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EVALUATION OF THE POTENTIAL OF WAVE ENERGY IN CHILE

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ABSTRACT

In Chile, incentives have been created during the past years for the installation of non-conventional renewable energy plants (NCRE). It is within this context that wave energy can be transformed into a feasible alternative for electrical power generation in the near future within the country. This work corresponds to the first approach to quantify the wave energy resources in Chile based in a technically superior manner. The first step in the assessment of a wave energy plant is to quantify the available resources, therefore the wave climate was obtained for various sites along the Chilean coastline and a deterministic assessment was made of the power of the waves and their main characteristics, especially the variability under different time horizons. In order to convert the mechanical energy of the waves into electrical power, an assessment was made of various offshore devices existing on the market. An estimate was made of the output power of these conversion devices based on the wave climate and on the energy conversion matrixes that define them, performing an analysis that is completely analogue to that of wave power. Waves in the Chilean coast arrive year in and year out with scarce variation during the various seasons, are very regular, with low directional dispersion and high periods. This determines the low seasonal variability of the power and the high capacity factors that conversion devices can develop. The characteristics of waves in Chile are due mainly to the presence of swell usually found in great oceans, which makes Chilean territory one of the most appropriate sites in the world for the generation of electrical power with energy from the waves.

1 INTRODUCTION

In Chile, the State as a regulatory institution has traditionally operated under the principle of neutrality; that is, showing no preference for one source of power over another. However, recently an attempt has been made to provide certain guarantees and incentives to small-scale power generators (up to 20 MW), which entails an opportunity for non-conventional power sources. The incentives include, among others, the exclusion of payment for transmission systems, access to wholesale market (spot), subsidies for feasibility assessments, etc.

Within this context it becomes necessary to assess the economical and technical feasibility of the use of waves as a resource for power. This assessment has two objectives: first, to quantify and analyze the power of waves in various sites located along the Chilean coastline, in a technically superior manner; and second, to estimate the power generated by those devices provided with a greater level of development which convert mechanical energy from the waves into electrical power, in order to subsequently perform a comparison between them.

2 BACKGROUND

Waves are an indirect manifestation of solar energy, which spread out continuously throughout the oceans. It is a resource which is available a great percentage of the time, and furthermore, the high concentrations of population which settle on the coastline cause that the source of energy is very close to the areas of consumption. The most relevant characteristics of waves for the generation and distribution of electrical power are

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[1] Correspondence autor

the density of the energy, the variability and the predictability (Bedard et al. 2005).

In some areas of the world there are high concentrations of wave energy per linear meter of coastline (Figure 1) within which pilot plants are being installed. In mentioned figure, the central and south zones of Chile appear with one of the greatest concentrations of power in the world. This, added to the great extension of this coastline, makes it attractive to perform an in depth assessment of the possibilities of exploiting this resource.

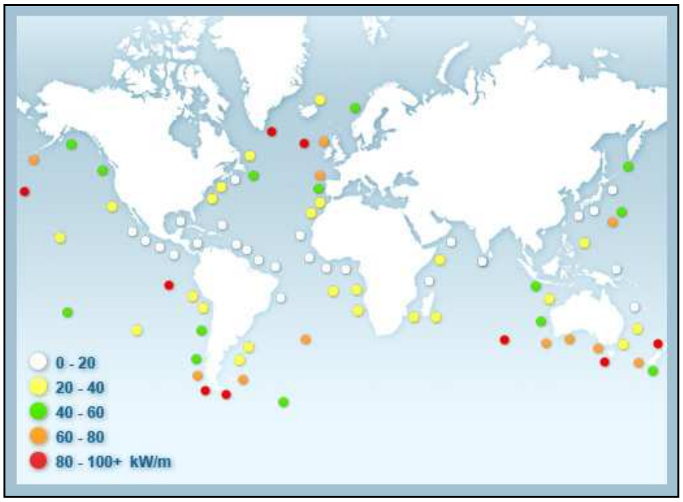

Figure 1: Density of wave power (source: www.aw-energy.com)

With regard to the devices that generate electrical power from wave activity, there are several patented types, with no technology so far dominating the scene in favor of the rest. Some have an advanced level of development with prototypes or pilot plants that are ready to sell on the market. Devices with the highest degree of development were selected for this study.

The methodology applied for estimating the available wave power and the output power from different devices is explained briefly in the chart in Figure 2, and is described in this document.

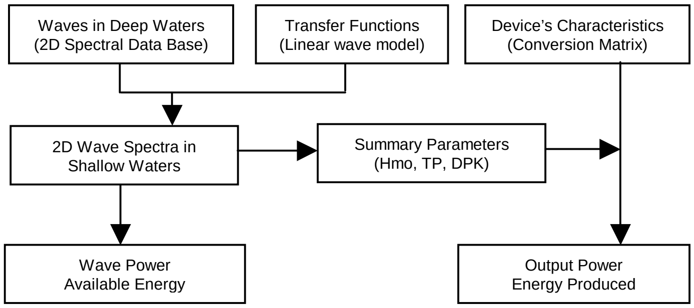

Figure 2: Methodology applied for the calculation of available wave power and generated power by mechanical devices

3 ESTIMATE OF WAVE POWER

3.1 Selection of analysis nodes

Ten sites were selected along the entire Chilean coastline, based on criteria that favor the development of an eventual project, such as the proximity to electrical power grid connection points and the proximity to a harbor, among others. Furthermore, those sites that are more exposed and have points or capes where energy is concentrated due to refraction effect of waves were favored. In each site three nodes were selected, located at water depths of 50, 25 and 10 meters, with a total of 30 nodes along the Chilean coastline. One of the advantages of the Chilean Sea is the steep slope of the seabed in comparison with other locations in the world, making it possible to reduce the cost of interconnecting from offshore to the power grid.

3.2 Waves in deep waters

In this assessment the wave database for deep waters known as Olas Chile II was used. The Olas Chile Project (Atria Baird Consultores S.A., 2001) is comprised by a long-term database for directional wave spectra in deep waters along the entire Chilean coastline. This project is based on a third generation hindcast model which in version II includes the generation of waves in the entire Pacific Ocean from 1985 to 2004. This numeric modeling and the resulting database, consisting in directional spectra every 3 hours for 20 years for the entire American Pacific Coastline, were validated in 22 points with wave measurements existing in Chile from TriAXYS buoys of Servicio Hidrográfico y Oceanográfico de la Armada de Chile (SHOA), of the National Oceanic & Atmospheric Administration (NOAA) and satellite data (Topex). See www.olasdelpacifico.com.

3.3 Spectral Transfer of waves towards shallow waters

The wave climate at each of the 30 nodes in shallow waters was obtained by means of bidimensional quasi-purist spectral transfer of waves in deep waters, performed by using the STWAVE (Steady state spectral WAVE model) numeric model, version 4.0, developed by the USACE (US Army Corps of Engineers). At each site transfer functions are obtained with STWAVE, which define change in height and direction of waves in the interest nodes. With these functions the bidimensional spectra are transferred towards the nodes, applying the corresponding wave height coefficient and associated change in direction to each of the energy spectrum bins, to subsequently reassemble the resulting spectrum in shallow waters. By following this methodology an adequate transfer is achieved of all the wave components in the directional spectra towards the interest points (Nicolau del Roure, 2004).

The resulting spectra in shallow waters are integrated in order to achieve the corresponding summary parameters, which represent the sea state associated to each spectrum. The mentioned parameters are defined as follow:

a) Wave Height Spectral Parameter (H_{mo}). It corresponds to the Significant Wave Height (H_s) at each site, calculated according expression (1):

$$H_{mo} = 3.8\sqrt{m_o} \qquad (1)$$

Where m_o is the zero-th moment of the spectrum,

b) Peak Period (T_p), which corresponds to the period related with the peak of the spectrum, and

c) Peak Direction (DPK), which corresponds to the wave direction associated to the peak of the spectrum.

3.4 Wave Power Calculation

Mean energy flow or mean wave power is defined as the mean energy transfer rate per width unit through a vertical plane perpendicular to the direction of the waves. The wave power was calculated from the reassembled spectrum in shallow waters and the celerity of the group of waves, using the expression (2):

$$P = \rho g \int_0^{\infty} \int_0^{2\pi} S(f,\theta) C_g(f,h)\, df\, d\theta \qquad (2)$$

Where P is mean power, ρ is the water density, S is the spectral energy as function of frequency (f) and direction (θ), C_g is the celerity of the group of waves as function of frequency and water depth (h). C_g was calculated using the expression from linear wave theory, as described in equation (3):

$$C_g = \frac{1}{2}\left[1 + \frac{4\pi h / L}{\sinh(4\pi h / L)}\right]\frac{gT}{2\pi}\left[\tanh\left(\frac{2\pi h}{L}\right)\right] \qquad (3)$$

Where T is the wave period and L is the wavelength. These were obtained from the calculated summary parameter T_p.

3.5 Wave Power Characterization

Based on the wave spectra in shallow waters and the relationships described in the above section, it was possible to calculate wave power series every 3 hours over a 20 year long period, for each site in shallow waters (30 nodes). In the following, the results of a few characteristics nodes are presented.

a) Wave Climate Parameters: In order to summarize the wave climate at each site, the statistics data for sea condition series by month, year, season and all year long (total) are obtained. Table 2 presents the mean figures of the summary parameters in three representative sites over a constant water depth of 25 m: in the north, the center and southern Chile.

Table 2 Mean figures for summary parameters for 25 m water depth

Site	H_{mo} (m)		T_p (s)		DPK (°)	
	Summer	Winter	Summer	Winter	Summer	Winter
North	1.30	1.50	12.6	13.2	228	229
Center	2.33	2.42	13.2	12.9	239	231
South	3.64	3.80	11.5	12.1	251	246

Table 2 exhibits one of the main characteristics of waves in Chile: the low seasonal variability and its high periods, independent of the latitude. It is enough to make a comparison with one of the most energetic sites in the world: the northeast coast of the United Kingdom (Table 3). In this case a comparison is made of the mean zero-crossing period Tz, which is lower than the spectral peak period.

Table 3: Comparison of summary parameters between Chile and the United Kingdom

	Hs (m)		Tz (s)	
Site	**Summer**	**Winter**	**Summer**	**Winter**
North East UK (Sinden, 2005)	1.50	3.50	5.2	7.2
Central Chile	2.33	2.42	10.4	10.6

b) Mean Power: Long-term power was calculated in order to represent the available power at each node in a general manner. This was estimated as the mean power over 20 years of wave spectra. Figure 3 shows the distribution of long-term power in deep waters and three different water depths along the Chilean coastline.

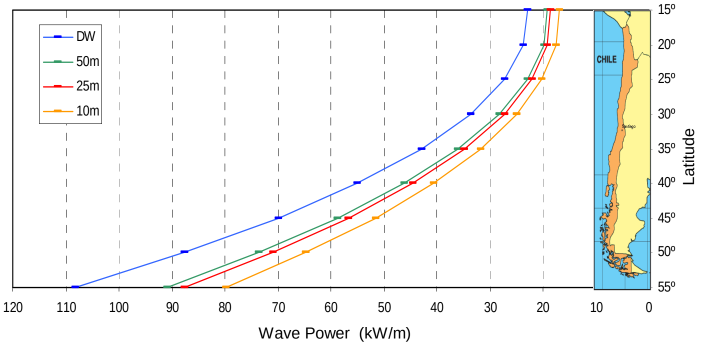

Figure 3: Distribution of wave power along the Chilean coastline as function of water depth

Long-term power in deep waters has a parabolic distribution along the nation's coastline, which ranges from 25 (kW/m) at the north end to figures close to 110 (kW/m) in the far south. In general, waves in deep waters in front of Chilean coast arrive mainly from SW and NW, with less percentage from W. Chilean coastline is aligned to W. Hence; wave power tends to decrease as it gets closer to the coast, due to the reduction in wave height caused by wave refraction. The reduction in celerity of the group of waves is more important in shallower waters, in the order of 10 m or lower. These effects are shown in Figure 3. However, if adequate sites are chosen, this reduction is compensated by the effect of shoaling and refraction focalized on headlands and capes, at sufficient water depth to avoid wave breaking. In average, the reduction of wave power is about 18% in sites that are 50m water depth compared with waves in deep waters, although this depends on the local bathymetry at each site. Note that average wave power at 50 m and 25 m water depth is almost equal. This reduces the connection distance to shore without decreasing the available energy. Wave power at 10 m water depth is considerably lower.

Based on the total power series various sub-series are obtained. In this case hourly, monthly and annual wave power distributions have been considered.

Figure 4 shows the monthly distributions in three previously defined characteristic sites at water depth of 25m. In the figure it is possible to see the difference between the levels of wave power in the north, center and the south of Chile. The difference between the months with higher and lower average power in the north is 7.1 (kW/m), while in the south it is 32.9 (kW/m). Higher levels of power are apparent in the winter and spring months (July to November).

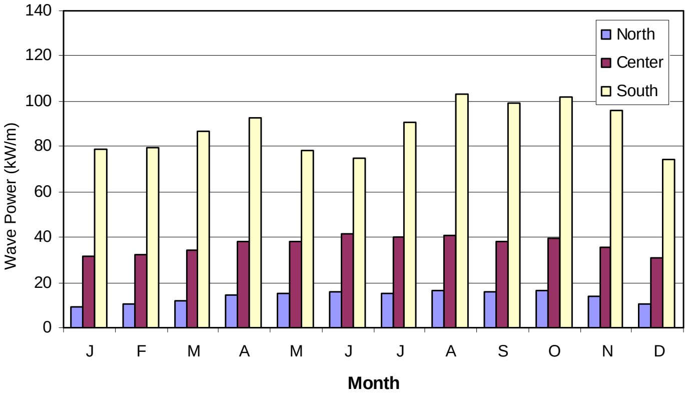

Figure 4: Monthly distribution of wave power for North, Central and South of Chile at 25 m water depth

Figure 5 shows the annual distribution of power at the site that represents the central zone of Chile. In this zone, the difference between the years with higher and lower mean power is 24.7 (kW/m), in the north of the country it is 9.2 (kW/m), and in the south it is 61.1 (kW/m).

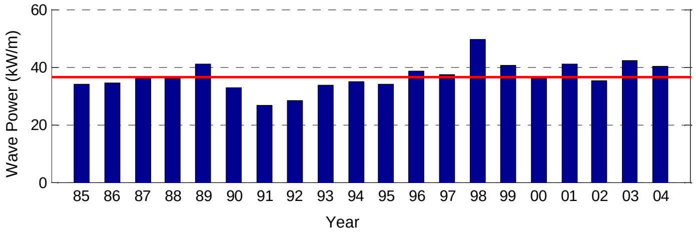

Figure 5: Annual distribution of wave power for Central Chile at 25 m water depth

Figure 6 shows the hourly distribution of wave power at the same site. At this site, the difference between the hours of greater and lower mean power is 2.8 (kW/m), in the north it is 0.4 (kW/m) and in the south 0.2 (kW/m), which indicates a low influence on the daily cycles, because waves are generated by phenomena at a synoptic scale (great spatial and temporary scale).

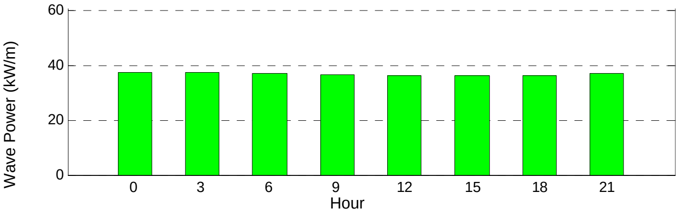

Figure 6: Hourly distribution of wave power for Central Chile at 25 m water depth

c) Power Variability: The annual, seasonal and daily variability are defined as long-term variation in energy from the waves, which are obtained from the respectively mean distributions. The variability is estimated from the variation range of each distribution as percentage of the average power. Annual variability is related to long-term atmospheric cycles, which influence wave generation. Seasonal variability is associated with seasonal changes in atmospheric conditions that generate the waves. Daily variability is associated to fluctuations in the resource caused by days and nights. Figure 7 shows the variability of the wave energy along Chile. The blue line represents the annual variability, which is the most significant and varies between 50% and 70%. The green line represents the daily variability, which is lower than 5%. This represents a small influence of the daily atmospheric cycles. The red line represents the seasonal variability of the resource. These changes refer not only to the actual site (wind sea), but also to distant sites in which swell systems are originated. This is especially relevant in Chile, were swell waves arrive from storms generated in the extra tropical regions, the Antarctic sea and even the Aleutian Islands in the Northern hemisphere around 12.000 km away (Atria Baird Consultores S.A, 2001). As can be seen in figure 7, the seasonal variability depends on latitude, with a minimum in the central part of the country. This dependency is due to the superposition of NW and SW wave components. During the summer in the southern hemisphere, the waves from the NW are more energetic (winter in Northern hemisphere), but this energy decreases from north to south. While in winter in Southern hemisphere, the waves of the SW are more energetic, which are decreasing in energy from south to north. However, both components are present all year round, known as bimodal wave pattern, and its combination generates the seasonal patterns from figure 7.

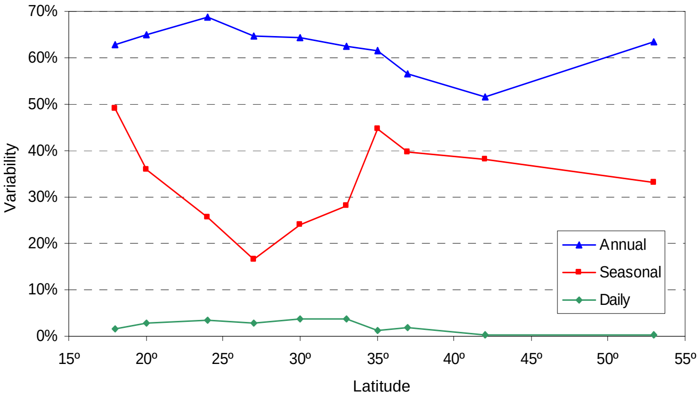

Figure 7: Wave power variability along Chile at 25 m water depth

Variability affects energy production, because it alters the relationship between output and consumption of electrical power. Lower levels of variability are preferable.

d) Exceedance Curves: Indicate the percentage of time during which a certain power value is exceeded. This may be actually taken as a probability. Figure 8 shows the exceedance curve in the site that represents the central zone. The figure shows all year long (total) and seasonal exceedance curves. In general, the winter curve is higher than the summer curve 100% of the time, although in sites such as the one in the figure, the relationship is reversed for wave power lower than 20 (kW/m).

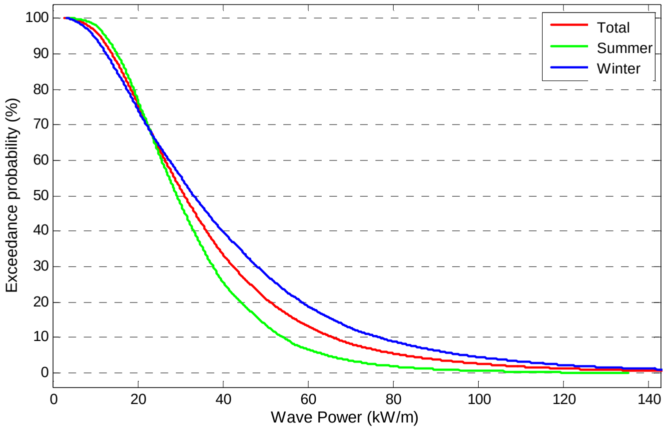

Figure 8: Wave power exceedance curve for Central Chile, 25m water depth

The exceedance levels or percentages are obtained from the exceedance curves, showing the level of power that is exceeded during certain percentages of time. In this case monthly distributions with exceeded levels of 90, 50 and 10% of the time are shown in Figure 9.

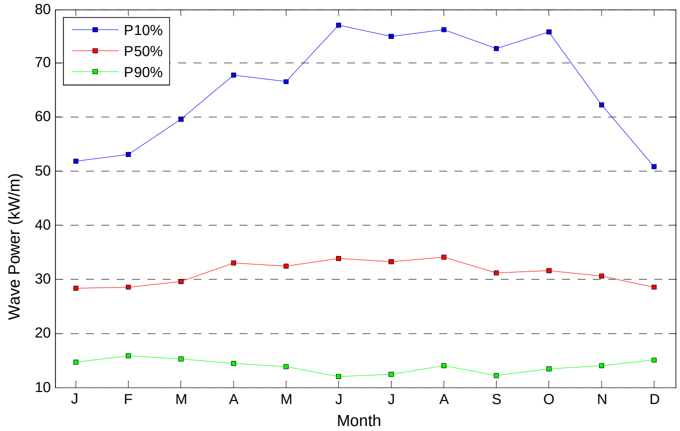

Figure 9: Monthly Distribution of Wave power exceedance for Central Chile, 25m water depth

The level of power exceeded for 90% of the time or P90%, can be relevant in terms of the optimum level of energy conversion. A device designed to generate power starting from this level, providing it for 90% of the time, is different to another device which is hydraulically more efficient and which will generate at lower levels, but with a higher cost than the former (Retief et al., 1982). In other words, it represents an optimum level of cut-in (startup) associated to the site. The devices included in this assessment assume a minimum wave height to generate of around 0.5 (m) or 5 (kW/m) of wave power. Therefore, if the monthly distribution curve of P90% is above this level, the site may be considered suitable for power generation with the analyzed technologies. All sites assessed in this study exceed 5 (kW/m), furthermore, in a great number of cases P90% never descends below than 10 (kW/m). This means that the entire Chilean coastline is a suitable location for electrical power generation with energy from waves.

Power level exceeded for 10% of the time or P10% is an accepted value to establish the rated power of a wave energy generator, achieving a balance between output power maximization and a minimization of the losses incurred in operating a generator below its rated power (Denniss, 2005).

e) Optimum capacity factor: The capacity factor is the ratio between annual energy production and maximum theoretical production, if the generator operates 100% of the time at its rated power. In other words this is the ratio between mean output power and rated power. The optimum capacity factor associated to a site is obtained based on the statistics of the resource. It is assumed that an optimum plant shall operate at rated power when the waves reach level P10%, considering the device converts the totality of the wave energy; and its median output power shall occur when the waves reach the average level (Denniss, 2005). Thus, we have:

$$CF_{optimum} = \frac{\overline{P}}{P10\%} \quad , \qquad (4)$$

where $\overline{P}$ is the average power. Figure 10 shows the distribution of the optimum capacity factor in deep waters according to the latitude, which varies between around 50 and 60%.

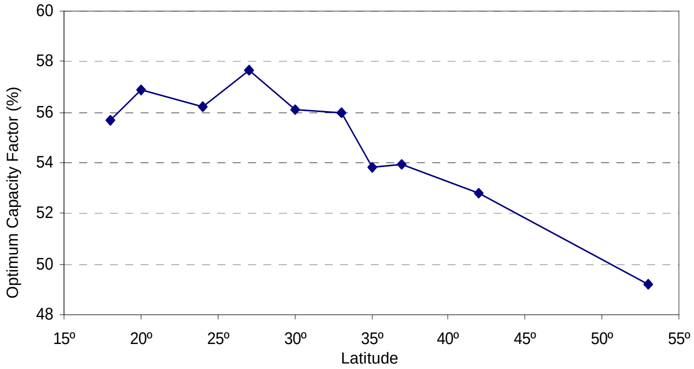

Figure 10: Optimum Capacity Factor along Chilean Coastline at 25m water depth

Table 4 shows the values for this parameter obtained by Denniss, 2005, in other highly energetic sites around the world. Note that the conditions in Hawaii are similar to those in Chile regarding to the high degree of exposure to waves from the entire Pacific Ocean, which results in similar values for the optimum capacity factor.

Table 4: Optimum capacity factor (Denniss, 2005)

Site	CF optimum
Central Chile (this research)	57.3%
Mokapu Point, Hawaii	54.4%
Port Kembla, Australia	44.0%
Bilbao, Spain	43.7%
Vancouver Island, Canada	43.9%

f) Mean medium power variation rate: Corresponds to the difference between median wave power at a certain point in time and the median power in the previous instant (Sinden, 2005). This parameter represents short-term fluctuation to which the electrical power system would have to adjust to. In the event of a small power generation facility in a major electrical power grid was to be analyzed, the impact is minor. However, if several power-generating facilities were to be considered, which jointly provide a major portion of power to the electrical power grid, the impact can be major. This aspect limits the level of penetration for this type of technology in a power distribution system, because backup plants would be required to absorb the variation. However, the integration of plants in various locations in the power grid contributes to the reduction of the variability (Sinden, 2005). Figure 11 shows the distribution of the mean variation rate of the wave power as percentage of the average power at the same site, along the Chilean coast at 25 m water depth. The red line represents the average increment of the wave power, while the blue line represents the average decrement of the wave power.

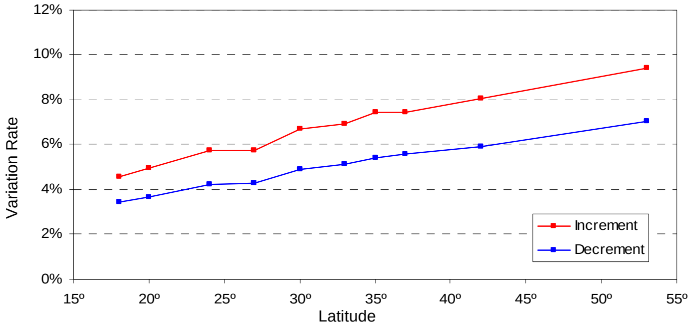

Figure 11: Average variation rate of wave power in Chile at 25 m water depth.

4 ESTIMATE OF OUTPUT POWER

This assessment focuses on offshore devices, mainly because of the greater availability of energy offshore in comparison with the coastline. Furthermore, they present other advantages such as the reduction of conflicts with other users of the ocean spaces, greater availability of surface for emplacement and a reduction of visual impact. However, costs of maintenance and interconnection to the grid increase.

The devices analyzed in this study were selected from the survey performed by Previsic et al, 2004.

4.1 Energy conversion matrix

The output power of each of these devices is obtained by means of their energy conversion matrixes (Figure 12), this being the power ratio that a device is capable of generating under diverse wave conditions (height and period). Each wave height (row) and wave period (column) is associated to a certain output power value of the device. Certain regions of the matrix exhibit a constant maximum level of output power, a value that is equal to the rated power of the device. Other regions exhibit zero output power, defined by both extremes values of wave climate: below cut-in level or startup and over the cut-out level or shutdown of the device. Based on the series of sea conditions the output power series are obtained for every 3 hours during 20 years for each node, which makes it possible to perform a completely analogue analysis to that performed with the wave power series. The mentioned analysis included all plants standardized at the same installed power in MW. For example, a park of 1000/750 = 1.33 units with 750(kW) rated power comprise a power generation facility of 1 (MW).

Significant wave height (H_{sig}, m)	Power period (T_{pow}, s)																
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8.0	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

Figure 12: Energy conversion matrix.
(Source: www.oceanpd.com)

4.2 Directional dispersion reduction factor

The effect of wave direction is considerable when estimating the captured power by a particular device. A directional dispersion reduction factor (DDRF) was defined in order to consider the reduction in energy level of those wave fronts approaching from other directions different from the peak direction, since the devices are oriented facing the mean peak wave direction. The details of this proposed DDRF are presented in the Annex A. In the calculation, a directional spectrum is associated to every wave data from the database. Figure 13 shows the distribution of average DDFR along Chile at different water depths. This factor on deep waters is 95% in northern Chile, decreasing to 85% in southern Chile. This is because wave directions are more dispersive when closer to storm generation centers, which in the southern hemisphere are located in the Antarctic Sea. Note that the factor increases if decreasing water depth due to the reduction in directional dispersion in shallow water caused by refraction.

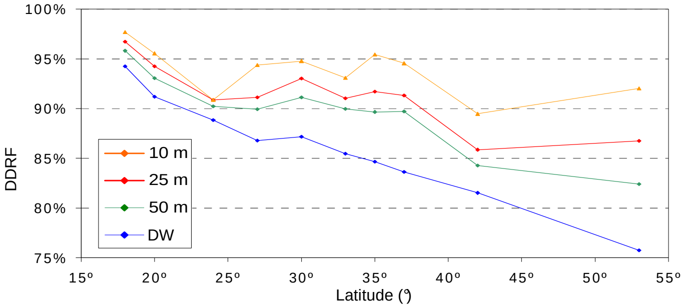

Figure 13: Average DDRF along Chile at different water depth

4.3 Characterization of output power

a) Mean output power: Figure 14 shows the distribution of average long-term output power for the three devices analyzed along the Chilean coastline at 25 m water depth. Output power increases with latitude, as wave energy, see figure 3.

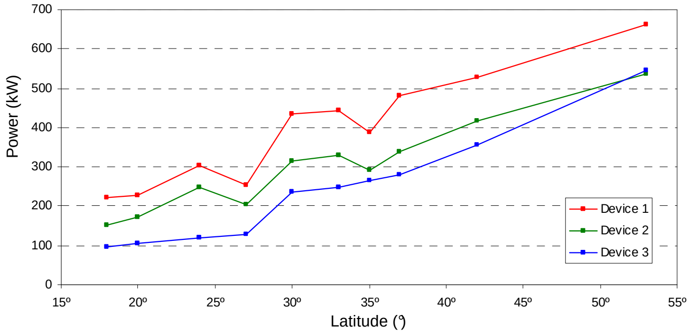

Figure 14: Mean Output Power. 25m water depth

Figure 15 shows the monthly distribution of output power of the devices placed in central zone at 25m water depth. In the same way as was done with wave power, annual and hourly distributions for output power were obtained, in addition to the exceedance curves for each device in the 30 nodes.

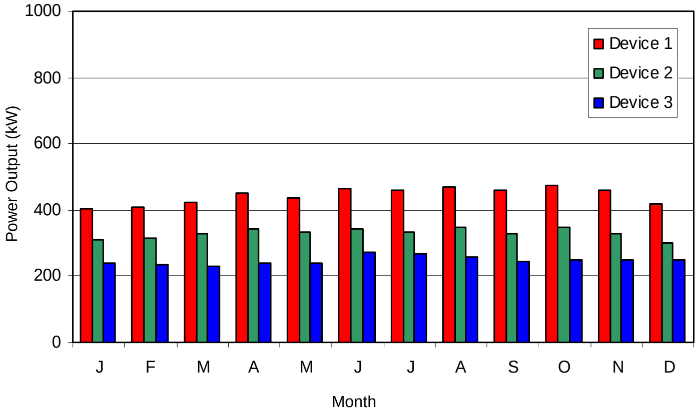

Figure 15: Monthly distribution of Output Power. Central Chile, 25m Water depth

Another way of analyzing seasonal distribution is comparing the percentages of energy produced in each season to the total energy generated in one year. Table 5 shows the average percentage of energy generated in one year in summer and in winter in Chile and the North East of United Kingdom. As can be seen from the table, in the UK site, six times more energy is produced in winter than in summer, while in Central Chile almost the same proportion is produced in both seasons, which confirms the low seasonal variability of the resource.

Table 5: Comparison of the seasonal proportion of output power between Chile and the United Kingdom

Site	**Average percentage of energy generated in one year**	
	Summer	**Winter**
Central Chile	24%	26%
North East UK (Sinden, 2005)	7%	42%

b) Actual capacity factor: The actual capacity factor of each of the analyzed devices is compared to the optimum capacity factor obtained based on the waves. The intersection of the actual and optimum curves provides, in theory, the best location for the installation of this device from the resource optimization viewpoint (Figure 16).

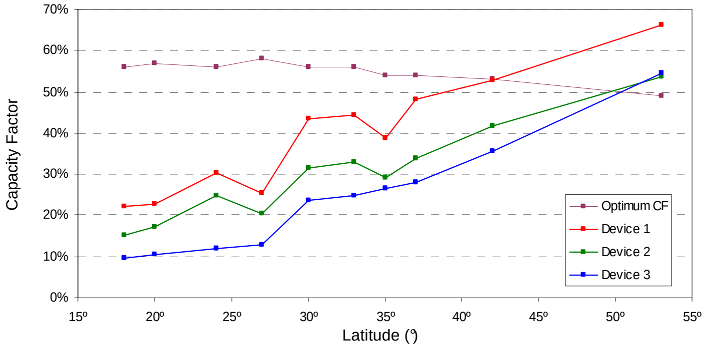

Figure 16: Comparison between optimum and estimated capacity factor for different devices

For example, the optimum location for the installation of a type 1 device is around parallel 43º S, although the most suitable emplacement depends also on other aspects such as those related with the civil works and grid connection mentioned before. Even than the capacity factor may be relevant to the optimization of plant design, the essential issue is the quantity of power generated with existing technology, because this directly influences in income stemming from the sale of energy. Based on this logic, the far south is the most suitable site for the installation of an electrical power plant. However, the most severe wave climate causes an increase in cost for installation, maintenance and contingency replacements in comparison to other sites further north. Another aspect that works against southern sites are the isolation conditions. However, this may not entail a disadvantage if it is desired to generate electrical power for small communities isolated from the major interconnected power grids.

On other hand, the capacity factor of the energy-converting device can be adjusted to any specific site in order to match the optimum capacity factor of the available wave power. Decreasing the rated capacity of the generator, for example, would reduce the cost of the device, increasing the CF ratio.

5 CONCLUSIONS

One of the characteristics of ocean wave climates is the rare occurrence of calm periods. In Chile, P90% never descends below 5 (kW/m) in all of the analyzed nodes. Furthermore, to a great extent a portion of these never descends below 10 (kW/m). This makes the entire Chilean coastline a suitable location for the generation of electrical power with energy from the waves.

Wave activity along the entire Chilean coastline does not exhibit significant variation in the various seasons of the year, which directly influences the low seasonal variability in generated power.

Wave power increases progressively with latitude, representing an advantage for those sites which are located towards the south of Chile, because these would achieve greater levels of electrical power generation, and therefore, greater income from energy sales. However, the increase in wave power results in greater costs for installation, maintenance and contingency replacement.

Wave power decreases as the waves approach the coast, representing an advantage for those devices that generate offshore. However, installation and maintenance costs increase as the distance from the emplacement of the electrical power plant to the coastline increases. The reduction in wave power is compensated by a reduction in its directional dispersion, positively influencing the production of energy in some devices.

The seasonal variability of wave power depends on latitude, with a minimum of 18% in Central Chile. In northern and southern Chile this value is around 50% and 30% respectively. This dependency is explained by the superposition of waves from SW and NW. Annual variability is higher than seasonal; then, long-term wave database has to be use to approach the evaluation of this kind of power plants. Daily variability is lower, with a maximum of 5%. This is an advantage of wave power plants over wind power plants.

Power generated by various devices at the same site varies considerably. This is due to the fact that some devices are better adapted than others to the wave climate in Chile. For optimum operation, it is necessary to modify the design of some of the devices in order to render them adequate to the wave period in Chile. Another major aspect to be taken into consideration are the effects of marine incrustation, because the Chilean ocean is characterized by an abundant proliferation of mollusks and other species which are lodged in marine structures. In mobile systems, the incrustation can bear heavily on the operational and maintenance costs of a power plant, therefore in Chile preference should be given to those devices with a lesser quantity of moving parts.

The optimum capacity factor in Chile is comparatively greater than the one in other energetic sites in the world. This parameter can also represents an evaluation of the variability of the resource, because it represents the ratio between two levels of wave power distribution. According that, the lower the dispersion (or variability) in power distribution, the greater the optimum capacity factor.

The actual capacity factor of a power plant shall depend on the design of the device. The actual capacities of each device are below the optimum values in most of Chile, but increase with latitude until these exceed the optimum values curve. The intersections of the actual and optimum curves provide the most adequate location for the installation of this device. However, the selection of the site depends on other factors independent of the available resource. The optimum site should be obtained from a benefit-cost analysis of all variables involved in the issue, but notwithstanding the above, the entire Chilean territory comprises one of the most suitable places in the world for the generation of electrical power from wave energy.

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ANNEX A

DEFINITION OF THE DIRECTIONAL DISPERSION REDUCTION FACTOR (DDRF)

The definition of the Directional Dispersion Reduction Factor (DDRF) considers two cases:

1.- The waves from the database are associated to a cosine power directional spectrum, defined as eq (5).

$$G_j(\theta)=\begin{cases} G_0\cos^{nn_j}(\theta) & -\frac{\pi}{2}<\theta<+\frac{\pi}{2} \\ 0 & other\ cases \end{cases} \qquad (5)$$

Where G_0 corresponds to a normalization constant, nn_j is a pair exponent depending on T_p, θ is the deviation of each frequency bin from the spectrum with respect to the peak direction Dir_j.

2.- The database consists on directional spectra, which has to be collapsed on the frequency axis, eq (6).

$$G_j(\theta)=\int_0^{\infty} S(f,\theta)\,df \qquad (6)$$

Figure 17 shows a squetch of a wave spectrum with peak direction Dir_j approaching to a device of width b_0 oriented in the direction of the mean peak direction $\overline{Dir}$. The effective width of a wave approaching the device depends of the deviation α with respect to the orientation of the device, and it is defined as eq (7).

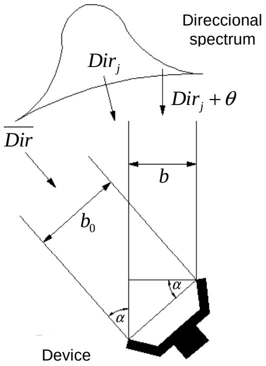

Figure 17: Directional dispersion and orientation of device

$$b(\alpha)=\begin{cases} b_0\cos(\alpha) & -\frac{\pi}{2}<\alpha<\frac{\pi}{2} \\ 0 & other\ cases \end{cases} \qquad (7)$$

The relation between θ and α is calculated as in eq (8)

$$\theta=\alpha-\left(Dir_j-\overline{Dir}\right) \qquad (8)$$

Considering the deviation of each wave direction component of the directional spectrum with respect to the orientation of the device, the directional dispersion reduction factor is defined as in eq (9):

$$FRDD_j=\frac{\int_{-\pi}^{\pi} b(\alpha)G_j(\alpha)d\alpha}{b_0\int_{-\pi}^{\pi} G_j(\theta)d\theta} \qquad (9)$$