9	670.9	617.3	514.3	426.1	353.1	298.6	
4.75	5.00			726.0	707.0	670.0	557.0	472.0	369.0	328.0	
5.00	5.25			743.3	733.4	709.4	609.4	501.1	405.3	341.6	
5.25	5.50			750.0	750.0	737.0	658.0	530.0	446.0	355.0	
5.50	5.75			751.5	752.7	747.7	688.4	575.7	479.6	382.6	
5.75	6.00			750.0	750.0	750.0	711.0	619.0	512.0	415.0	
6.00	6.25			796.9	750.0	750.8	733.8	638.3	547.5	449.0	
6.25	6.50			750.0	750.0	750.0	750.0	658.0	579.0	481.0	
6.50	6.75				750.0	750.0	752.4	706.4	595.6	502.9	
6.75	7.00				750.0	750.0	750.0	750.0	613.0	525.0	
7.00	7.25				796.9	750.0	750.0	755.8	647.6	559.8	
7.25	7.50				750.0	750.0	750.0	750.0	686.0	593.0	
7.50	7.75					750.0	750.0	750.0	719.1	613.5	
7.75	8.00					750.0	750.0	750.0	750.0	625.0	
8.00	8.25										

Fig. 4. Example of a power matrix for a WEC. Values given in kW.

C. *Scenarios*

For the SI Ocean project a more general approach determining the overall wave energy potential was needed. A set of scenarios was set up as seen in Table 1.

Table 1. Deployment criteria for wave energy scenarios

	Distance from shore	**Depth**	**Resource**
Round 1	<10km	<100m	>30kW/m
Round 2	<50km	<200m	>30kW/m
Round 3	<100km	<300m	>25kW/m

Based on the criteria shown in Table 1 lines were drawn on a map at the offshore edge of the areas defined by Table 1 and the wave energy flux through the lines were calculated and summed up.

IV. EXTRACTED RESULTS

Firstly, the general resource mapping results from SI Ocean will be described and these results will be put into perspective by further analysis of the data. Secondly, the work carried out has enabled DHI to investigate a series of what-if scenarios relevant to the potential production of wave energy in Europe such as:

- What if we place WEC's at a certain distance from the shore?

- What if we place them only in wave climates that have a certain wave energy level?
- What if we avoid locations with too high extreme wave conditions?
- What if the distance to the nearest service fort should be limited?
- What if we only place devices with a certain water depth range?

The primary results from the SI Ocean resource mapping were based on the criteria stated in Table 1. The ambition was to locate places at limited water depth and distance to shore where high wave energy occurred along the western coasts of Europe. This would lead to potentially high values of potential wave energy and identify the best places for early array deployments seen purely from a wave energy perspective. The identified areas were subtracted areas defined by constraint layers such as cables, Natura 2000, offshore installations, shipping lanes and wind farms. The identified areas can be seen in Fig 5.

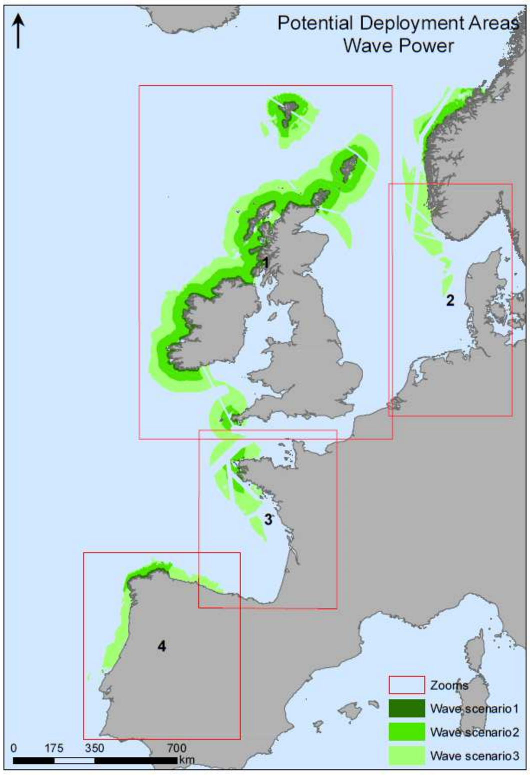

Fig. 5. Deployment areas according to the criteria shown in Table 1. Dark green indicates round 1 and light green indicates round 3.

A frontage line was drawn along the outer rim of the determined deployment areas for rounds 1, 2 and 3. Subsequently, the level of resource along the lines was drawn from the DHI wave power map and accumulated along the different sections (see Fig 6).

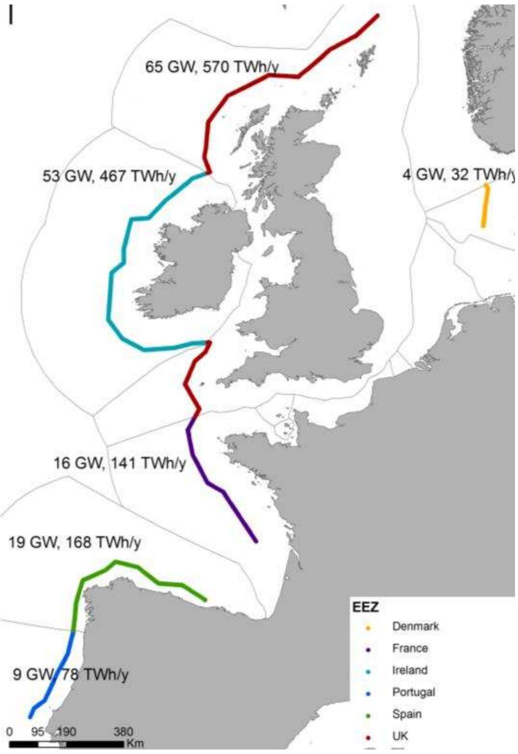

Fig. 6. Total wave resource across marked lines

The assumption by this approach is that the wave energy passing the frontage lines corresponds to the total amount of available wave energy for the area between the frontage line and the coastline. More energy could be available as the free fetch behind the frontage lines makes it possible for waves to build up again in the area. The total wave resource gives a reference number (see Table 2). Table 2 also shows an estimate of a technical wave resource. The technical resource is an estimate on how much energy it would be feasible to extract if in fact wave energy devices were deployed along the European coastline. As part of the assumptions, additional rows of devices were added such that the last row of devices only produces 10% of the first row's production. In this case 15 rows behind each other was assumed.

Table 2. Total and technical wave resource Atlantic Arc

	Total Theoretical Wave Energy (TWhr/year)						
Round	**DK**	**UK**	**IE**	**FR**	**ES**	**PT**	**Total**
1	0	391	312	47	71	0	821
2	0	520	396	87	83	0	1086
3	32	570	467	141	168	78	1456
	Total Technical Wave Energy (TWhr/year)						
1	0	99	75	14	21	0	206
2	0	133	103	28	26	0	290
3	13	145	125	45	50	25	408

As comparison for the numbers in Table 2 the countries in EU consumes 3126 TWhr/year in 2012 according to EuroStat [9], meaning that about 13% of the electricity could be covered by WEC's. There is only one small catch; 15 rows of WECs with a distance between each WEC of 100m would need to be installed along the frontage lines shown on Fig 6. This amounts to 573,300 WECs given the efficiency of the current technology and given that they work with a 100% uptime. In comparison a total of 2488 offshore wind turbines have been erected in Europe until now, producing around 70 TWhr/year (EWEA, 2014) [10].

The numbers above are maybe not so interesting. Other studies have shown larger values or smaller values for the wave resources, but as a target for EU to deploy even a few hundred WECs within the next ten years is ambitious numbers then the production estimates of half a million WECs is not very relevant.

More interesting is how much the wave resource changes if criteria for distance to shore, minimum wave power level, etc. is varied. To investigate this, frontage lines along Europe's coast lines were drawn up as seen in Fig 7. These lines were combined with the SI ocean data to produce a lookup database from which numbers on the wave resource given sets of criteria could quickly be derived. This allows for answering some of the posed questions.

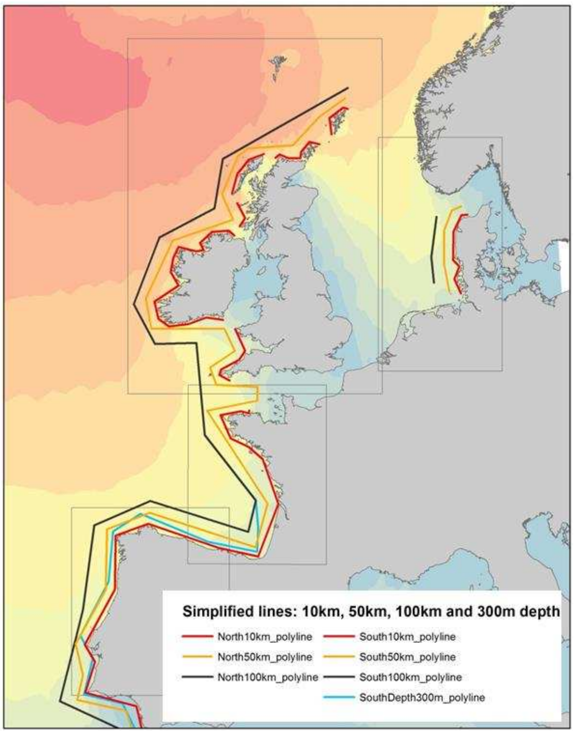

Fig. 7. Lines across which the wave energy flux was queried.

Some of the parameters that will be studied in the following can be relevant to study on a country by country level. However, here all data are presented in a north category (UK, Ireland, and Denmark) and a south category (France, Spain and Portugal).

The prepared data from the SI Ocean project allows for studying how the wave energy resource changes when areas are excluded due to various criteria. The criteria considered here are:

- Constraints
- Min Wave Power
- Max water depth
- Max Extreme significant wave height (H_s)
- Max distance to service port
- Max distance to high voltage substation

All the presented levels of wave energy resource are based on total wave energy flux. So, the numbers should be adjusted by how much can actually be extracted (maybe around 30% of the total) and subsequent reduced by transmission loss.

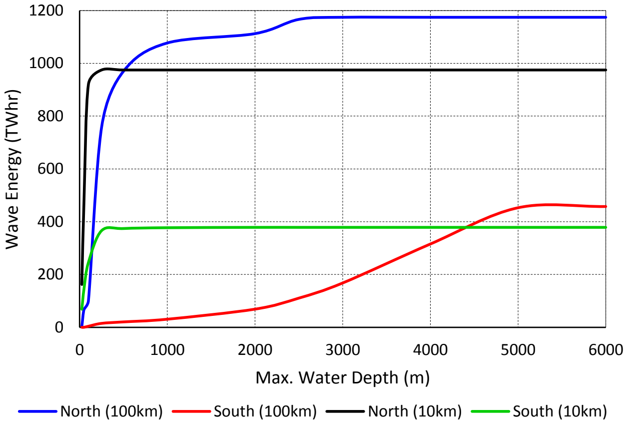

Fig. 8. Wave energy resource when excluding locations with water depths above a certain level.

As seen from Fig. 8 there is little influence from excluding areas with water depths larger than 500-1000 meter except for 100 km from the coast for the southern section. As water depth rapidly becomes very large at the Portuguese coast, the red curve decreases already at 5000m. Along the 10km line resource is excluded for maximum water depth less than 100m.

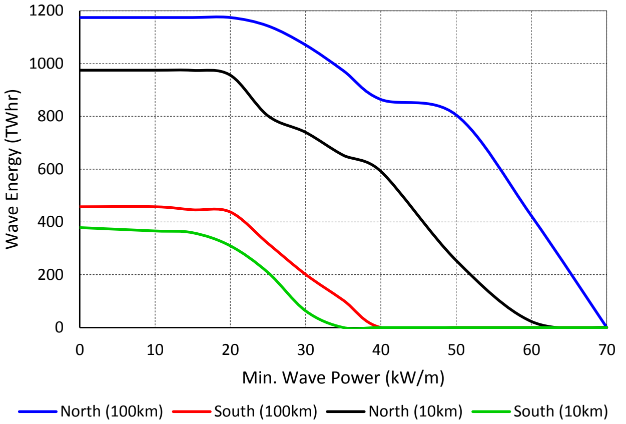

Fig. 9. Wave energy resource when excluding locations with wave power below a certain level.

To conceive a realistic business plan it may be necessary to aim at placing WECs in areas with high wave energy intensity. For this purpose Fig. 9 shows that in the northern section there are location with wave power level all the way to 60-70 kW/m.

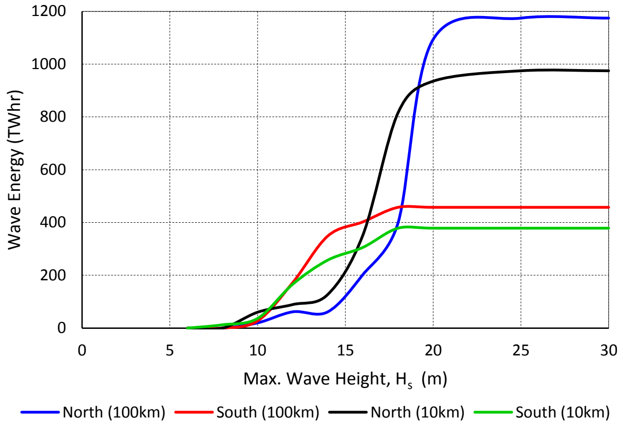

Fig. 10. Wave energy resource when excluding locations with extreme wave heights (50 yr return period H_s) above a certain level.

Fig. 10 shows that as areas where extreme conditions with H_s smaller than 20m are excluded the wave resource starts decreasing. This means that if you have only designed your device to survive e.g. a 18m high wave (10m H_s) then there are limited areas to place this device along the lines indicated. An overall conclusion could be that WECs should all be designed to withstand H_s = 20m in order not to limit the potential.

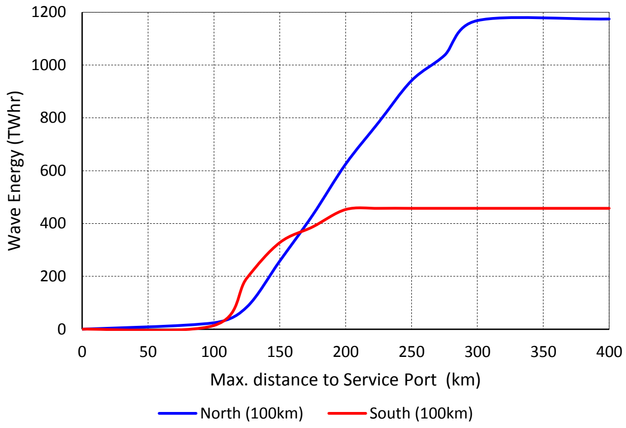

Fig. 11. Wave energy resource when excluding locations with a distance to a service port above a certain level.

Fig. 11 shows the 100km lines, so there will be a minimum of 100km to the port if it is located on the coast just where the WEC is located. As seen there is a maximum of 200km to service ports in the south but up to 300km in the north. The question is what are acceptable steaming time to port for the deployment areas in reality and how far can you realistically place a power cable to the coast? The answers to these questions may drastically reduce the wave resource.

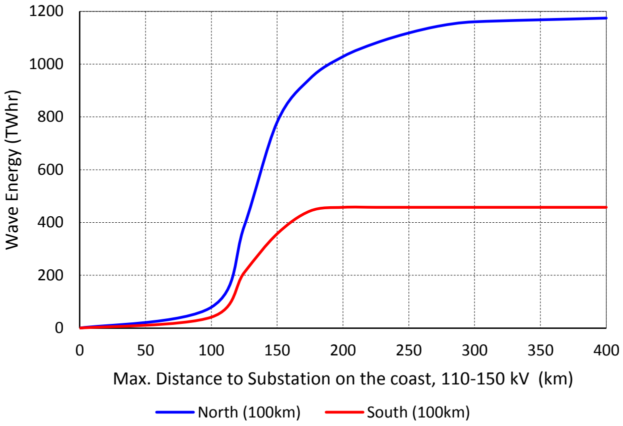

Fig. 12. Wave energy resource when excluding locations with a distance to high voltage substations on the coast above a certain level.

Table 3. Wave energy resource variation with constraints (Values in TWhr)

Constraint	North 100km	South 100km	North 10km	South 10km
None	1174.4	457.5	974.8	378.5
Cables	1159.9	451.8	968.1	375.8
Offshore installations	1171.4	457.5	974.8	378.5
Wind farms	1174.4	457.5	974.8	378.5
Natura 2000	1161.6	443.4	858.8	371.5
Shipping lanes	1108.0	404.2	931.8	356.1
All	1089.2	385.0	827.6	347.0

Table 3 shows the influence of various constraints on the wave resource. E.g. the “North 100km” area the resource reduces from (None) 1174.4 TWhr to (Cables) 1159.9 TWhr when excluding areas with cables. Far offshore (100km) it is seen that there is only a small reduction of the wave resource due to area constraints (9%). When getting closer to the coast this reduction increases to 13%.

Table 4. Distance to the coast: 10km, Min wave power: 20 kW/m, Max distance to service port: 50km, Water depth between: 10-40m. (Values in TWhr)

Max. Wave height Hs (m)	North	South
10	25.9	0.0
15	59.6	23.2
20	83.6	43.2
Any	83.6	43.2

The resource mapping established under the SI Ocean allows for investigating a range of scenarios. Table 4 shows an example. Here we imagine that you will place WECs in Europe no further offshore than 10km, the minimum wave power level should be 20 kW/m, there must be a maximal distance to a service port of 50km and the feasible water depth is 10-40m. If this basis is combined with maximal extreme condition of e.g. 15m H_s you get a total wave resource of 82 TWhr exploiting all feasible locations along the 10km frontage line. This is quite far from the 1456 TWhr given in Table 2.

Suitable areas for deployment of WECs can be from a European perspective be found by querying the GIS data available from SI Ocean. An example of this is seen in Fig. 13.

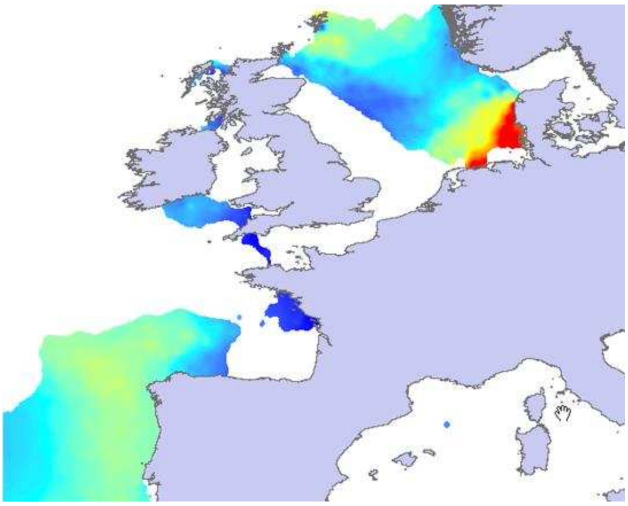

Fig. 13. Locations where you get the most wave energy above 20 kW/m with the lowest extreme wave height less than Hs = 15m. Red color indicates the best ratio between wave power and extreme conditions.

V. CONCLUSIONS

This paper has shown that the available wave energy resource in Europe along the Atlantic arc countries vary considerably dependent on criteria set for distance to port, minimum wave energy level, etc. But even when taking into account these limitations there are ample opportunity to place WEC devices in Europe.

The barriers for the advancement of wave energy in Europe identified through the SI Ocean project does highlight the paramount barrier of the status of the technology. Better and proven technology is needed before the overall wave resource become a concern. However, the wave resource data established can assist in pointing out which range of wave conditions (average and extreme), water depths, etc. WECs should be designed for in order not to exclude the technology from the main resource areas.

At a later stage it will become crucial that proper marine spatial planning is established across Europe to expedite the consenting process needed for space beyond test locations for a few prototypes emerges – hopefully.

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