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ASSESSING THE PORTUGUESE WAVE-POWER RESOURCE

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Abstract—The Portuguese wave-power resource is estimated using 3 years of data from the U.K. Meteorological Office's wind-wave model, in addition to available wave buoy measurements for northern Portugal. The large-scale resource assessment includes basic statistics and the variability. The annual power averages 30–40 MW/km for the northern coasts, the main power being incident from directions between North and West. The variability is studied by means of power-duration curves and scatter tables. The present paper also includes a brief description of the preliminary survey of the Azores and Madeira archipelagos and of the mainland southwestern coast.

INTRODUCTION

Portugal and its offshore islands lie to the south of the main storm areas of the North Atlantic. It is therefore not surprising to find that its highest wave-power levels, averaging 30–40 MW/km, lie on the north side of the Azores and in northern Portugal and, in each case, apply to installations facing approximately northwest. These levels are not quite as high as for the best Atlantic coasts (Ireland, 40–50 MW/km) but are higher than for the coasts where the first full size prototypes have been installed (Norway, 15–30 MW/km) and represent a very substantial potential contribution to Portugal's energy requirements. The overall resource of Portugal's continental coast is estimated at 10 GW mean, of which approximately half might potentially be exploited. This estimate is considerably greater than Portugal could use in the foreseeable future (electricity consumption currently averages nearly 3 GW or approximately 25 TWh/yr). The preceding statement applies even more strongly to the islands, which could not at present utilize more than about 1 km of their resources.

The technology to exploit the large-scale resource requires offshore devices and is still at the research and development stage. Small coastal devices generating up to about 1 MW are at the demonstration stage. The present survey identified a number of promising coastal sites, and feasibility studies are now being undertaken for two contrasting sites in the Azores.[1]

Wave power originates from the loss of wind energy through drag to the sea surface. Though the areal input rate is small, typically a fraction of a watt per square metre, wave energy can travel thousands of kilometres with only small losses, so that power levels averaging of the order of 50 kW/m (=50 MW/km) are available off coasts with good oceanic exposure.[2]

Recent interest in wave power was stimulated by the oil crisis of 1973.[3] In the first few years, research was concentrated on floating devices, aimed at exploiting the open-sea resource.[4,5] Such devices still seem essential for exploitation of the resource on a large scale, but more recent work has mainly been concentrated on small-scale shoreline devices.

Small-scale devices (of the order of 10 m in width) can be used to take advantage of the "point absorber effect", which theoretically allows us to capture a width up to L/π in waves of wavelength L (see Ref. 6); small-scale devices near or onshore can also benefit from focussing effects due to wave refraction. However, only a fraction of the energy which reaches the shore can be exploited economically: coastal topography includes occasionally very favourable sites

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such as natural gullies but also (particularly on volcanic islands such as the Azores and Madeira) long stretches with shoals, boulders or unstable rock formations.

Prototypes of two quite different OWC (oscillating water-column) and TAPCHAN (tapered channel) designs[7] began operating near Bergen in Norway in November 1985, their installed capacities being 500 and 350 kW, respectively. Figure 1 shows a schematic representation of an OWC power plant and Fig. 2 presents an artist's impression of a TAPCHAN. Britain's first OWC prototype of about 180 kW rated power is being completed on the island of Islay off the west coast of Scotland, and Portugal is planning to start building its first power plant in 1992, which is rated at approximately 500 kW, on the island of Pico in the Azores.

The aims of the present study were, first, to estimate the large-scale offshore resource using data from the U.K. Meteorological Office's wind-wave hindcasting model,[8] together with available measured wave data from a site off Figueira da Foz in continental Portugal. Second, to survey coasts with a favourable wave climate, especially with a view to identifying a small number of sites suitable for prototypes. This survey made use of the aerial photographs, charts and geological maps, and local knowledge. Third, to consider the wave-power resource in relation to Portugal's electricity requirements. The islands in particular have relatively small requirements, mostly in the range 1–50 MW, so that large-scale developments are not currently of interest. However, their present reliance on expensive diesel-generated electricity means that small-scale contributions from new power sources would be particularly welcome in the islands.

THE LARGE-SCALE RESOURCE

Wave-power

The energy in surface waves is half potential and half kinetic. Using linear wave theory for progressive waves (see, e.g., Sarpkaya and Isaacson[9]), the average kinetic energy per unit of

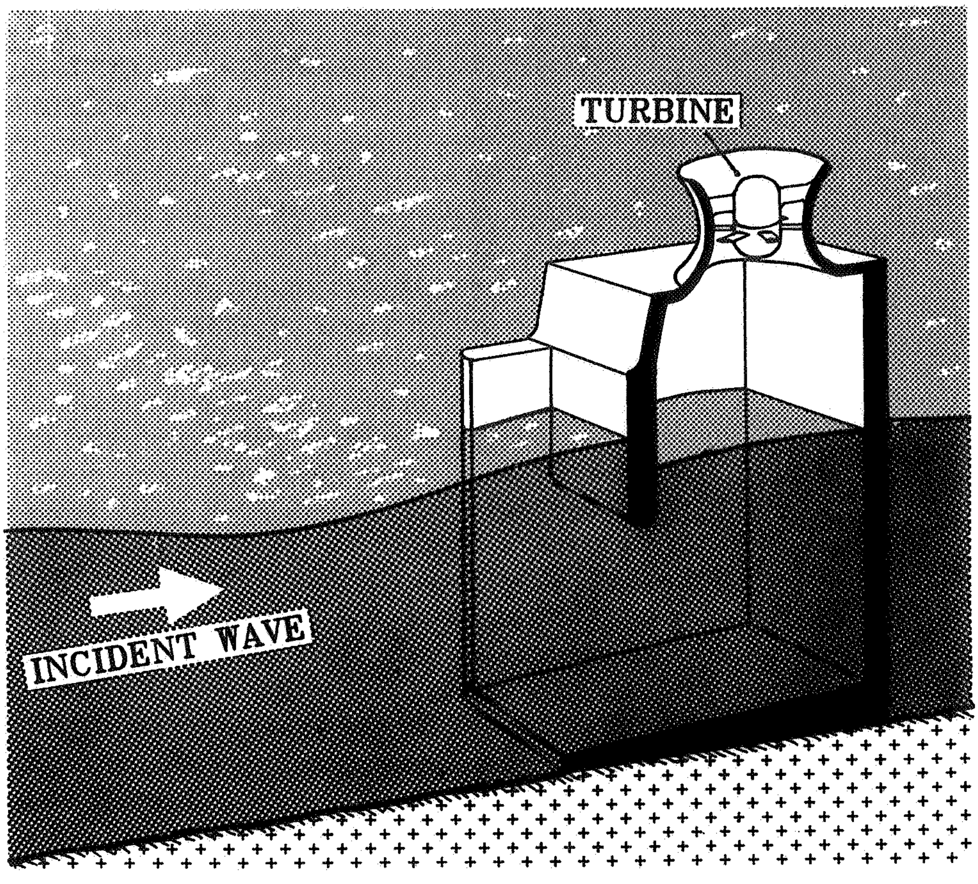

Fig. 1. Schematic representation of a wave-power plant of the oscillating water-column type. It consists basically of a structure forming a chamber open at the submerged bottom. The waves incident upon the structure make the inside water free surface to oscillate, driving a reciprocating flow of air through a turbine located at the top of the structure.

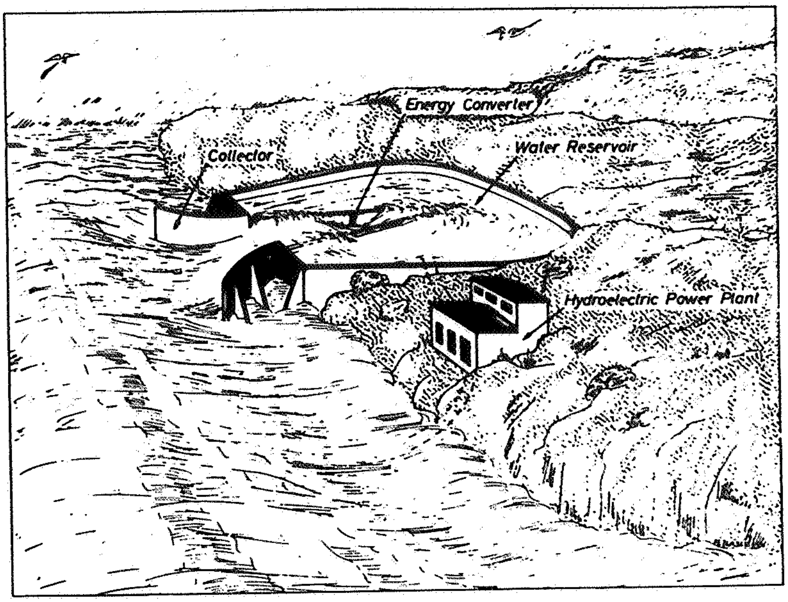

Fig. 2. Schematic representation of a TAPCHAN (from Ref. 7). It consists of a funnel-shaped channel open towards the sea that concentrates the energy of predominant waves. Inshore of the funnel is a long smoth-walled tapering channel with an upper height corresponding to the top of the reservoir. As walls narrow, the wave height increases; when the crest of a wave is higher than the edge of the converter channel, the waver pours over the edge and into the reservoir. Water flows out of the reservoir back to the sea through a conventional low-head turbine. The reservoir acts as a small storage.

horizontal area E_k and the average potential energy per unit of horizontal area E_p are given by

$$E_p = E_k = \tfrac{1}{16}\rho g H^2,$$

where ρ denotes the sea water density, g the acceleration due to gravity and H the wave height. The average energy density E per unit of horizontal area is the sum of E_k and E_p

$$E = \tfrac{1}{8}\rho g H^2. \tag{1}$$

Power is the rate of transmission of energy and the wave power P transmitted per unit width across a plane perpendicular to the wave propagation direction is equal to the product of the energy and its propagation velocity, the group velocity, given by

$$c_g = \frac{1}{2}\left(1 + \frac{2kd}{\sinh 2kd}\right) c,$$

whereas the speed with which the waveform propagates, the phase velocity c, is given by

$$c^2 = \frac{g}{k}\tanh(kd).$$

Both velocities depend on the wavelength λ ($k = 2\pi/\lambda$ is the wave number) and the water depth d.

In the sea, the values of energy (or power) associated with wave components of frequency f and direction θ are to be added together. The power per unit wave front is given by

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

where the spectral energy density $S(f, \theta)$ describes the total energy distribution in the frequency and direction domains. In deep water, Eq. (2) reduces to

$$P = C_1 \int_0^{2\pi}\int_0^{\infty} f^{-1} S(f, \theta)\, df\, d\theta = C_1 H_s^2 T_e, \tag{3}$$

where $C_1 = \rho g^2/64\pi$. The significant wave height H_s is computed from

$$H_s = 4m_0^{1/2}$$

and the energy-equivalent period T_e is the appropriate period defined as

$$T_e = m_{-1}/m_0,$$

where m_n denotes the nth moment of the spectral distribution

$$m_n = \int_0^{2\pi}\int_0^{\infty} f^n S(f, \theta)\,df\,d\theta.$$

Since $T = 1/f$, T_e is the average value of T with respect to the spectral distribution.

The net power flux P_θ in the direction θ is found[2] by multiplying the energy of each component by its group velocity resolved in the direction θ, viz.

$$P_\theta = C_1 \int_0^{\infty}\int_{\theta-\pi/2}^{\theta+\pi/2} f^{-1}S(f, \theta)\cos(\phi - \theta)\,df\,d\phi; \tag{4}$$

the directionality coefficient d_θ is defined as P_θ/P.

Data

The Portuguese large-scale wave-power resource was assessed using waverider buoy measurements off Figueira da Foz on the mainland west coast (e.g., Ref. 10), complemented by directional hindcast estimates of the U.K. Meteorological Office's deep water wind-wave hindcast model. Estimates were obtained for grid points off the mainland west coast and also for the Azores and Madeira areas. The model does not take into account the presence of the islands. Therefore the results do not include the sheltering effects of some islands of the Azores on the wave climate of the others.

Waverider frequency spectra for the period between June 1981 and December 1988 were analysed. These spectra were obtained from 20-min records every 3 h. The monthly percentage data recovery varies between the winter and summer seasons. The U.K. Meteorological Office's numerical model gives separate estimates of wind-sea and swell. Data were analysed for the period between February 1983 and July 1986 for one grid point off Figueira da Foz, for one point off the island of Faial, Azores, and for one point off Madeira. There were very few missing records. Estimates given at 12-h intervals consist of height, period and principal directions of swell and wind-sea.

Table 1. Annual mean power levels and their division into swell and wind-sea and directional patterns. The direction is given in degrees measured from the North and is in the clockwise direction. Measurements off Figueira da Foz (F.FOZ) using a waverider buoy were made at 40°10'N, 9°08'W, 90 m depth, between June 1981 and December 1988. Deep water estimates off Figueira da Foz at 40°8'N, 10°33'W, off the Azores (Faial) at 37°47'N, 28°59'W and off Madeira at 33°18'N, 17°0'W were used for the period between February 1983 and June 1986.

SITE	ANNUAL MEAN POWER (kW/m)				BEST DIRECTION	d_θ
	GROSS POWER	SWELL	WIND-SEA	$\overline{P}_\theta$		
F.FOZ (meas.)	29.2	—	—	—	—	—
F.FOZ (estim.)	48.6	36.6	12.0	38.1	315°	0.78
AZORES (estim.)	51.3	37.2	14.1	35.5	320°	0.69
MADEIRA (estim.)	34.5	29.5	5.0	27.9	335°	0.78

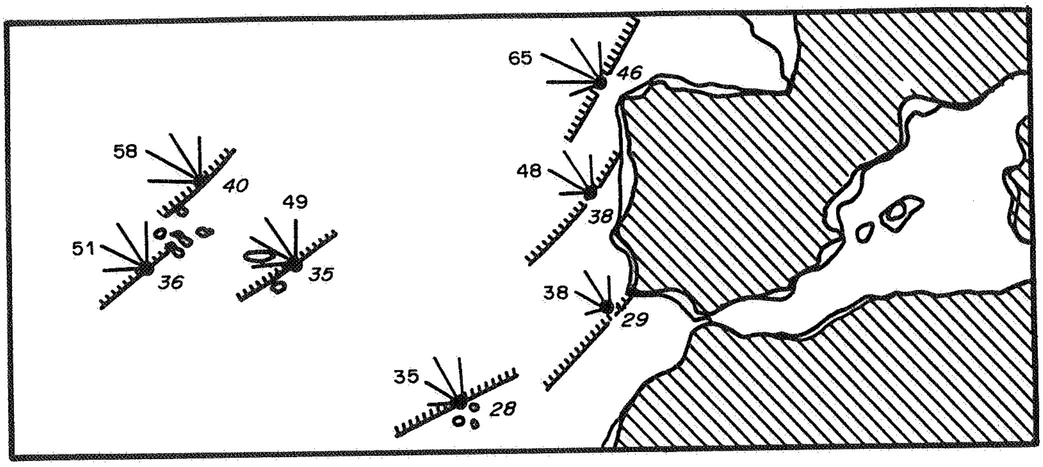

Fig. 3. Wave power estimates for the Portuguese coast, including Madeira and the Azores, based on the U.K. Meteorological Office's wind-wave hindcast model. Wave roses show the mean power from each 30° sector, with the line length proportional to the power. Gross power levels are shown in kW/m; also shown is the net power $\bar{P}_\theta$ (*in italics*) crossing lines whose direction maximises $\bar{P}_\theta$ for the particular site; from Ref. 2.

Basic Statistics

Table 1 includes the annual mean gross power and its directional pattern obtained from measurements off Figueira da Foz, and the estimates off Figueira da Foz, Azores (Faial), and Madeira. The division into wind-sea and swell from the model estimates indicates that the energy that reaches the coast is mainly due to swell, roughly 75% for the mainland and the Azores and 85% for Madeira. In Portugal, power is incident mainly from directions between North (360°) and West (270°), rotating slightly to the northeast as we move southwards. The values of d_θ indicate a concentrated directional distribution. Figure 3 shows wave-roses for the Portuguese coast, including the Azores and Madeira.

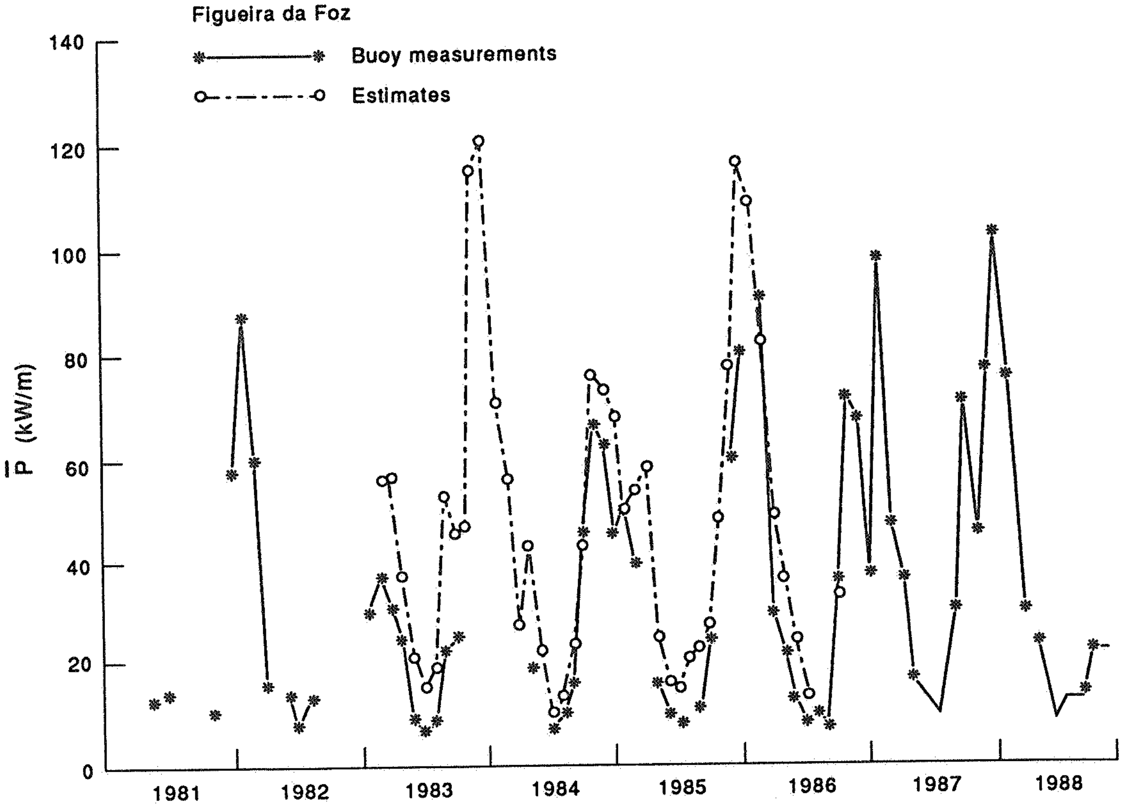

Fig. 4. Monthly mean power level off Figueira da Foz. Waverider data at 90 m depth (*———*), the U.K. Meteorological Office's hindcast deep-water model estimates (∘—·—·—∘).

Variability

Wave power is more abundant when it is most needed: in winter. Figure 4 shows measured and estimated monthly-mean power levels off Figueira da Foz. The estimates are generally higher than the measured power levels but the plot shows good correlation between them. Since the measurement site is further inshore and is in only 90 m depth, the difference between the two can be at least partly explained as due to refraction and bottom-friction losses (Refs. 2 and 11). Figure 5 shows the comparison of estimated and measured power and includes the linear regression line fitted to (measured, estimated) pairs of power levels and its correlation coefficient. The value of the correlation coefficient is 0.83, which indicates a good correlation. The figure for the r.m.s. error is 34.2 kW/m, which is of the same order as the average measured power.

Figure 6 shows "instantaneous" (20 min averages) measured and estimated power levels off Figueira da Foz (the same site) during December 1984, as an example of a typical winter month. This plot illustrates the variability of the wave-power resource and shows that it can increase or decrease by a factor of two or even three between two consecutive 3-hourly measurements. During this month many measured data exceeded the estimated power levels, which is the contrary of average trend as can be seen in Table 1. This usually occurs for sea

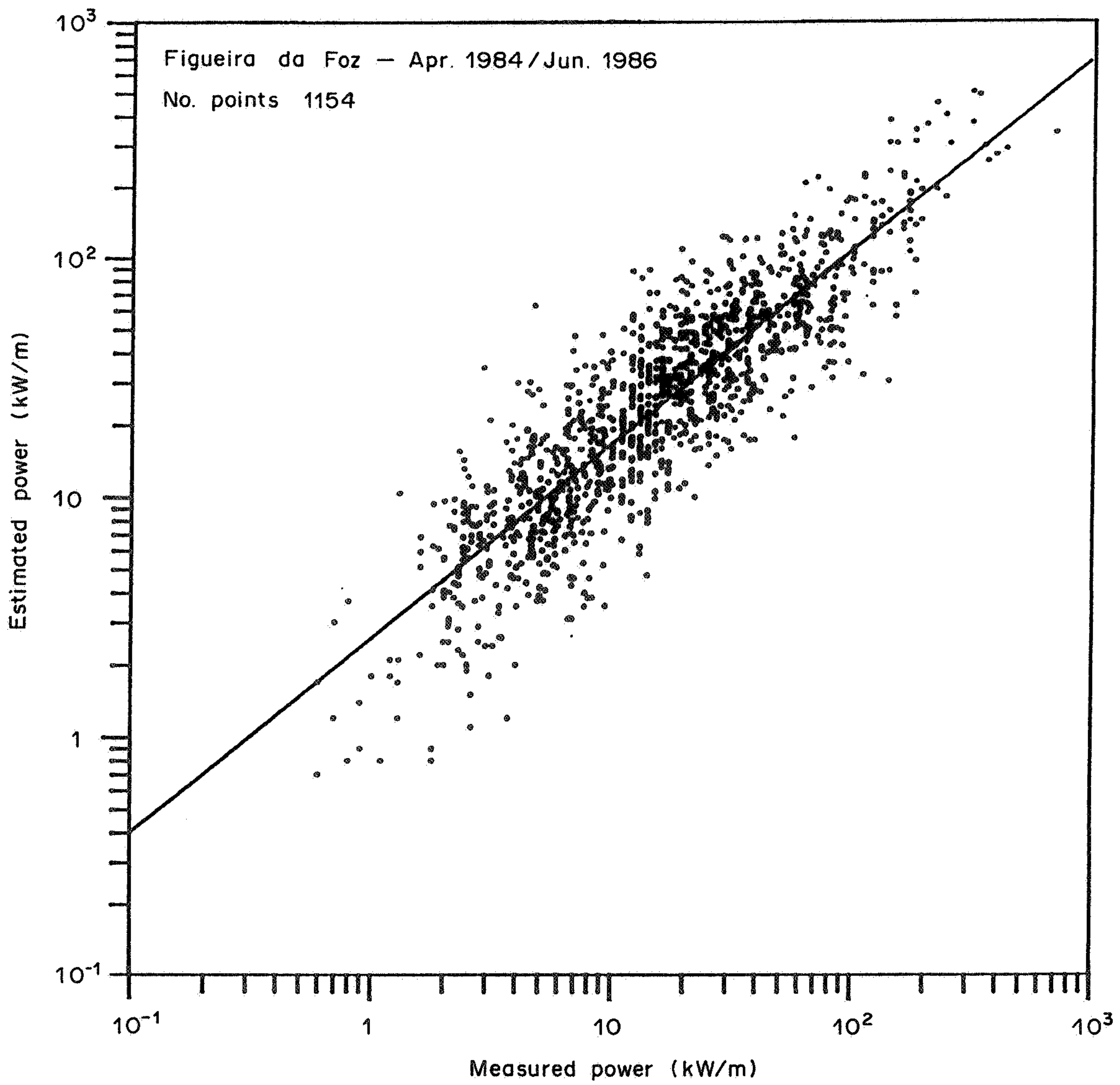

Fig. 5. Power level comparison between "instantaneous" (20 min av.) waverider data and the U.K. Meteorological Office's deep-water estimated values off Figueira da Foz for the period between April 1984 and June 1986. $\bar{P}_{meas} = 30.6$ kW/m, $\bar{P}_{estim} = 41.4$ kW/m, r.m.s. error = 34.9 kW/m, correlation coefficient $r = 0.83$.

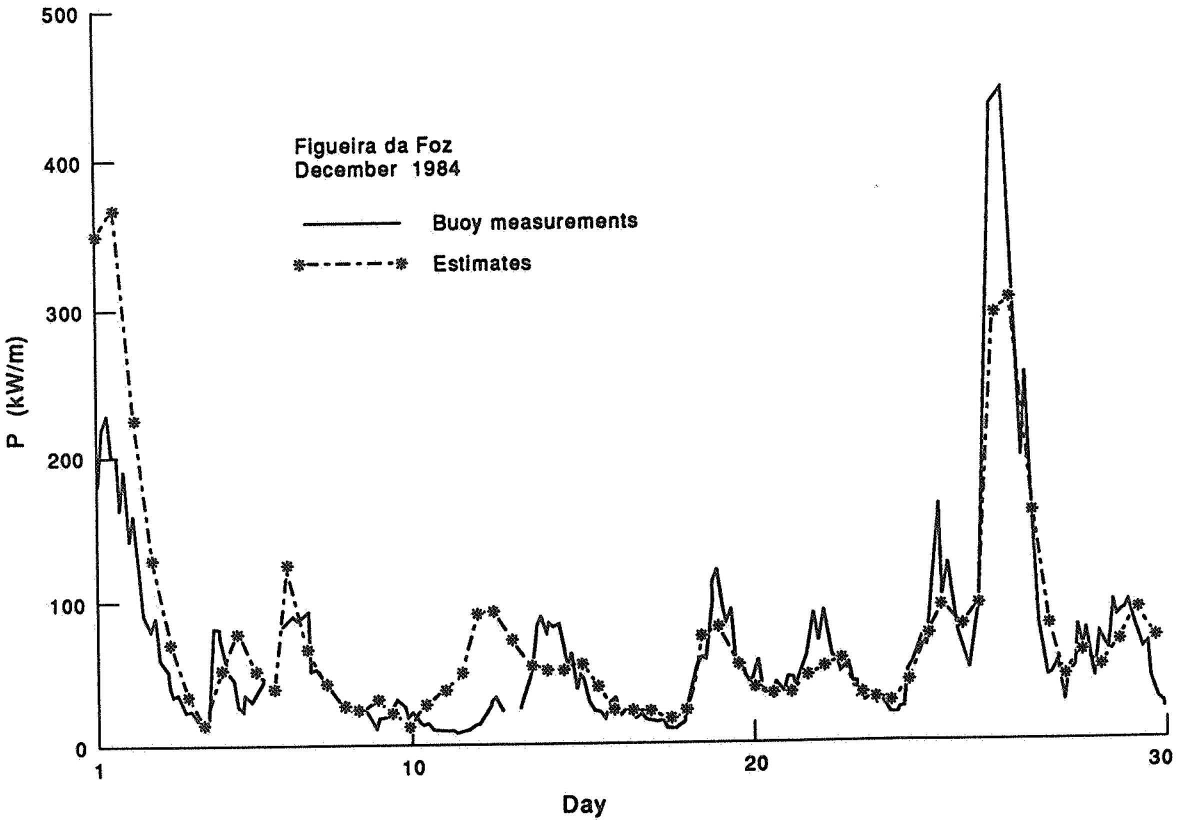

Fig. 6. Time series of "instantaneous" power levels off Figueira da Foz in December 1984. Waverider data at 90 m depth (———), the U.K. Meteorological Office's deep-water hindcast model estimates (*—·—·—*).

states with sharp power level variations. In these cases, the power estimates change more slowly than the measurements and do not reach such high levels. This feature is common to several hindcasting models.

The seasonal variation of the duration curves, obtained from Figueira da Foz measurements, for the whole year, "Winter" and "Summer", are shown in Fig. 7. Similar curves from Figueira

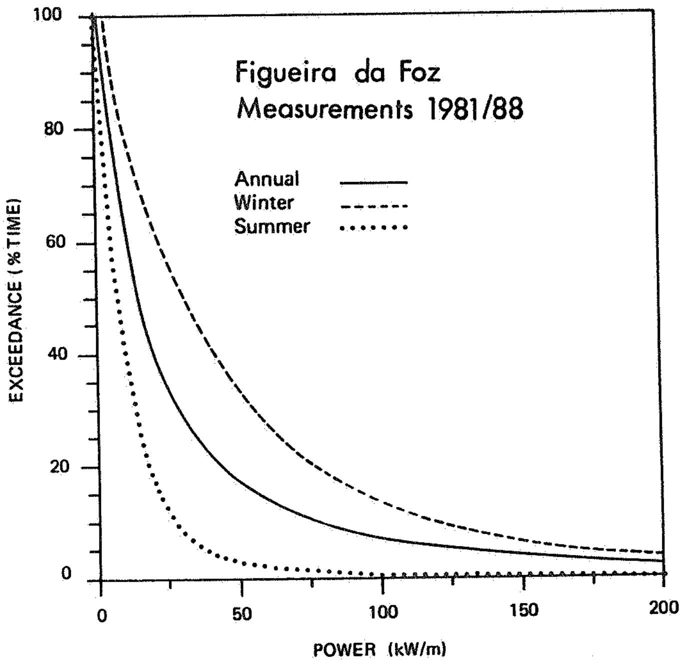

Fig. 7. Seasonal variation of the distribution of "instantaneous" power levels off Figueira da Foz for the whole waverider measuring period (June 1981/December 1988).

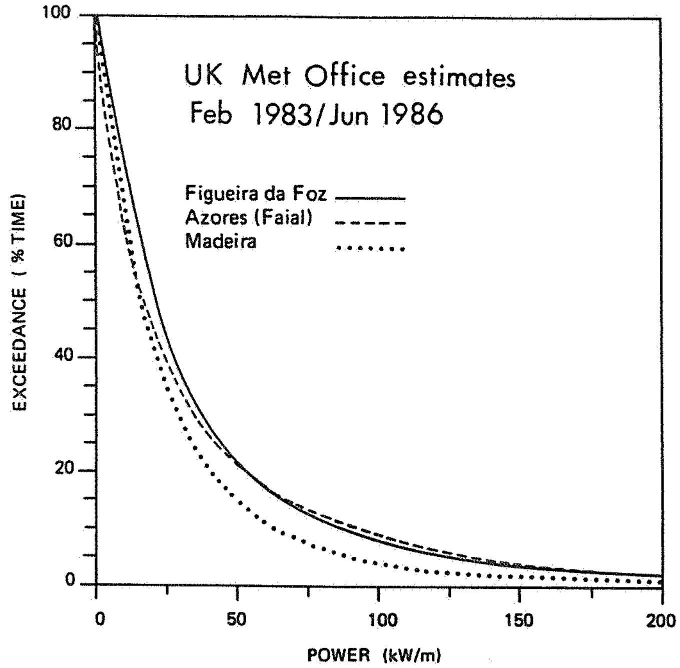

Fig. 8. Distribution of "instantaneous" power levels from the U.K. Meteorological Office (February 1983/June 1986) estimates.

Table 2. Scatter table relating the significant wave height (H_s, steps of 0.5 m) to the energy period (T_e, steps of 1.0 sec) for the whole measurement period (June 1981–December 1988) off Figueira da Foz.

$H_s(m)$	$T_e(s)$														TOTAL
	< 5	–6	–7	–8	–9	–10	–11	–12	–13	–14	–15	–16	–17	> 17	
> 7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
–7.0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
–6.5	0	0	0	0	0	0	0	1	0	0	1	1	0	0	3
–6.0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	4
–5.5	0	0	0	0	0	0	0	1	2	2	1	0	1	1	8
–5.0	0	0	0	0	0	1	2	3	3	3	1	1	2	2	18
–4.5	0	0	0	0	0	2	4	5	3	3	1	1	1	5	25
–4.0	0	0	0	1	2	4	6	6	5	3	2	1	1	6	37
–3.5	0	0	0	3	4	7	10	11	8	5	2	2	1	8	61
–3.0	0	0	2	11	11	15	16	13	8	4	3	2	2	10	97
–2.5	0	0	10	22	25	23	20	15	8	6	4	4	4	11	152
–2.0	0	4	25	39	36	34	25	16	10	8	6	3	3	7	216
–1.5	1	12	34	48	38	30	24	15	8	5	4	3	3	6	231
–1.0	0	12	27	32	24	15	12	5	4	4	2	1	1	2	14
< 0.5	0	0	1	1	1	1	1	1	0	0	0	0	0	0	6
TOTAL	2	28	99	157	141	132	120	93	60	44	29	19	19	58	1000

Table 3. Relative power distribution (parts per thousand) for the wave height (H_s, steps of 0.5 m) and energy period (T_e, steps of 1.0 sec) for the same site and measurement period as is used in Table 2.

H_s(m)	T_e(s)														TOTAL
	< 5	-6	-7	-8	-9	-10	-11	-12	-13	-14	-15	-16	-17	> 17	
> 7.0	0	0	0	0	0	0	0	0	3	3	5	2	0	7	20
-7.0	0	0	0	0	0	0	0	0	1	3	8	2	3	2	19
-6.5	0	0	0	0	0	0	0	6	2	4	6	6	4	4	32
-6.0	0	0	0	0	0	0	1	3	9	7	9	4	2	4	39
-5.5	0	0	0	0	0	1	2	6	10	12	7	2	1	8	49
-5.0	0	0	0	0	0	1	8	13	12	15	8	3	3	17	80
-4.5	0	0	0	0	1	5	12	17	13	12	5	4	5	22	96
-4.0	0	0	0	1	3	8	15	16	16	10	6	5	4	22	106
-3.5	0	0	0	4	6	12	18	23	18	13	5	5	4	24	132
-3.0	0	0	1	9	11	17	20	19	12	7	5	4	4	20	129
-2.5	0	0	2	13	17	18	18	14	8	6	5	4	4	18	127
-2.0	0	1	8	14	15	16	13	9	6	5	4	2	3	7	103
-1.5	0	2	6	9	8	8	7	4	3	2	2	1	1	2	55
-1.0	0	1	2	3	2	2	1	1	1	0	0	0	0	0	13
< 0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	0	4	19	53	63	88	115	131	114	99	75	44	38	157	1000

da Foz, Faial and Madeira estimates for the whole calculation period, facing the best direction for each site, are presented in Fig. 8. In calculating seasonal figures, we follow Mollison[2] in using only two main seasons. "Winter" refers to the six months from October to March when power levels are generally high and "Summer" to the four months from May to August when power levels are generally low. April and September vary considerably but generally have intermediate levels.

In addition to giving an overall feel for the scale of the wave power, the scatter table also shows the extreme variability of the wave energy supply. Table 2 reproduces the scatter table of frequency of occurrence of combinations of H_s and T_e in parts per thousand for Figueira da Foz measurements. The table shows that the most frequent sea states occur for $1.0 < H_s$, $m \leqslant 2.0$, $7.0 < T_e$, $s \leqslant 10.0$. Table 3 shows the relative power distribution for the same data, the predominant contributions being due to the sea states with $2.0 < H_s$, $m \leqslant 4.0$, $11.0 < T_e$, $s \leqslant 13.0$.

THE SMALL-SCALE RESOURCE

Introduction

A preliminary survey was carried out of sites suitable for the installation of onshore wave-power stations, either of the oscillating water column (OWC) or TAPCHAN type.

The main criteria in site selection relate to the wave climate, the shore topography, and access.

The shoreline wave climate is much more difficult to estimate than the offshore climate, for a number of reasons. In intermediate depths, say 200–10 m, a significant proportion of power may be lost through bottom friction[11] while refraction and diffraction can change its directional distribution, focusing energy in some places ("hot spots"), defocusing in others. But the greatest sources of variability are at the shoreline itself. At best, we may find deep water (at least 5–10 m) close inshore and natural resonance to concentrate the energy.

The main topographical requirements are for good rock onshore, suitable for civil engineering works, and for an absence of boulders in the sea, which might absorb energy through wave breaking and damage structures. More obvious requirements are that access for construction and connection to the local electricity grid can be provided at a reasonable cost.

Sites satisfying all of these criteria are quite rare. This is particularly true in the volcanic islands of the Azores and Madeira, where the coast commonly consists of high cliffs, and the water near the shore is often shallow and strewn with boulders. However, the electricity demands of the islands are modest, so that they may nevertheless have a sufficiently great shoreline wave-power resource for their likely future needs. More immediately, the small number of especially promising sites identified in the survey should suffice for the development stage of the Portuguese wave-power programme.

Because of the relatively greater potential of wave power to contribute to their electricity requirements, the present survey was concentrated on the islands, particularly the Azores were the offshore resource had already been identified as highest.

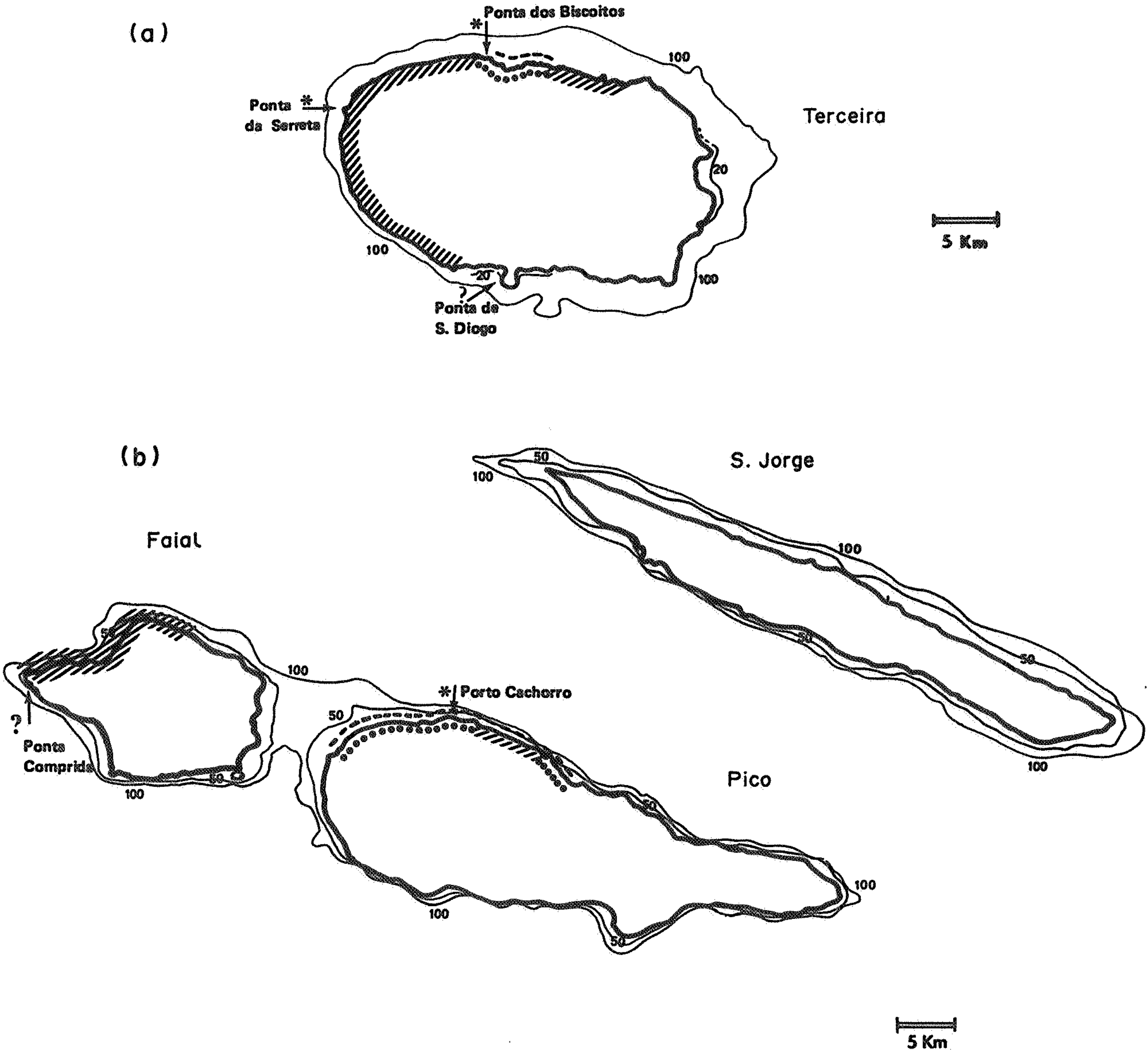

Fig. 9. (*Caption opposite*).

Azores

Five of the nine islands were surveyed: Faial, Pico, Terceira, São Miguel, and Santa Maria. These were selected on the criteria of their having sites worth investigating and of their need for additional electricity generation.

The Azores are a chain of still active volcanic islands. High cliffs, often over 100 m, are also common. Many of the coastal rocks are young and break down easily, so that the near-shore zone consists of shallow water with many boulders, unsuitable for shoreline wave-power devices. Further out, the water depth increases rapidly, so that deepwater devices could be sited close to the coast.

One factor favourable to shoreline wave power devices is the small tidal range (0.5–1.5 m). In a few places, hard volcanic rocks provide particularly promising sites, such as at Biscoitos on Terceira and Porto Cachorro on Pico. Since for each of the islands only a short stretch of good coast would be required to make a significant contribution to the electricity supply, the survey was concentrated on identifying such high-quality sites, rather than trying to establish the total potential resource. The survey also emphasized the north and west coasts of the islands since the predominant wave direction is close to 315°.

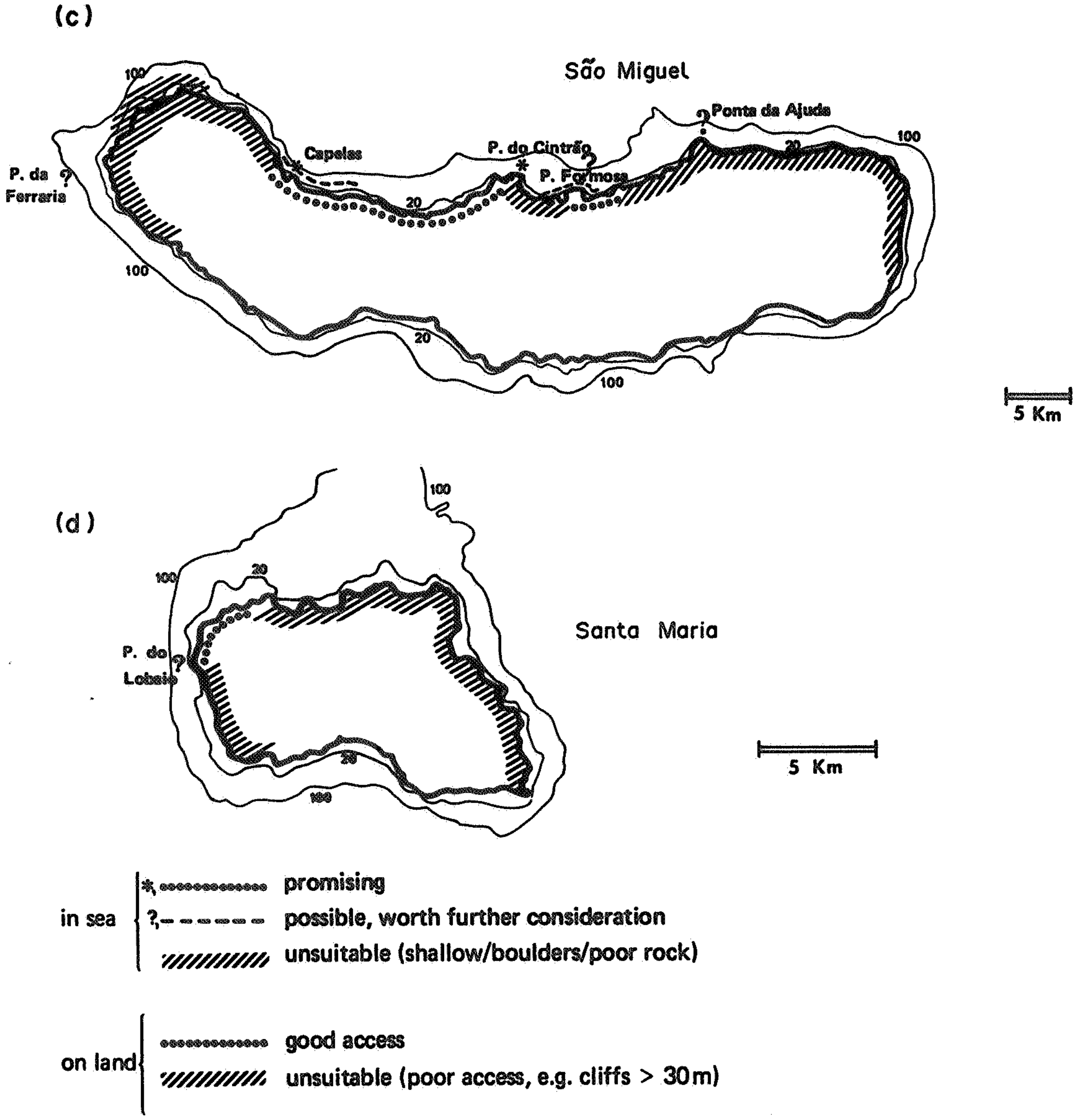

Fig. 9. Surveyed islands of the Azores archipelago. The most promising sites are identified and a broad classification of the coasts is included. Depth contours in metres are also shown.

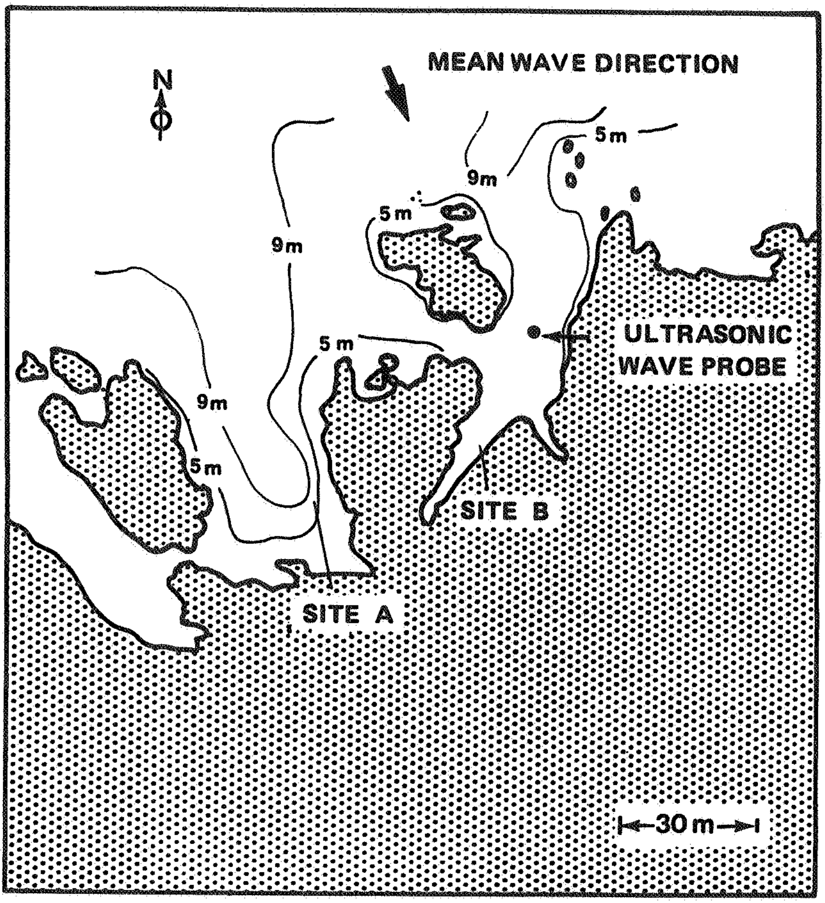

Fig. 10. Porto Cachorro on the north coast of the island of Pico in the Azores was selected for a feasibility study. It is planned to start building a power plant, rated at approximately 500 kW, in 1992.

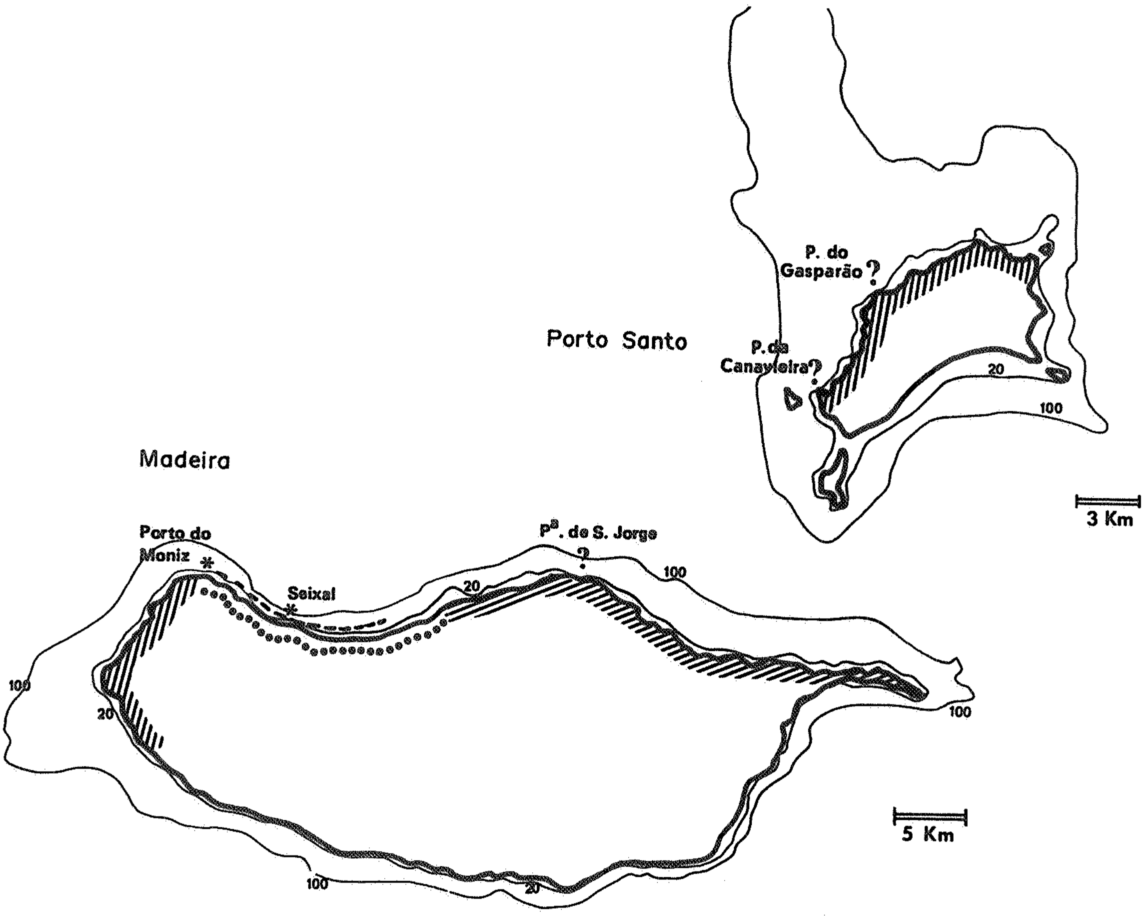

Fig. 11. Location of promising sites and broad classification of coasts for the islands of Madeira and Porto Santo. Depth contours in metres are included.

The most promising sites identified are shown in Fig. 9. The figure also broadly classifies the remainder of the coasts surveyed, so as to indicate whether they are less promising because of poor land access (usually because the cliff height is >30 m) or unfavourable shoreline conditions (poor rock, shallow water, boulders).

Perhaps the most promising of these sites is the resonant harbour at Porto Cachorro (Fig. 10), which is now the subject of a feasibility study. This site was formed in the 18th century by a lava flow from the mountain of Pico.

Madeira

Madeira is again a volcanic archipelago. On the main island, land access is virtually impossible for more than half the north coast, and again boulder-strewn shallows are common. Some interesting sites were identified near the west end of the north coast (see Fig. 11), especially a 500 m wide bay at Seixal and a site at Porto Moniz with rock similar to Biscoitos in the Azores.

The smaller island of Porto Santo is unusual in the islands in that shallow water (depths of <50 m) extends for several kilometres off the coast: the shoreline is often a low shelf, washed by waves. Both of these features are common on the continental coast (see next).

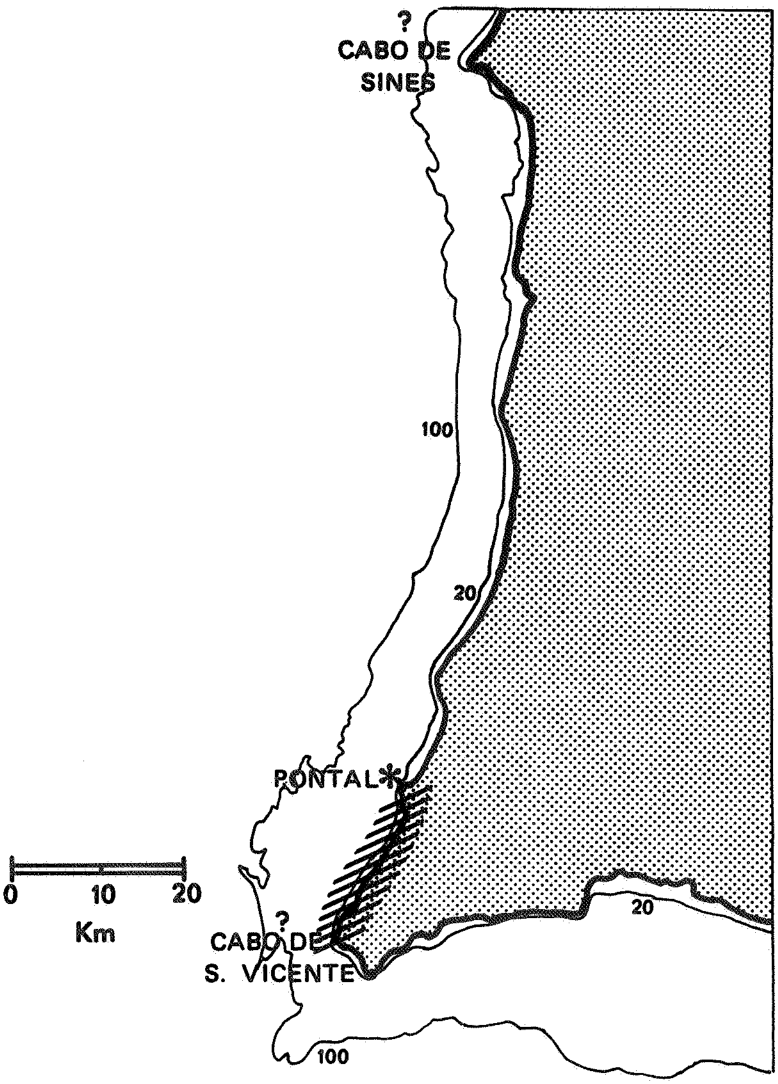

Fig. 12. Surveyed west coast of continental Portugal, south of Cabo de Sines. The best site found for wave-power utilization is at Pontal.

Continental Portugal

Much of the continental coast is unsuitable for shoreline wave-power exploitation since it consists of beaches (particularly in northern Portugal), bouldery shallows, or rock platforms stretching out into the sea at or near sea level. The latter are often associated with high cliffs; in other places, they do occasionally present formations favourable for harbour or TAPCHAN type devices.

This coast also has a greater tidal range (1.5–3 m) which presents problems for some shoreline devices. It also has an extensive continental shelf, so that there is more loss of power as the waves approach the shore.

Following examination of maps and aerial photographs, the survey was concentrated on the southern part of Portugal's west coast, from Sines to Cabo de São Vicente. As in the islands, we found a pattern of a few specific sites and long stretches of unpromising coast (see Fig. 12). The best site was at Pontal, a north facing point made of hard doleritic rock, with cliffs of 10–20 m into deep water.

Thus, while the shoreline wave resource of the islands is quite large in relation to their energy requirements, the same is not true of continental Portugal, with its much larger population and mean electricity demand of about 3 GW. However, as in the islands, there do exist a few good sites suitable for the development of prototypes and the long-term potential is at least tens, possibly hundreds, of megawatt.

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