INTERNATIONAL JOURNAL OF ENERGY RESEARCH
Int. J. Energy Res. 2007; **31**:1156–1168
Published online 29 May 2007 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/er.1326

Digital mapping of California wave energy resource

A. Beyene[1,*,†] and J. H. Wilson[2]

[1] *Department of Mechanical Engineering, San Diego State University, San Diego, CA 92182, U.S.A.*
[2] *Neptune Sciences, Inc., 4250 Pacific Highway, Suite 219, San Diego, CA 92110, U.S.A.*

SUMMARY

A collection of deepwater wave records, especially those from Coastal Information Data Program (CDIP) Data from UCSD Scripps Institute of Oceanography were assessed to create a statistical average wave data set. Then, a long-term annual average and monthly offshore wave probability distributions were created for 1° latitude bins bound by 100 and 1000 m depth contours seaward of California coast. The probability distributions were used to simulate and quantify the potential for useful energy extraction from the coastal wave of California using software, Simulating Waves Near-shore (SWAN). The method is used to map the wave energy resource for possible wave energy conversion. The results indicate that the west coast of the continental North America has energetic waves that increase northward—from as low as about 10 kW m^{-1} in the shallow waters of the south, to as high as 32 kW m^{-1} in the north. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: wave energy; renewable energy; modelling; energy conversion; California coast

1. INTRODUCTION

Ocean wave offers a highly concentrated form of renewable energy in coastal areas. The worldwide potential estimates this energy potential at about 2 TW, more than half of the currently installed worldwide electric capacity of 3.5 TW. Thirty-seven per cent of the world's population lives within 60 miles of a coastline. This fact establishes a good match between resource and demand.

Serious research in wave energy conversion is fairly recent, led by the UK, Japan, and Norway. Over the last 5 years, there has been a growing interest in wave energy conversion in North America. It is expected that wave energy conversion research will benefit from offshore technology of the oil and gas industry and also from advances in the wind energy industry.

*Correspondence to: A. Beyene, Department of Mechanical Engineering, San Diego State University, San Diego, CA 92182, U.S.A.
† E-mail: abeyene@rohan.sdsu.edu

Contract/grant sponsor: California Energy Commission

Received 15 October 2006
Accepted 9 January 2007

The technology will also surely benefit from the established knowledge of fluid mechanics and great advances made in weather forecast simulation tools. This emerging technology enjoys a considerable research support in the UK and in few other countries that have supported the establishment of small wave farms. In the US, the west coast features a high-energy wave climate and a fast dropping ocean floor, suggesting that ocean waves could be very attractive renewable energy resources.

Considerable wave energy resource analyses have been conducted abroad, much less in the USA. Thus, the most critical factor in developing WEC in California is the lack of research, knowledge base, and co-ordinated efforts to advance the technology. Lack of research support to identify successful technologies among the hundreds of proposed concepts, combined with environmental and economic concerns have put the US and California wave energy research far behind that of Europe and Asia. The European Commission has increased its generous support for WEC projects since 1992 with the start of the Joule Programs. The R&D represents a wealth of fund projects worth of over 10 million EURO. The 'Atlas of Wave Energy Resource in Europe' (1996) and the 'Exploitation of Tidal and Marine Currents' (1996) are two of the European prime contributions of the last decade. The European combined efforts also produced two outstanding pilot projects: the Pico and the Limpet plants now in operation. Furthermore, in 1999, the European Commission invited 14 wave energy representatives from various European countries to co-operate in the 'European Thematic Network on Wave Energy'. The Network was launched in 2000 and anticipated producing a report regarding the shortage of co-ordination and lack of investor confidence in WEC technologies (Thorpe, 2000). The project addresses important scientific, technical, and economic issues and will produce a variety of guidelines in the areas of standards, recommendations, software, R&D, support base, outreach, etc. R&D on WEC is also conducted in a number of countries outside Europe including Australia, Canada, China, India, Israel, Japan, Sri Lanka, Indonesia, Iran, Korea, Mexico, and Russia.

With the exception of a limited research conducted (Hagerman, 2001) to estimate wave energy resource for the west coast, little WEC research has ever been undertaken in the US, and no large WEC deployment is anticipated in the near future with the exception of a few pending projects. Government and institutional support has been modest. However, there is a large amount of data on west coast wave parameters, in some cases collected for over three decades, and abundant scientific and engineering base to initiate robust fluid and hydrodynamic models to start WEC program for the US. In this sense, the most immediate challenge to developing WEC as a renewable resource for California remains to be adopting the mathematical and engineering knowledge base for modelling, material selection, and design development.

Most energy recovery systems commonly use pneumatic or hydraulic systems. The most popular pneumatic system is the oscillating water column, using the Wells turbine in which the pneumatic pressure is converted to electricity *via* self-rectifying turbines. The turbine has low drag loss when idling, i.e. when there is no wave-induced airflow. The blades are also easy and inexpensive to manufacture.

A number of performance enhancement design measures have been suggested to the Wells turbine (Raghunathan and Beattie, 1996; Setoguchi *et al*., 1988). Some of these measures relate to geometric variables such as solidity, number of blades, or blade aerodynamics and optimum incidence angles. They may also relate to blade configurations such as using biplane and counter-rotating rotors, guide vanes, or variable pitch in monoplane turbine. Efficiencies of these configurations and design innovations to the Wells turbine have been analysed and

DOI: 10.1002/er

compared for various load ranges. System performance may greatly vary with these modifications, and the modifications greatly affect part-load performances. Peak efficiencies of these design options at an optimum flow rate range from about 0.7 to just under 0.8. However, these peak efficiencies are true for a narrow scope of the non-dimensional flow rate range, dropping significantly as the flow rate increases. Exceptions are blades with a variable pitch design, which maintain higher than 60% efficiency until the flow rate reaches about 0.5 (Curran, 2003). Modifications that may fit a certain configuration may be unfavourable to another scenario. Furthermore, such performance comparisons may suffer inherent consequences of generalizing restricted research outputs.

More recently, a new turbine has been suggested for wave and wind energy conversion (Beyene *et al.*, 2006). Numerical model and prototype wind tunnel tests have confirmed that the new turbine concept offers superior efficiency, especially at part load than the Wells turbine.

Hydraulic WEC systems tap from principles of various design solutions applicable to pumps. The most common ones with a potential of replication are centrifugal, rotary, and reciprocating types. Centrifugal devices are less likely candidates for WEC application because they require high velocity to produce high pressure. Their efficiencies also decline significantly at part load, as much as 50% drop for 50% reduction in capacity. Rotary types have relatively smooth flow which depends on speed, viscosity, and pressure difference. But leakage and slip which are common to rotary pumps, may limit their adoption to WEC devices, unless high viscosity flows can be used. The leak in reciprocating pumps is negligible and volumetric efficiencies are very high. Rotary pumps are not greatly affected by pressure variations, which should be a plus for WEC. The piston/cylinder, i.e. reciprocating types pups typically have high and constant efficiency for up to 80% drop in capacity.

Reciprocating hydraulic machines can be either the power pump type with crank or crankshaft, or direct acting type driven by differential pressure. Power pumps are used when pressure is less than 13 790 kPa (2000 psi), but direct acting pumps like plunger pumps can be used to generate much higher pressures exceeding 68 948 kPa (10 000 psi). Direct acting types have no bearing, no crankcase, or oil reservoir, i.e. less sensitive to hostile atmosphere such as that of WEC. A reciprocating device works by trapping a fixed volume liquid and discharging it at higher pressure. This is accomplished by the reciprocating motion of piston, plunger, or diaphragm which provides a fixed displacement per revolution with pressure pulsation which can be damaging to parts. Unlike centrifugal machines, it does not require high velocity to achieve high pressure, and low pumping speed means no limit on flow viscosity. The capacity depends on the speed and less on the discharge pressure—nearly the same flow rate can be handled even after significantly increasing the pressure. Overall efficiencies of reciprocating pumps range from 85 to 94%.

Like all positive displacement units, reciprocating devices require a relief valve and bypass to prevent over-pressuring the pump or the pipes. Speed is also controlled by throttling the flow, and the speed remains constant as long as the flow remains constant. This limits the overall system efficiency because it is not capable of converting all the available wave energy to useful energy.

2. MODELLING

The modelling process follows steps shown in Figure 1. In order to simulate wave energy potentials, available wave records must be summarized to establish the statistical average profile

DOI: 10.1002/er

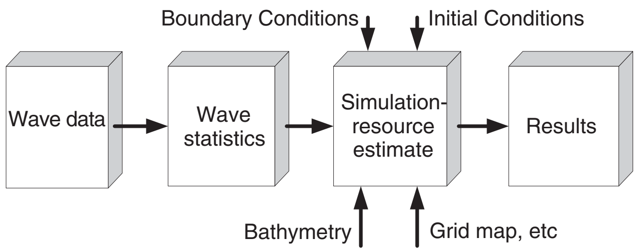

Figure 1. Simulation process of mapping wave energy resource.

of the wave parameters. For this purpose, a long-term annual average and monthly offshore wave probability distribution are created for 1° latitude bins bound by 100 and 1000 m depth contours seaward of California coast. Since buoy data are well validated, they will be used as the primary source for estimating the deep-water wave resource and the resulting energy flux density as a function of latitude, month, significant wave height, and dominant wave period. The probability distributions were used as an input to simulate and quantify the potential for useful energy extraction from the coastal wave of California. To generate the wave statistics needed to assess WEC performance inside the 100 m contour, a wave propagation model, Simulating Waves Near-shore (SWAN), was run to compute ocean wave propagation transfer functions (WPTF) from deep water to shallow water inside the 100 m contour. The deep-water wave statistics were determined outside the 100 m depth contour for ten 1° latitude cells along the California coast. This allowed a mapping of the wave energy resource for possible wave energy conversion. Only the simulation aspect of this research, without the statistical data analyses, is presented in this paper.

2.1. Swan

Coastal regions may have estuaries, tidal inlets, barrier islands, channels, underwater mountains, etc. Simulation and realistic estimates of randomly generated waves in such conditions for a given bottom topography and ambient conditions including wind and current field is needed to quantify wave energy. One such model, used to simulate near-shore wave parameters, is the SWAN software developed at Delft University of Technology, Delft, the Netherlands (Allard *et al.*). It is a third-generation, the successor of the stationary second-generation HISWA, and a stand-alone (phase-averaged) wave model for the simulation of waves in waters of deep, intermediate, and finite depth. It is also suitable for use as a wave hindcast model (Holthuijsen *et al.*, 1993; Ris, 1997). Thus, SWAN can be applied to near-shore wave modelling and wave hind-casting. SWAN simulates wave propagation in time and space accounting for shoaling, refraction due to current and depth, frequency shifting due to currents and non-stationary depth. It is also capable of simulating wave generation by wind and incorporates nonlinear wave–wave interactions, bottom friction and depth-induced breaking, and blocking of waves by current. Diffraction is not explicitly modelled in SWAN but its effects can be simulated by applying directional spreading of the waves. Reflections are also not included in SWAN. SWAN is integrated to Delft3D model in order to simulate circulation models such as wave-driven

DOI: 10.1002/er

currents and sediment transport models such as stirring by wave breaking. SWAN's superiority over other models is apparent when it is applied to cases with relatively high geographic resolution.

HISWA, predecessor of SWAN, is still widely used despite some drawbacks. In HISWA wave propagation is limited to a directional sector of less than 120°, i.e. strong refractions cannot be accommodated. Besides, the computational grid has to be orientated in the mean wave direction, which is operationally inconvenient. HISWA simulates multimodal wave fields, and the modification and addition of physical processes are very difficult. These limitations have been defeated by the new SWAN model (Holthuijsen *et al.*, 1989). The first- and second-generation models are still available because they are much simpler and more affordable than SWAN.

The SWAN model is a non-stationary third-generation wave model, i.e. it is based on an Eulerian formulation of the discrete spectral balance. It is fully spectral, therefore, valid over the total range of wave frequencies and over the entire 360°. As a non-stationary model, SWAN is based on the discrete spectral action balance equation and is fully spectral, meaning it is applicable over the entire range of wave frequencies for 360° range. This suggests that short-crested random wave fields propagating simultaneously from variable directions can be accommodated. The wave propagation is based on linear wave theory, including the effect of currents. The processes of wind generation, dissipation, and nonlinear wave–wave interactions are simulated explicitly.

The SWAN model can also be used for stationary models where such use is warranted, such as most coastal applications where the travel time of the waves from sea to the coast is small relative to the timescale of variations in incoming wave field.

SWAN provides many output quantities including two-dimensional spectra, significant wave height, mean wave period, average wave direction, directional spread, root-mean square of the orbital near-bottom motion, and wave-induced force. These parameters make it possible to estimate the wave energy potential. SWAN has been validated by comparisons with analytical solutions, laboratory, and field observations (Ris, 1997).

Two steps were employed to assess the potentials of harnessing electric energy from ocean waves off the California coast and map the wave energy resource:

- Compile a statistical database of characteristics based on buoy measurements and hindcast modelling. The database of information will include annual mean significant wave height, 20-year maximum significant wave height, and wave period. The information was compiled as a function of geographical location (using no greater than 1° increments in latitude and longitude), and by season.
- Estimate the energy potentially available from ocean waves.

The deep-water wave statistics off the California coast were divided into ten 1° latitude by the east–west area between the 100 and 200 m depth contours. SWAN was run to predict WPTFs from these 10 areas to grid points within the 100 m depth contour. These WPTFs do not depend on the measured deep-water monthly wave statistics in the 10 areas in any wave. The WPTFs are estimated using SWAN by propagating the wave tri-statistics from deep water to grid points spaced 5 km apart within the 100 m contour. The actual wave tri-statistics are then multiplied by the WPTF for a defined California bathymetry. The reconstructed wave statistics within the 100 m contour are used to assess potential WEC performance at various sites.

The wave tri-statistics in deep water west of the 100 m depth contour and east of the 1000 m depth contour are spatially homogeneous for the two California regions defined as north and south (Wilson *et al.*, in press).

SOCAL—California coast south of Point Conception covering two 1° latitude regional boxes with (Figure 2):

- San Diego County (32.5–33.5°N);
- Orange, Los Angeles, Ventura, and Southern Santa Barbara counties (33.5–34.5°N).

NORMIDCAL—California coast north of Point Conception covering eight 1° latitude boxes with:

- northern Santa Barbara and southern San Luis Obispo counties (34.5–35.5°N);
- northern San Luis Obispo and southern Monterey counties (35.5–36.5°N);
- northern Monterey and southern San Mateo counties (36.5–37.5°N);
- northern San Mateo, San Francisco, Marin and southern Sonoma counties (37.5–38.5°N);
- northern Sonoma and southern Mendocino counties (38.5–39.5°N);
- northern Mendocino and southern Humboldt counties (39.5–40.5°N);
- northern Humboldt county (40.5–41.5°N);
- Del Norte county (41.5–42°N).

The modelling process involved three distinct phases:

I Separate the 'deep-water' wave tri-statistics into:

- ten 1° latitude cells;
- twelve monthly cells;
- three year groups: 1950–2002, 1993–2002, 1950–1993;
- thirteen significant wave height bins;

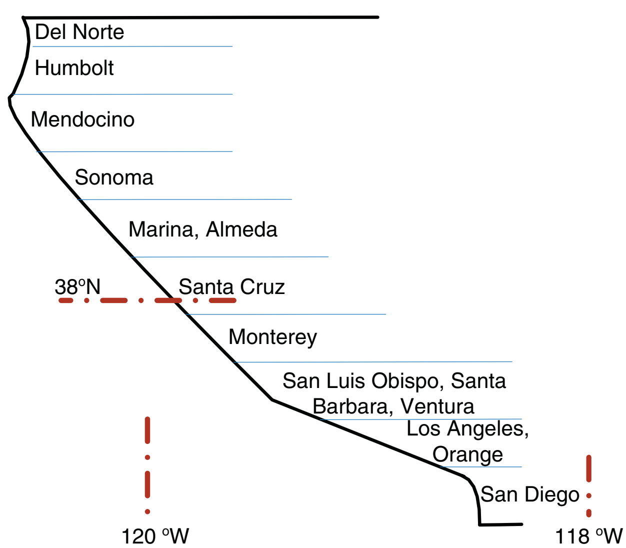

Figure 2. Ten 1° latitude cells used in the California Wave Resource Study.

- nine dominant wave period bins; and
- seven wave direction bins.

II Develop WPTFs using the SWAN model to propagate each wave tri-statistic bin with unit amplitude from deep water into shallow water grid points spaced 5 km apart within the 100 m depth contour where the probable WEC sites are located. This phase does not depend on the measured wave tri-statistics from Phase I.

III Multiply the SWAN-generated WPTFs from Phase II by the wave tri-statistics from Phase I for the same 1° latitude cell, for the same year group, and for each of the $13 \times 8 \times 8 = 832$ deep water tri-statistic cells. Note that there is one WPTF for each grid point for all the above combinations.

The Phase I wave tri-statistics bins are:

- Every 0.5 m in significant wave height with the first bin containing all wave observations with significant wave heights less than 0.5 m and the last bin being all waves with significant wave heights greater than or equal to 11 m.
- Every 2 s in dominant wave period with the first bin containing all observations less than 4.5 s and the ninth bin containing all observations greater than or equal to 22 s.
- True bearing bins—waves from seven directions.

The development of WPTFs using SWAN in Phase II is complex. The WPTFs are independent of measured wave tri-statistics and depend only on ocean wave propagation factors, such as bathymetry and bottom sediment type, and need to be calculated only once. SOCAL and NORMIDCAL SWAN initialization boxes were used for the two sets of model runs made. SWAN was run with a single uniform tri-statistic bin until steady-state conditions were achieved within the 100 m contour. Then the tri-statistics generated at the grid points within the 100 m contour by SWAN. These shallow water tri-statistics are then stored in a database, and another SWAN run with a different tri-statistics bin is commenced. For example, the first SWAN run may be for (significant wave height, period, direction) = (1.0 m, 8 s, W) and the second for (2.0 m, 8 s, W). By the time the ocean wave tri-statistics bin is propagated from deep water into shallow water within the 100 m contour its significant wave height may have changed from 1.0 m in deep water to 0.5 m at a specific shallow water grid point and its direction may have changed from W in deep water to NW at that specific shallow water grid point. Furthermore, the wave tri-statistics may vary from grid point to grid point in shallow water from the same wave tri-statistics bin in deep water. The wave conditions just south of Dana Point are much more mild than the wave conditions just north of Dana Point for W or NW swells due to the sheltering effect of Dana Point headlands. The SWAN model is initialized by wave spectra (not the wave tri-statistics themselves) and a spectral fit to the wave tri-statistics, called the modified Pierson–Moskowitz (MP–M) fit. The SWAN model offers spatial distribution of swell including a wave height prediction for a specified coastal zone (Figures 3 and 4).

2.2. *Wave energy resource*

An integrated estimate of the wave resource within the 100 to 1000 m depth contours in all ten 1° latitude cells along California's coast can be made from the long-term monthly time series of significant wave height. Only buoy data in a depth of greater than 100 m will be used in the deep-water wave statistics. The northern cell 10 has no buoy measurements between depths of 100

DOI: 10.1002/er

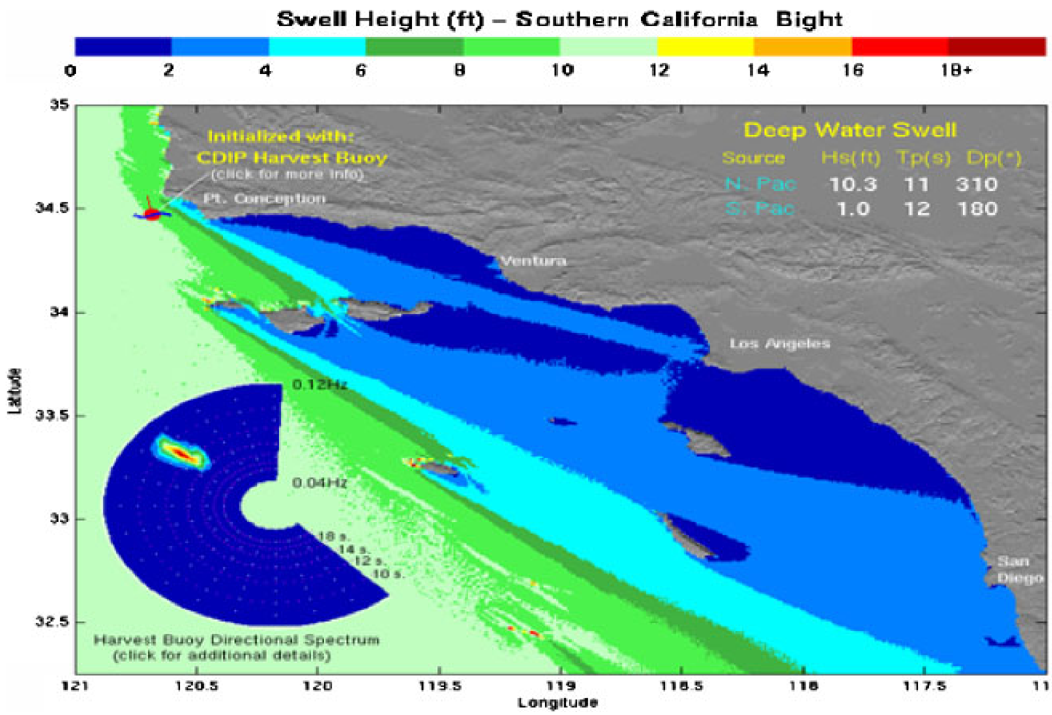

Figure 3. The spatial distribution of swell in SOCAL showing the blockage of outer islands [http://cdip.ucsd.edu/?nav = recent&sub = nowcast&xitem = socal_now].

and 1000 m. Some buoy data were processed even if their depth was less than 100 m in order to estimate the dissipation of wave energy by bottom friction loss as the depth decreases shoreward. No upper depth limit need be made since the wave statistics in deep water are spatially homogeneous. Data from buoys with depths greater than 100 m will be used as the statistical database for deep water.

The maximum significant wave height is a vital wave parameter that has a serious economic and safety impact; waves can be large enough to snap the moorings or destroy the WEC installed. Since it only takes one rogue wave to do the damage WEC designers must take the maximum wave statistics into account in system and site selection. Thus, the time-series data show that 14–16 m waves are possible every few years, especially north of Point Conception, and this must be considered, in WEC site selection.

Most oceanographers assume the wave energy loss occurs slowly as the depth decreases from 100 m to just outside the surf zone, and that it takes a wide, shallow continental shelf like the one seaward of the eastern United States coastline. Furthermore, recent measurements over the eastern US continental shelf indicate that the large waves lose the most energy. An empirical approach first taken in this report where shallow water NDBC and CDIP buoy measurements over many years are compared to the long-term annual average deep-water energy flux densities and significant wave height just estimated for each 1° latitude cell north of Point Conception. Then the loss in energy flux density is plotted *versus* depth to empirical establish a rule of thumb for California's coast north of Point Conception.

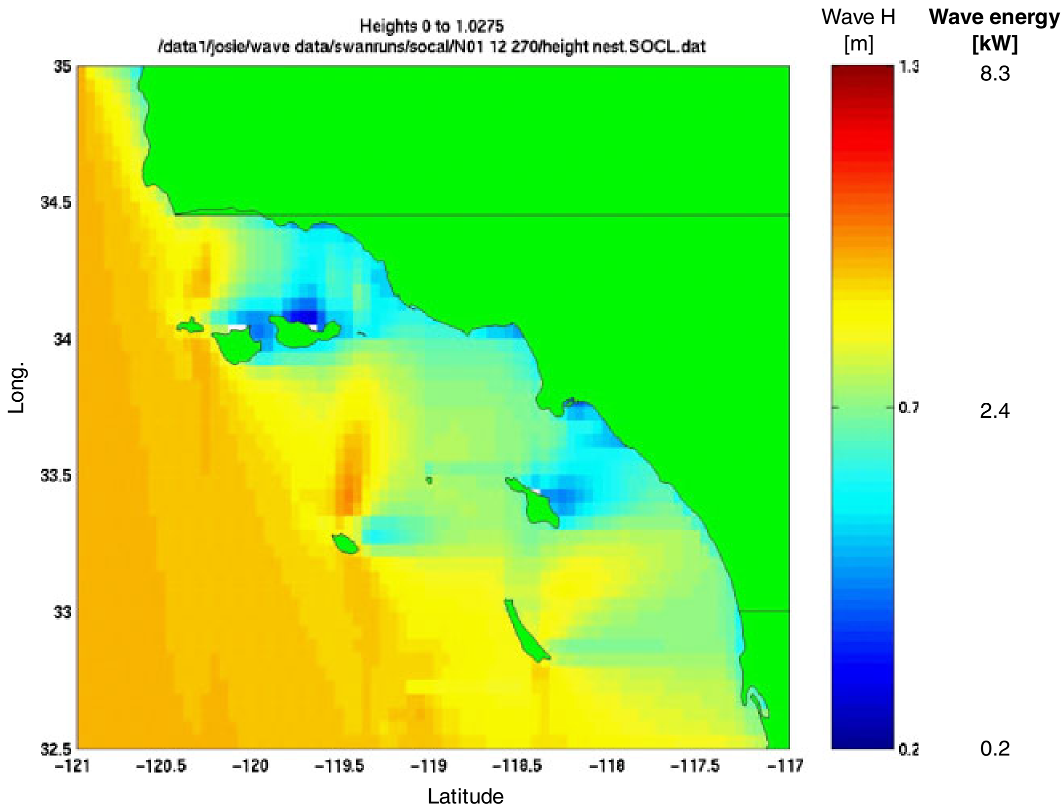

Figure 4. SWAN wave height prediction and wave energy results for SOCAL for initial Pierson–Moskowitz wave field representing a period of 12 s—direction from the west, with superimposed energy estimates.

A second approach is to run the SWAN model to calculate the WPTFs east of the 100 m depth contour to provide an independent estimate of the wave energy loss. The result is that more wave energy is lost (as empirically determined from buoy measurements) than expected from oceanography models like SWAN. This dissipation is measured north of Point Conception where grid-connected applications are expected soon. The fact that energy flux density is proportional to significant wave height squared can cause large losses in energy flux density. For example, if significant wave height decreases shoreward from 3 m at the 100 m depth contour to 2 m at the 60 m contour, over half of the energy flux density is lost.

3. RESULTS

Neptune Sciences, Inc. (NSI) has developed a product called the shallow water ocean-wave propagation (SWOP) model in which SWAN is initialized with the MP–M wave spectra in deep water and SWAN is used to determine the wave transfer propagation functions (WTPFs) at every grid point selected from the 100 m depth contour to the surf zone. A 5 km grid was chosen for this analysis, but a finer grid could be chosen for site-specific WEC applications, if desired. NSI performed over 16 000 SWOP runs using SWAN to determine the WTPFs. The WTPFs do not depend on wave statistics, only on the propagation environment. In this section, typical wave tri-statistics (significant wave height, h_s; dominant wave period, T_p; and wave direction, $^\circ$) based on the results of the previous section are applied to the WTPFs to estimate the loss of wave energy due to bottom friction loss and wave refraction in shallow water.

The effect of island blocking is very clearly shown and one may not consider the reduction in significant wave height, h_s, from 1 m in deep water to 0.5 m and below in near-coastal areas as a significant decrease, but energy flux density depends on h_s^2. Thus, if WECs are to be sited east of the islands in SOCAL, over half of the energy flux density is lost due to bottom friction.

The shallow water wave propagation towards the coast does not change wave period significantly outside the surf zone, but wave direction changes from 270° (west) in deep water to approximately 230° (southwest) near-shore due to refraction and the SOCAL coast orientation to the southwest. Wave refraction changes the wave direction in shallow water so the wave direction generally is $\pm 15^\circ$ from being perpendicular to shore. One would rarely see waves making large angles with the shoreline.

There is no island blockage in NOCAL, but the effect of California's NOCAL coastline north of Point Conception not being a perfectly west-facing coast is seen clearly. The waves in deep water are travelling west and encounter the California coast south of Eureka first since that is the western most point in the state. From Eureka south to Point Conception the coast orientation is approximately west–southwest, and the west travelling deep-water waves start to refract to the west–southwest as they 'feel' the bottom and more wave energy is lost in the NOCAL region south of Eureka to Point Conception. The loss in h_s from 2.0 to 1.8 m near typical WEC sites in NOCAL south of Eureka illustrates why the long-term average annual energy flux density slightly decreases from 27 kW m^{-1} in latitude near Humbolt to 21 kW m^{-1} in latitude near Point Conception. The reduction in energy flux density from Eureka to Point Conception, assuming E (kW m^{-1}) in Eureka's near-shore is 27 kW m^{-1}, is given by

$$E_{(\text{Pt Conception})} = \left(\tfrac{1.8}{2}\right)^2 \times E_{(\text{Eureka})} = 21.87 \text{ kW m}^{-1} \quad (1)$$

which is very close to the long-term average annual energy flux density near Point Conception determined from years of wave statistics in the previous sections. The above calculation assumes that dominant wave period remains fairly constant as the waves propagate into shallow water and this is a reasonable assumption based on measured data. Similar results were obtained from SWOP runs for larger storms with $h_s = 4$ m and above.

It can be concluded from the SWOP runs that:

- The blockage of Point Conception and the outer islands has a very significant impact in reducing energy flux density in SOCAL east of the outer islands from storms from the west and northwest.
- Cape Mendocino south of Eureka has a moderate impact in reducing energy flux density slightly in NOCAL south of Eureka to Point Conception due to storms from the west and northwest.

The wave statistics in deep water off the California shore are generally spatially homogeneous within two parts of California: north and south of Point Conception. North of Point Conception the annual average significant wave heights are higher with somewhat shorter wave

DOI: 10.1002/er

periods than the deep-water waves south of Point Conception. The wave direction north of Point Conception shifts from west in the winter to northwest and west in the summer, while the waves south of Point Conception shift from west in the winter to south/southwest in summer. Higher annual average significant wave heights, longer, dominant wave periods, and more unidirectional waves throughout the year, generally result in better WEC performance. Also, absence of extreme waves with peak to trough wave heights of 15 m or greater will reduce the probability of significant damage or destruction of the WEC installation by powerful waves.

The energy flux density E, is calculated in terms of the significant wave height, h_s, and dominant (T_p) or average (T_z) wave periods from the well-established equation (Nielsen, 2002; Hagerman, 2001)

$$E(\text{kW m}^{-1}) = 0.577 h_s^2 T_z = 0.412 h_s^2 T_p \tag{2}$$

where $T_p = 1.4\,T_z$. This energy flux density does not consider the 'capacity factor' of individual WEC types, so that the actual electricity realized ashore will be reduced by the WEC system capacity factor. A 'rule of thumb' states that an average energy flux density, E (kW m^{-1}) of 20 kW m^{-1} or greater is desired to make WECs commercially viable in the near term, but low seasonal variability allows WECs to perform commercially for energy fluxes from 10 to 20 kW m^{-1}.

3.1. Mapping

There is over 1200 miles of useable coastline along California, and the combined electricity generation of the primary and deep offshore sites is over 37 000 MW (Wilson and Beyene, in press). The electricity generation potential of only the deep near-shore sites is approximately 22 000 MW. Table I provides a linear breakdown of the deep near-shore and deep offshore wave energy resources along the ten 1° latitude cells.

Table I. California's wave energy resources along ten 1° latitude cells, based on statistical data (Beyene and Wilson, 2003).

		Deep near-shore		Deep offshore	
Landmark	Density (kW m^{-1})	Length (km)	Power (MW)	Length (km)	Power (MW)
San Diego	32.18			162	5213
Los Angeles	32.18	35	1126	104	3347
Santa Barbara	26.43	127	3357		
Monterey	29.65			127	3766
Santa Cruz	28.03	None		127	2838
San Francisco	30.26	104	3147	18	545
Sonoma	32.18	127	4087		
Mendocino	28.53	130	3709		
Humboldt	33.71	116	3910	None	
Del Norte	27.81	81	2253		
Total		720	21 589	538	15 709

4. CONCLUSION

The top three NORMIDCAL sites with WEC potential, with a caveat that many superior sites may exist and that the best ones will not be known until detailed WEC installation project summaries are completed, would be:

- Point Sur SOSUS facility 32.2 km (20 miles) south of Carmel/Monterey;
- Eureka—Superior in all respects with unknowns related to the environment;
- Point Arguello—LOMPOC and Vandenberg with AFB nearby.

For SOCAL, the superior sites are the outer islands and sites that are west of the blockage of Point Conception. WEC grid-connected applications are valid especially if highly efficient systems are developed for relatively low-wave resource. In summary:

- California's wave resource north of Point Conception averages 25 $\mathrm{kW\,m^{-1}}$ and emerging commercial grid-connected WEC farms can compete with other forms of electricity generation.
- California south of Point Conception has lower but seasonally stable wave resource, and with integrated approach could offer good part-load performance and should not be eliminated from consideration for grid-connected applications. California's continental shelf falls off rapidly and the ideal commercial WEC sites will be the ones north of Point Conception closes to shore. For example, Eureka and Big Sur are ideal sites while the near-shore west of San Francisco Bay remains relatively shallow as one proceeds westward.
- WEC site placement in deep water near the 90 m depth contour is recommended due to wave bottom friction losses in shallower water. It is speculated that California's long-term average energy flux density of 26 $\mathrm{kW\,m^{-1}}$ is needed to maximize WEC capacity factors in the 30–40% range. If WECs are sites in the shallow contour, the diminished energy flux density may greatly reduce WEC capacity factors since most emerging commercial WECs are designed for optimum performance in wave resources with energy flux densities greater than 25 $\mathrm{kW\,m^{-1}}$ of ocean wave front.
- WEC in the US in general, and California in particular can be considered to be a commercially competitive technology requiring more research support and recognition as a renewable source to exhibit innovative technical advances that attract successful market penetration.

ACKNOWLEDGEMENTS

We gladly acknowledge that the research that led to the production of this paper was supported and funded by California Energy Commission. Dr Marshall Earle of NSI, Ms Josie Fabre, and Mr Dean Wakeham, have all made valuable contributions.

REFERENCES

Allard R, Rogers E, Carroll SN, Rushing KV. 2006. Naval Research Lab Stennis Space Center MS. Software design description for the simulating waves nearshore model (SWAN), http://www.stormingmedia.us/77/7719/A771904.html, accessed on 26 March 2006.

Beyene A, Mangalekar D, Miller R, Alexander S, Villegas S. 2006. A new turbine concept. *Oceans '06 Asia Pacific IEEE*, Singapore.

Beyene A, Wilson HJ. 2003. California wave energy resource evaluation. *California Energy Commission*.

Curran R. 2003. Productivity of ocean-wave-energy converters: turbine design. *Journal of Energy Engineering* **August**: 13–31.

Hagerman G. 2001. Southern England wave energy resource potential. *Building Energy 2001*. New England Sustainable Energy Association: Boston, MA.

Holthuijsen LH, Booij N, Herbers THC. 1989. A prediction model for stationary, short-crested waves in shallow water with ambient currents. *Coastal Engineering* **13**:23–54.

Holthuijsen LH, Booij N, Ris RC. 1993. A spectral wave model for the coastal zone. *Proceedings of 2nd International Symposium on Ocean Wave Measurement and Analysis*, New Orleans, U.S.A., 630–641.

Nielsen K. 2002. Development of recommended practices for testing and evaluating ocean energy systems. *International Energy Agency Technical Report*, ANNEX II.

Raghunathan S, Beattie CW. 1996. Aerodynamic performance of counter-rotating wells turbine for wave energy conversion. *Journal of Power Energy* **210**:431–447.

Ris RC. 1997. Spectral modelling of wind waves in coastal areas (*Ph.D. Dissertation*, Delft University of Technology, Department of Civil Engineering), Communications on Hydraulic and Geotechnical Engineering. *Report No. 97-4*, Delft, The Netherlands.

Setoguchi T, Kaneko K, Matsuki E, Hamakawa H, Inoue M. 1988. Some techniques to improve the performance of the biplane wells turbine for wave power generator. *Proceedings of First Pacific Asia Offshore Mechanical Symposium*, Lupertino, California, vol. 1. International Society of Offshore and Polar Engineers: Lupertino, CA.

Thorpe TW. 2000. Wave energy for the 21st century. *Renewable Energy World*, 7/8.

Wilson HJ, Beyene A. California wave energy resource evaluation. *Journal of Coastal Research*, in press.

DOI: 10.1002/er