INTEGRATION OF WAVE AND WIND ENERGY OFF THE CALIFORNIA COAST

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DEDICATION

I would like to dedicate this to my parents and grandparents. Without them, none of this would have been possible.
ABSTRACT OF THE THESIS

Integration of Wave and Wind Energy Off the California Coast
by
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There is a rising need to produce electricity from renewable energy sources. Wave and offshore wind energy are two such sources that can greatly contribute to the energy portfolio of the United States. Offshore wave and wind energy conversion is especially advantageous for coastal states with high electricity charges such as California. This study inspects the combined wave and wind energy potential off the California coast for three varying scenarios in order to provide time dependent energy resource calculations and simulations. This is accomplished by dividing the California coast into 10 cells and using a wave modeling software named SWAN which necessitates the user to input wave boundary condition, wind boundary conditions and bathymetric data. Once ran, each of the 10 cells had a representative integrated energy density for every month of all three years culminating in a location which would be ideal for an integrated platform. An integrated platform design with a rated capacity of 584 kW was proposed. Such a platform would produce 4,524,339 kWh/yr and have a capital cost of $5,261,481.
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# NOMENCLATURE

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<tbody>
<tr>
<td>A</td>
<td>Cross-sectional area</td>
</tr>
<tr>
<td>a</td>
<td>Wave amplitude</td>
</tr>
<tr>
<td>ai</td>
<td>Amplitude of ith wave</td>
</tr>
<tr>
<td>C</td>
<td>Scale parameter</td>
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<tr>
<td>cg</td>
<td>Group velocity</td>
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<tr>
<td>Cp</td>
<td>Power coefficient</td>
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<tr>
<td>Cp,eq</td>
<td>Constant equivalent power coefficient</td>
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<tr>
<td>Cp,max</td>
<td>Maximum power coefficient</td>
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<tr>
<td>cx</td>
<td>Propagation velocity in x space</td>
</tr>
<tr>
<td>cy</td>
<td>Propagation velocity in y space</td>
</tr>
<tr>
<td>cΘ</td>
<td>Propagation velocity in Θ space</td>
</tr>
<tr>
<td>cσ</td>
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</tr>
<tr>
<td>E</td>
<td>Energy density</td>
</tr>
<tr>
<td>E(σ)</td>
<td>Energy density spectrum</td>
</tr>
<tr>
<td>E(σ,Θ)</td>
<td>Wave energy density</td>
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<tr>
<td>Ec</td>
<td>Kinetic energy</td>
</tr>
<tr>
<td>Etot</td>
<td>Total energy</td>
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<tr>
<td>g</td>
<td>Acceleration due to gravity</td>
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<tr>
<td>h</td>
<td>Water depth</td>
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<tr>
<td>Hs</td>
<td>Wave height</td>
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<tr>
<td>hrs</td>
<td>Hours</td>
</tr>
<tr>
<td>J</td>
<td>Wave power</td>
</tr>
<tr>
<td>k</td>
<td>Dimensionless shape parameter due to ground topology</td>
</tr>
<tr>
<td>K</td>
<td>Wave number</td>
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<tr>
<td>k→</td>
<td>Wave number vector</td>
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<tr>
<td>km</td>
<td>Kilometer</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt-hour</td>
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<tr>
<td>l</td>
<td>Wave length</td>
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<td>Meter</td>
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</table>
M Mass
m/s Meters/second
m0 0th moment of sea surface variation
mn Variance of sea surface elevation
MW Megawatt
n Number of directional bins
N Action density
P Wave power density
p(U) Probability density function
p(v) Power generated
Pavailable Available power
R Radius
r Co-ordinate perpendicular to s
s Seconds
S Source and Sink
s Co-ordinate in wave propagation direction of Θ
s(f) Non-directional wave spectrum
TW Terawatt
t Time
Tp Wave period
TWh/yr Terawatt hours per year
U Time series of wind speeds observations
V0 Known velocity
V1 Air velocity
Vi Velocity at desired height
x Geographic space x
y Geographic space y
yr year
Z0 Known height
Zi Desired height
α Ground coefficients
αi Phase of the ith wave
<table>
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<tr>
<td>$\beta$</td>
<td>Blade pitch</td>
</tr>
<tr>
<td>$\Delta E$</td>
<td>Wave energy flux loss</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Elevation of sea surface</td>
</tr>
<tr>
<td>$\Theta$</td>
<td>Wave direction</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Tip speed ratio</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Wave frequency</td>
</tr>
<tr>
<td>$\sigma_i$</td>
<td>Circular frequency of $i$th wave</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Time lag</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Rotational velocity</td>
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## LIST OF ABBREVIATIONS

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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AWP</td>
<td>Average Available Wind Power</td>
</tr>
<tr>
<td>CC</td>
<td>Capital Cost</td>
</tr>
<tr>
<td>CDIP</td>
<td>Coastal Information Data Program</td>
</tr>
<tr>
<td>CIP</td>
<td>Cost of an Integrated Platform</td>
</tr>
<tr>
<td>CR</td>
<td>Cost Reduction percentage of an Integrated Platform</td>
</tr>
<tr>
<td>CRM</td>
<td>Coastal Relief Model</td>
</tr>
<tr>
<td>DOE</td>
<td>Department Of Energy</td>
</tr>
<tr>
<td>EffA</td>
<td>Efficiency of Wind Conversion Device</td>
</tr>
<tr>
<td>EffW</td>
<td>Efficiency of Wave Conversion Device</td>
</tr>
<tr>
<td>ES</td>
<td>Electricity to Reach Shore</td>
</tr>
<tr>
<td>HAWT</td>
<td>Horizontal Axis Wind Turbine</td>
</tr>
<tr>
<td>I</td>
<td>Incentives from SGIP</td>
</tr>
<tr>
<td>ICWEC</td>
<td>Individual Cost of WEC Device</td>
</tr>
<tr>
<td>ICWT</td>
<td>Individual Cost of Wind Turbine</td>
</tr>
<tr>
<td>LAS</td>
<td>Live Access Server</td>
</tr>
<tr>
<td>LC</td>
<td>Length of Wave Conversion Device</td>
</tr>
<tr>
<td>MI</td>
<td>Miles From Shore</td>
</tr>
<tr>
<td>MOC</td>
<td>Max Operating Condition</td>
</tr>
<tr>
<td>NCC</td>
<td>New Capital Cost, Incentive Based</td>
</tr>
<tr>
<td>NDBC</td>
<td>National Data Buoy Center</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>NOMADS</td>
<td>National Operational Model Archive and Distribution System</td>
</tr>
<tr>
<td>NPP</td>
<td>New Simple Payback Period, Incentive Based</td>
</tr>
<tr>
<td>OHF</td>
<td>Wave Device Time of Operating at Full Capacity</td>
</tr>
<tr>
<td>OHFW</td>
<td>Wind Turbine Time of Operating at Full Capacity</td>
</tr>
<tr>
<td>OHP</td>
<td>Wave Device Time of Operating at Part Capacity</td>
</tr>
<tr>
<td>OHPW</td>
<td>Wind Turbine Time of Operating at Part Capacity</td>
</tr>
<tr>
<td>PTC</td>
<td>Renewable Electricity Program Tax Credit</td>
</tr>
<tr>
<td>PWC</td>
<td>Rated Wave Capacity</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
<td>--------------------------------------------------</td>
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<tr>
<td>PWTC</td>
<td>Partial Wind Turbine Capture</td>
</tr>
<tr>
<td>RF</td>
<td>Capacity Reduction Factor</td>
</tr>
<tr>
<td>ROC</td>
<td>Rated Operating Condition</td>
</tr>
<tr>
<td>ROMS</td>
<td>Regional Ocean Modeling System</td>
</tr>
<tr>
<td>RP</td>
<td>Retail Price</td>
</tr>
<tr>
<td>SGIP</td>
<td>Self-Generation Incentive Program</td>
</tr>
<tr>
<td>SPP</td>
<td>Simple Payback Period</td>
</tr>
<tr>
<td>SWAN</td>
<td>Simulating Waves Nearshore</td>
</tr>
<tr>
<td>TC</td>
<td>Tax Credit from PTC</td>
</tr>
<tr>
<td>TCC</td>
<td>Total Capital Cost</td>
</tr>
<tr>
<td>TCP</td>
<td>Total Capacity of Platform</td>
</tr>
<tr>
<td>TCTP</td>
<td>Total Cost of Two Platforms</td>
</tr>
<tr>
<td>TE</td>
<td>Total Earnings</td>
</tr>
<tr>
<td>TEP</td>
<td>Total Electrical Produced</td>
</tr>
<tr>
<td>TL</td>
<td>Transmission Loss</td>
</tr>
<tr>
<td>TLC</td>
<td>Transmission Line Cost</td>
</tr>
<tr>
<td>TOC</td>
<td>Threshold Operating Condition</td>
</tr>
<tr>
<td>TSR</td>
<td>Tip Speed Ratio</td>
</tr>
<tr>
<td>TWTC</td>
<td>Total Wind Turbine Capacity</td>
</tr>
<tr>
<td>U.S.</td>
<td>United States of America</td>
</tr>
<tr>
<td>USACE</td>
<td>United States Army Corps of Engineers</td>
</tr>
<tr>
<td>VAWT</td>
<td>Vertical Axis Wind Turbine</td>
</tr>
<tr>
<td>WAEP</td>
<td>Wave Platform Energy Production</td>
</tr>
<tr>
<td>WAPC</td>
<td>Wave Platform Cost</td>
</tr>
<tr>
<td>WC</td>
<td>Wave Capacity</td>
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<td>WIS</td>
<td>Wave Information Study</td>
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<td>WTC</td>
<td>Rated Wind Turbine Capacity</td>
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ACKNOWLEDGEMENTS

I would like to acknowledge my parents and grandparents who helped me get through college, my advisor Dr. Beyene who pointed me in the right direction, Brian Stiber who took the time to teach me what he knows and everyone else who helped me along the way.
CHAPTER 1

INTRODUCTION

In 2011, the United States (U.S.) used fossil fuels for roughly 82% of the nation’s energy while only 9% came from renewable sources [1]. The contribution of renewable energy has steadily increased over the past 10 years, increasing from 2% to approximately 14% of the total energy used by the nation [2]. Figure 1.1 [1] shows the main sources of energy that the U.S. used to meet demand in the year 2011 [1].

![Energy Source Pie Chart]

Figure 1.1. Energy used by source. Source: Center for Sustainable Systems. U.S. Renewable Energy Factsheet. MI: University of Michigan, Pub No CSS03-12, 2012.

The reevaluation of energy dependency at a policy level, as well as the contribution of fossil fuels to climate change have led to the passing of several legislations in the U.S. to facilitate larger share of renewable energy. A case in point is California’s Senate Bill 107, expanded in 2011 under Senate Bill 2, known as California's Renewables Portfolio Standard (RPS), which mandates that 33% of the state’s energy supply come from renewable energy
by 2020 [3]. States such as Arizona, Colorado, Hawaii, Connecticut, and Delaware have passed similar legislations [3].

At the Federal level, the New Energy for America initiative mandates 25% of the nation’s electricity comes from renewable sources by 2025 [4]. Thus, there is a growing legislative pressure and desire to significantly increase the U.S. contribution of renewable resources to the energy supply, and the drive at the global level is nearly as robust, at least in the industrialized world. Wind and wave energy are two renewable sources that can help accomplish this goal.

Wind and wave can be considered to be two of the growing renewable energy resources expected to match the rising global demand for power. The formation of wind is a result of different regions on earth receiving uneven amounts of solar radiation, thus some regions become warmer than the rest. These warm territories create a low pressure zone while the colder areas create a high pressure zone. This pressure gradient leads to the creation of the global winds and the severity of the gradient determines the wind velocity. On a global scale, the rotation of the earth combined with gravitational forces imposes a fairly structured and defined vector of the wind and wave energy distributions. Combining this with the Coriolis effect - caused by the earth’s rotation - results in wind that is moving north, to curve east and wind that is moving south, to curve west. Local winds are also created by pressure differences but these pressure variations are primarily caused by the inconsistencies in material absorptivity coefficients as opposed to the amount of incident radiation a surface receives. A visual representation of the creation of local wind can be seen in Figure 1.2 [5].

A consistently overlooked portion of the renewable energy resource is the offshore potential of wind. There is more than 4 TW of wind energy available surrounding the U.S. and of that 2.5 TW is over water deeper than 60 meters [6]. Offshore wind tends to have a higher velocity and flows more uniformly than on land. When the wind turbine is constructed offshore there is an increase in generation due to a higher wind resource and steadier operation due to low turbulence levels [7].

With the proper conditions, wind has the ability to form waves in the ocean. As wind travels over the ocean it encounters surface friction, leading to the creation of ripples. The
ripples combine to form larger waves with more energy and are known as wind waves. Wind waves lose energy once they have traveled away from the original source of disturbance, unless enough underlying energy is present to turn the wind wave into a swell. The wind wave will transition into a swell once a period equal to 15 seconds or greater has been attained [8]. If there is not enough energy the wind wave will dissipate due to the surface tension of the calm water. However, if there is enough energy to form a swell, the swell can travel far distances with very little energy dissipation.

There are three main factors affecting the amount of energy transferred to the ocean from the wind: the wind velocity, the ocean surface area that the wind interacts with, also known as the fetch, and the amount of time or duration that the wind interacts with the ocean, Figure 1.3 [8]. The surface of the ripples will continue to receive energy from the wind until the wave is out of the fetch or is traveling faster than the wind. Each swell receives a different amount of energy. Swells with similar amounts of energy will form a group and travel together. Once the energy of the newly joined swell is distributed throughout the group, the wave becomes bound. In general, a group is structured with the smaller waves in front and rear with the largest waves in the middle [9].

The wave energy resource of the U.S. coast is estimated to be at 2,600 TWh/yr and with current devices approximately 1,100 TWh/yr is recoverable [10]. However, most of this wave energy potential is located in depths or distances that are unreachable by current technology.
Offshore winds and waves have the potential to greatly contribute to the U.S.’s renewable energy portfolio [1]. However, some concerns have been expressed due to the fact that the energy contained in either source fluctuates to a high degree which means that the grid is unable to fully rely upon them [7]. The cost of converting offshore energy is also a point of concern since the cost of construction and maintenance is increased since this must take place in the ocean where weather can be vile and safety is difficult to insure [7].

Some of these concerns are reduced if not alleviated with the idea of integrating the conversion of offshore wave and wind energy onto one structure. This will not only reduce the overall cost but is also expected to generate more electricity for the grid [7].
CHAPTER 2

WIND AND WAVE ENERGY

The escalating global demand for power can in part be satisfied by two of the growing renewable energy resources: wind and wave.

2.1 WIND ENERGY

Wind energy has been converted to do useful work since 5000 B.C. where boats on the Nile River captured it in their sails [11]. Wind was converted into electricity by James Blyth who built the first wind turbine, powering a local house in 1887 [12]. The amount of work converted depends on the kinetic energy of the wind and can be approximated by [13]:

\[ E_c = \frac{1}{2} * M * V_1^2 \]  \hspace{1cm} (2.1)

where \( E_c \) is the kinetic energy, \( M \) is the air mass and \( V_1 \) is the air velocity. With this, the available specific power equation can be derived [13]:

\[ P_{\text{available}} = \frac{1}{2} * \rho * A * V_1^3 \]  \hspace{1cm} (2.2)

where \( \rho \) is the air density and \( A \) is the cross-sectional area of air under consideration, mainly the swept area of the blades. The power output of a given turbine varies with the cube of the wind velocity, thus, even a small increase in wind speed makes a difference in respect to the available power. The Betz limit, having a value of 59.3%, designates a maximum efficiency for a turbine when converting wind energy [13]. Modern turbines have reached efficiencies around 50% [14].

Aerodynamic characteristics of the blade directly affect turbine performance. The Tip Speed Ratio (TSR) - power coefficient relation is used to define one such blade characteristic. The TSR is defined by, [13]:

\[ \lambda = \frac{\omega * R}{V_1} \]  \hspace{1cm} (2.3)
where $\lambda$ is the TSR, $R$ is the radius of the rotor and $\Omega$ is the rotational velocity of the blades [13]. Additionally, the power coefficient, $C_p$, is linked to the blade design, tip angle and the relationship between the rotor speed and the wind speed [14]. $C_p$ defined by:

$$C_p = \frac{p(v)}{P_{available}}$$  \hspace{1cm} (2.4)

where $p(v)$ is the power generated by the wind turbine in watts [14]. $C_p$ should be kept near its peak, accomplished by varying the rotational speed of the rotor, in order to maximize the energy output of the turbine. The most accurate power curve approximation according to Carrillo et. al, is [14]:

$$p(v) = \frac{1}{2} \rho A \frac{C_{p,eq}}{V_1^3}$$ \hspace{1cm} (2.5)

where $C_{p,eq}$ is a constant equivalent to the power coefficient [14].

The relation of $C_p$ and TSR for a given blade pitch, $\beta$, is shown in Figure 2.1 [13] and the optimum TSR for different types of turbine configurations can be found in Figure 2.2 [13].

![Figure 2.1. $C_p - \lambda$ relation for $\beta=\Gamma$. Source: ABB. “Technical Application Papers No. 13 Wind power plants.” Bergamo, Italy: Technical 1SDC007112G0201 – 10/2011 – 4.000, 2011.](image-url)
A typical way of calculating the wind energy is through the Weibull distribution [7]:

\[
p(U) = \frac{k}{C} \left( \frac{U}{C} \right)^{k-1} \exp \left[ -\left( \frac{U}{C} \right)^k \right] \quad \text{for } U \geq 0, C > 0, k > 0
\]  

(2.6)

where \( k \) is dimensionless shape parameter, \( C \) is the scale parameter, \( U \) is the time series of wind speed observations and \( p(U) \) is the probability density function [7]. The Weibull distribution can also be used to describe the time allotment of the wind speed [13]. Graphically the Weibull distribution is shown in Figure 2.3 [13].
The dimensionless shape parameter, $k$, represents the dissipation of the wind speed due to ground topology. The values of $k$ for different ground morphology are given in Table 2.1 [13].

### Table 2.1. Different Shape Parameters

<table>
<thead>
<tr>
<th>Shape parameter, $k$</th>
<th>Ground morphology</th>
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<td>1.2-1.7</td>
<td>Mountains</td>
</tr>
<tr>
<td>1.8-2.5</td>
<td>Large hilly plains</td>
</tr>
<tr>
<td>2.5-3.0</td>
<td>Open countryside</td>
</tr>
<tr>
<td>3.1-3.5</td>
<td>Sea coasts</td>
</tr>
<tr>
<td>3.5-4.0</td>
<td>Island</td>
</tr>
</tbody>
</table>


The measured wind speed, usually 10 meters from the ground, is not the correct wind speed to use in the above equations. The velocity used in the specific power equations is the velocity at the hub height and can be estimated as [13]:

$$V_t = V_o \times \left(\frac{Z_t}{Z_o}\right)^\alpha \quad (2.7)$$

where $V_t$ is the velocity at the wanted height $Z_t$, $V_o$ is a known velocity at a known height $Z_o$, and $\alpha$ is a coefficient defined in Table 2.2 [13].

### Table 2.2. Different $\alpha$ Coefficients

<table>
<thead>
<tr>
<th>Coefficient, $\alpha$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09</td>
<td>Calm sea</td>
</tr>
<tr>
<td>0.12</td>
<td>Open area with limited low obstacles</td>
</tr>
<tr>
<td>0.16</td>
<td>Open areas with limited obstacles (6-8 m)</td>
</tr>
<tr>
<td>0.20</td>
<td>Areas with numerous obstacles (6-8 m)</td>
</tr>
<tr>
<td>0.30</td>
<td>Urban areas</td>
</tr>
</tbody>
</table>


### 2.1.1 Wind Energy Conversion

Wind energy conversion devices can be designed as lift or drag types. Lift type blades allow the wind to flow on either side of a non-uniform profile. This non-uniformity creates a high and low pressure side resulting in lift [13]. This type of blade needs wind speeds of
around 5 m/s to start, 14 m/s to deliver the rated capacity and anything over 25 m/s, known as the cutoff speed, the turbine is inoperative [13].

Drag type blades exploit stagnation pressure on one side to generate rotation around a vertical axis [15]. Any tangential force on the blade will produce rotation. The drag type blades have a lower cut-in speed and produce a higher torque but operate at a lower rpm. Drag type devices have a $C_{p,\text{max}} \approx 0.16$ [16].

There are two main types of wind turbines which are organized based on their axis of rotation: Horizontal Axis Wind Turbine (HAWT) and Vertical Axis wind Turbine (VAWT).

### 2.1.1.1 Horizontal Axis Wind Turbine

Recent advances in HAWT technology have allowed these turbines to reach heights of 90 to 120 meters with a rotor diameter of 120 to 130 meters [13]. The $C_p$ value for this type of turbine is normally between 0.40 and 0.50 [17]. HAWTs with two or three blades have a high TSR, low starting torque and are used for energy production while HAWTs with a large number of blades, low TSR, and high starting torque are used for mechanical pumping [16]. The pitch on the blades can be controlled, changing the blades angle of attack on the wind. This in turn modifies the rotor speed to ensure maximum power output which allows the turbine to be used in a broader range of wind states [18].

An advantage over VAWTs is that HAWTs have a higher efficiency since it receivers power from the entire rotation of the blade [18]. A disadvantage is that HAWTs require faster wind speeds to start producing power than VAWTs [18]. Furthermore, HAWTs can’t accept wind from any direction but this is rectified by incorporating a yaw system which determines the direction and speed of the wind and changes the orientation of the turbine to match [13].

### 2.1.1.2 Vertical Axis Wind Turbine

VAWTs are more suitable for power production in areas of high wind velocities and turbulent wind flows [19]. The generator and supplementary equipment are mounted on the ground allowing easier repair and maintenance of the generator as well as reducing the stress and loads on the tower [17]. Additionally, VAWTs can extract energy from wind originating in any direction without modifying the turbines alignment with a yaw system [17]. This translates into more power production since no energy is lost due to the apparatus correcting
itself during temporary wind changes [17]. However, VAWTs produce less power, are less efficient, have a low starting torque, are not self-starting and have a torque ripple [18]. This affects the life of the drive train and power quality, nevertheless, this can be reduced by increasing the number of blades or operating the turbine at a variable speed [17].

In order to increase the efficiency of VAWTs, Daegyoum and Morteza have proposed the installation of a deflecting plate in front of the turbines [20]. These deflecting plates keep the incoming wind from interacting with the returning blades while still allowing interaction with the blades normal to the wind direction.

VAWTs can be divided into Darrieus, Savonius and combined Darrieus-Savonius types.

2.1.1.2.1 Darrieus Type

The Darrieus turbines vary in configuration and have the highest efficiencies [19]. This device can have variable pitch blades which allows the turbine to overcome the issue of low starting torque and increases the efficiency leading to a $C_p \approx 0.215$ [19]. With a two tier configuration, the turbine is able to self-start with a wind velocity of 1.6 to 2 m/s while maintaining an efficiency of 40% [19].

2.1.1.2.2 Savonius Type

The Savonius turbine consists of blades that are hollow cup like cylinders fixed to an axis which spins to turn a generator. Modern forms of this device have exchanged the hollow cup blades for a spiral flute design. Drag is the main motive force behind this type of turbine reaching efficiencies of 20% and mainly used for wind velocimetry applications [19]. The ability to self-start is the Savonius greatest advantage and has a $C_p \approx 0.3$ [19]. End plates can be added in order to increase the average $C_p$ value and make the turbine more efficient at higher TSR [21].

2.1.1.2.3 Combined Savonius and Darrieus Type

The Savonius and Darrieus turbines were combined to couple the efficiency of the Darrieus with the high starting torque of the Savonius. This design was found to have a $C_p$
value as high as 0.35 with an overlap ratio of 0.167 [22]. Gupta et. al. have found that the power and torque coefficients increase as the overlap ratio is increased [22].

**2.1.2 Offshore Wind Energy Conversion**

In 2009, the first full-scale floating wind turbine was installed and tested in the U.S. by Statopil Hywind and had a rated capacity of 2.3 MW [23]. Currently, there is an installed offshore wind turbine capacity of 2,300 MW all of which are owned by European countries [23]. The total wind resource for the European coast is 2,600 TWh/yr [24]. There are no installed offshore devices in the U.S. despite the fact that the total resource for the country is above 4,150 GW and nearly 1,700 GW is located in a water depth less than 60 meters [23, 25]. Nonetheless, the U.S. has started to fund research into offshore wind power. In September 2011, the Department of Energy (DOE) awarded $43 million to 41 different projects in order to speed technical innovations, lower costs, and shorten deployment time for offshore wind conversion systems [26, 27].

Dvorak et. al. found that the potential for wind energy conversion is highest around Cape Mendocino, Point Conception, west of the San Miguel Islands and around Santa Rosa Island [28]. However, with the exception of Cape Mendocino, these spots are located 50 km offshore in relatively deep water [28]. The peak energy usage by coastal cities coincides with the strongest winds meaning that the energy converted can be used immediately [23].

More than half the cost of the turbine goes to balancing the station which includes the substructure/platform, electrical distribution, substation, grid connection, installation and regulatory and permitting processes [23]. However, the higher costs associated with installing offshore devices is countered with a 30% increase in power production compared to onshore turbines [13].

Locating wind energy conversion devices offshore is advantageous since:

- offshore wind has a higher velocity due to the influence of the marine boundary layer [28]
- turbulence levels are decreased leading to a smoother and more consistent power generation [7]
- they can be bigger in every aspect than their land based brother because they do not have to worry about the noise pollution or the safety of towns nearby [23]
Higher wind velocity and lower turbulence levels culminates in a higher capacity factor for offshore turbines than their land based brothers [25]. Additionally, increased size leads to the turbine operating at a lower torque which translates into using inexpensive drive-train components [23].

Offshore devices face many challenges such as:

- the lack of infrastructure to support the installation, maintenance, and operation of the turbines [25]
- the cost of transmitting [28]
- designing the platform and anchor system to withstand the most extreme wind and wave loads that the area can offer while keeping construction and maintenance cost down [28]
- transporting the devices to the proposed site under harsh weather conditions [28]
- the conflicting uses such as shipping lanes, recreation uses, marine and wildlife refuges, fisheries and other uses that can be found through the National Oceanic and Atmospheric Administration's (NOAA) national Marine Protected Areas Center
- obtaining the right permits and abiding by all the regulatory statues in place [6, 25]

2.2 Wave Energy

Specific wave parameters depend on several factors including longitude and latitude orientation, solar forces, temperature gradients and bathymetry [29]. The overall wave energy is derived from solar and wind energy but has a higher energy density than either [10]. The wave height, dominant wave direction, mean wave period, and the distance from the seafloor must be known to correctly estimate the wave energy resource [29]. Figure 2.4 shows these parameters as they relate to a wave.
The energy stored in a wave can be predicted by [30]:

\[ J = \rho \cdot g \cdot c_g \cdot \left( \frac{a^2}{2} \right) \]  

(2.8)

where \( J \) is the wave power, \( \rho \) is density of sea water, \( g \) is the acceleration due to gravity, \( a \) is the wave amplitude and \( c_g \) is the group velocity defined as, [30]:

\[ c_g = (\pi \cdot \sigma / K) \cdot \left[ 1 + \left( \frac{2 \cdot K \cdot h}{\sin h} \right) \right] \]  

(2.9)

where \( \sigma \) is the wave frequency, \( K \) is the wave number defined by \( K = 2 \cdot \pi / l \) where \( l \) is the wave length, and \( h \) is the water depth [30]. Most of the energy stored in a wave is dissipated by the seafloor due to frictional losses, however the minimum depth contour at which no frictional loss is observed is 100 meters [29]. An equation provided by Beyene and Wilson predicts the wave energy flux loss, \( \Delta E \), as a function of water depth, \( h \), for depths less than 100 meters and is as follows [29]:

\[ \Delta E(x) = 0.23h - 23 \]  

(2.10)

The total wave power density in watts per meter is calculated as [31]:

\[ P = \frac{\rho \cdot g^2}{4 \pi} \cdot \int_0^\infty \frac{S(\sigma)}{\sigma} \left[ 1 + \frac{2 \cdot K \cdot h}{\sinh(2 \cdot K \cdot h)} \right] \tanh(K \cdot h) \, d\sigma \]  

(2.11)

where \( P \) is the wave power density, \( S(\sigma) \) is the non-directional wave spectrum, \( K \) is the wave number and \( h \) is the water depth [31]. The non-directional wave spectrum \( S(f) \) is calculated as [31]:

\[ S(f) = \int_0^{2\pi} S(\sigma, \theta) \, d\theta = \frac{2\pi}{n} \sum_{i=1}^{n} S(\sigma, \theta_i) \]  

(2.12)

where \( n \) is the number of directional bins and \( \theta \) is the wave direction [31].

A study by Beyene and Wilson found pertinent wave statistics for various regions of California which are [10, 29]:

- Northern San Luis Obispo and Southern Monterey counties (normical) which have an average wave height of 2.5 meters, period of 10 seconds, a dominate wave direction of west and northwest and an average energy-flux density of 34 kW/m
- Orange, Los Angeles, Ventura and Santa Barbara counties (socal) which have an average wave height of 1 meter, period of 12 seconds, a dominate wave direction of southwest and west and an average energy-flux density of 6 kW/m

The ideal place for a wave energy conversion (WEC) device in California would be north of Point Conception in water about 90 meters deep to minimize bottom friction or in Eureka which has an average energy flux of 27 kW/m [10, 29]. The best sites for a WEC mechanism in socal would be the outer islands and sites west of the blockage effects of Point Conception [32]. However, the socal site would have a high cost of transmitting energy to shore since it is so far out.

### 2.3 WEC Devices

WEC devices must be able to [30]:

- operate reliably
- survive the worst storms even after being deployed for many years
- convert energy over a broad range of sea states
- convert the randomness of wave energy into a smooth output to the grid

WEC apparatus acts like high-pass filters and are unable to absorb more wave energy than their capacity packing density permits [31]. A WEC device can be broken up into three operating conditions: threshold, rated, and max. Below the threshold operating condition (TOC) the device is idle and energy is only dissipated because of reflection and refraction. Above the TOC but before the rated operating condition (ROC) the device is capturing energy with its efficiency increasing as machine nears the ROC. Above the ROC but below the max operating condition (MOC) power is still being produced but becomes less efficient as the device nears the MOC. Above the MOC the device will turn off to prevent damage. It has been found that California should have a TOC of 3 and a MOC of 300 [31]. WEC device’s efficiency will deteriorate greatly if it is not properly aligned with the incident wave direction [30].

There are four well known types of WEC devices being utilized, all converting energy in a different way.
2.3.1 Symmetrical Point Absorber

The symmetrical point absorber is a device that can either be on the surface of the water or submerged below and does not depend on the direction of the wave since they are so small in size [33]. Energy is captured through hydraulic rams and a high pressure take-off system; storing the converted energy in the form of high pressure seawater that can later be extracted by a turbine [34].

Symmetrical point absorbers have two configurations:

1. one open end with one closed end and is submerged under water converting energy from a pressure differential between the top and bottom causing the piston to move [34]

2. both ends closed and is normally filled with a mixture of air and water to make the apparatus buoyant, extracting energy as the buoy rides the crest and trough of each passing wave [34, 35].

One example of a point absorber is Ocean Power Technology’s Powerbuoy [36].

2.3.2 Oscillating Water Column (OWC)

The OWC is a device that channels the water from an incoming wave into a closed chamber, forcing the water to pressurize the air within. When the water recedes it causes a negative pressure, forcing air back into the chamber. The air passes through a self-rectifying turbine when exiting and entering the chamber [33]. Even though the air is bi-directional the turbine only spins one way as a result of the self-rectifying aspect. The air chamber within the OWC needs to be designed based on the wave characteristics of the local area. If the chamber is improperly designed the waves could resonate within resulting in a net zero passage of air through the turbine [36]. One example of a proposed offshore OWC device is the MK series being developed by Oceanlinx [37].

The most common type of OWC is the wells turbine. This device has a peak efficiency of 70-80% depending on the configuration [32]. Much focus has been given to the blade profile of the wells turbine. Thakker and Adbulhadi suggests that the best profile is the CA 9 because this blade has a wider operating range of sea conditions even though the NACA 0015 blade achieved a higher mean efficiency [38]. Mohamed et. al suggests a different blade that increases the tangential force and thus increases the efficiency by 1%, [39]. For bi-directional flow the preferred solidity is 64% [40], while another study suggests
that the solidity be under 50% when using a multi-plane turbine with guide vanes [41]. Others have found that the optimum setting angle for a wells turbine blade is around 2 degrees [42] while others have purposed a variable pitch approach that changes with the sea conditions [41].

The optimum duct area ratio profile should be 1.5 with a 7 degree duct angle which leads to a 9% increase in efficiency and delays stalling [43]. It has also been shown that wells turbine with end plates, being heavily dependent on the size and position, are superior to those without [44].

2.3.3 Overtopping Terminator

The overtopping terminator is a device that captures water in a reservoir above the average sea level. The water is then allowed to return to the sea through a turbine where the useful power converted is a product of the flow, head, water density and gravity [33]. This device has the potential to be used as breakwaters as well as conversion devices because of the calm sea state left in its wake [45]. One example of an overtopping device is the Salter’s Duck being developed by the University of Edinburgh. Another example of an overtopping device is the Wave Dragon.

2.3.4 Attenuator

The attenuator is a device that lies parallel to the incident wave and is composed of multiple sections that move in relation to each other. This motion is used to pressurize a fluid which then turns a turbine [46]. An example of an attenuator type conversion device is the Pelamis developed by Ocean Power Delivery.

2.4 Hybrid System

An integrating energy conversion platform has many advantages such as, [7, 47]:

- less daily and monthly variability as seen in Figures 2.5 [47] and 2.6 [47]
- lowered structural and erection cost due to a shared sub-sea transmission cable
- lower ocean surface space requirement

The design of an integrated platform poses many challenges for example, [48, 49]:

- the effects of both the wave and wind loads and how the induced motion will affect each turbine


- making the platform motion stable
- holding up under internal stress and fatigue loads
- resisting corrosion
- operating with little maintenance
- being constructed economically.

A study by Jenkins et al. found that the best place for converting both wind and wave energy in California is located at Cape Mendocino [47]. Stoutenburg et al. found that by integrating the two conversion techniques there was a reduction in the amount of time when no power is produced and the best wind to wave mix is either 75%-25% or 25%-75% respectively, depending upon requirements given, Figure 2.7 [38].

A mix of 25% wind and 75% wave displaces almost as much generation capacity as it does energy in the California power system [47]. Furthermore, a 50% wind to 50% wave and 25% wind to 75% wave reduces the zero power production time improving the grid interconnection and lowering the transmission loss [50].
One proposed design for an integrated system is a jacketed frame wind turbine with a symmetrical point absorber located inside [51]. Another configuration offered would be a large WEC device with wind turbines on top or a large floating wind turbine with small wave converters [51]. A current hybrid floating concept is the Hywind project which consists of large spar-buoys for wave conversion and a conventional wind turbine on top. Another floating concept is the SWAY which is an integrated spar-buoy concept that is stabilized and kept in position with a tension leg and a gravity anchor [48]. There is also the Poseidon floating platform which has a row of large wave absorbers with several conventional wind turbines placed on top [52].

Figure 2.8 shows this studies interpretation of a possible integrated platform. The design consists of a wells turbine used as the platform and is combined with two VAWT’s located on top. All three turbines connect to a single generator which transmits the power, via a single subsea transmission line, to shore. This design will cut down on the cost of the platform, the generator, the transmission line, and other various costs [47]. This design was part based off a study by Beyene and MacPhee [53].
Figure 2.8. Integrated platform.
CHAPTER 3

PROBLEM STATEMENT

The intent of this study is to examine the combined wave and wind energy potential off of the California coast for three distinct scenarios in order to understand the temporal relationship that wave and wind share. The three scenarios that will be examined: 1989 which was an El Niño year, 2008 which was a calm year, and 2011 which was a recent normal year. These years were selected to address a range of sea and wind states over a discernable length of time.

This study aims at:

1. Providing time dependent energy resource calculations and simulations for the wave and wind energy potential along the entire coast of California on a monthly bases for all the three years in order to give a more realistic and accurate estimate of the total energy
2. Tabulating the dominate wave period, height and direction for all 10 cells along the California coast for every month of the three years considered
3. Determining the relationship between wave and wind parameters
4. Estimating the percent that each energy source provides
5. Establishing an area that would be ideal for a combined wave and wind energy conversion platform
6. Suggesting a design for an integrated platform
7. Estimating the savings, cost and payback period of an integrated platform

A brief overview of the method used to ascertain the above stated goals are to:

1. Obtain wave and wind data to establish boundary conditions for wave modeling
2. Estimate the wave energy potential
3. Use wind data to estimate the wind energy potential
4. Correlate the time and location for each energy source to compute the total combined energy resource for an integrated design

This analysis is limited by the availability and accuracy of the data used in the simulations. Ocean buoys, the source of wave data for this study, are sparse in some locations. Furthermore the blended sea model, the source of wind data for this study, is only reported for every quarter degree of longitude and latitude. This, combined with the fact that
buoys just record data at points which is then used as a boundary condition for the entire computation, opens the door for errors. There are also the limitations introduced by the software.
CHAPTER 4

RESEARCH METHODOLOGY

Computing the combined resource of wave and wind energy necessitates calculating each resource separately at first, then combining the energy resource based on location and time period. To find the wind energy resource, Equation 2.1 must be utilized with available wind vectors, culminating in location and time specific wind energy figures. Computing the near-shore wave energy resource requires the use of a wave modeling software which necessitates the user to input:

- wave parameters
- wind vectors and magnitudes
- bathymetry data

This essential data, gathered from various sites, was organized and sorted to get the important components for each month of the years in question. The final results from the wave model, along with the gathered wind data, were used to find the combined energy resource along the California coast. An approximate energy baseline was found which will allow the determination of factors such as the size and economic feasibility of an integrated platform.

4.1 DATA

The California coast was divided up into ten one-degree computational cells. Table 4.1 gives the exact longitude and latitude for each of the ten cells used in the computations and Figure 4.1 gives a visual representation [54]. Each respective cell has its own specific wave height, period and direction used as boundary conditions which are found from the coastal run. The coastal run was set up to include all of California with a computational grid from 30.8 N to 42 N and -125.4 W to -115.4 W. This step was necessary so that any effects by ocean obstacles were mitigated.
Table 4.1. Latitude and Longitude Coordinates for Each Cell

<table>
<thead>
<tr>
<th>Cell</th>
<th>Longitude (W)</th>
<th>Latitude (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-120.6 to -116.6</td>
<td>32 to 33.5</td>
</tr>
<tr>
<td>2</td>
<td>-121.7 to -117.7</td>
<td>33.5 to 34.5</td>
</tr>
<tr>
<td>3</td>
<td>-122.2 to -119.5</td>
<td>34.5 to 35.5</td>
</tr>
<tr>
<td>4</td>
<td>-123 to -120.8</td>
<td>35.5 to 36.5</td>
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<tr>
<td>5</td>
<td>-124 to -121.7</td>
<td>36.5 to 37.5</td>
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<td>-125 to -123</td>
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<td>9</td>
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</tr>
<tr>
<td>10</td>
<td>-125.3 to -124</td>
<td>41.5 to 42</td>
</tr>
</tbody>
</table>

Figure 4.2 shows a simple schematic of the modeling process for reference. First, the three needed inputs are gathered and supplied to the wave modeling software for the coastal computations. Once the coastal computations are done, the wave modeling software outputs the wave boundary conditions for all ten individual cells. These outputted data, along with the bathymetric data and wind boundary conditions, are used to complete the wave simulation within each individual cell. After all individual cell computations are completed, the yielded wave data from the modeling software are compared to the supplied CPID and NDBC buoy data. The coastal computation was completed 36 times while the individual cell computations were completed 360 times.

![Figure 4.2. Schematic of modeling process.](image)

### 4.1.1 Wave Data

The specific buoy data for all calculations and subsequent comparisons was taken from the Wave Information Studies (WIS), the University of California, San Diego Scripps Institute of Oceanography’s Coastal Information Data Program (CDIP) and NOAA’s
National Data Buoy Center (NDBC). The vast amount of data was structured and refined to get the minimum, maximum, average, standard deviation and variance of the wave height, period and direction for every month of the 3 years under consideration. This was done for each of the buoys listed in Table 4.3 (pp. 26). All in all, around 700,000 data entries were processed.

4.1.1.1 WIS

The WIS is a project sponsored by the U.S. Army Corps of Engineers (USACE) in which consistent hourly wave data along all the U.S. coastlines are generated for long periods of time [55]. This project gets its data through wave hindcasting, which is a method used to find past wave characteristics based on current data. The WIS provides wave components for the entire California coast, giving data every half a degree latitude in water roughly eight longitudes away from shore. These wave parameters were then used as the boundary conditions for the coastal runs as seen in Figure 4.2. The WIS buoys used, as well as their location and depth are listed in Table 4.2.

Table 4.2. WIS - Buoy Locations and Years of Data Used

<table>
<thead>
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<th>ID</th>
<th>Year</th>
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<th>Lon(deg W)</th>
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<td>81073</td>
<td>89,08,11</td>
<td>33.5</td>
<td>-124.5</td>
<td>4,406</td>
</tr>
</tbody>
</table>
4.1.1.2 CPID and NDBC

The buoys used from CPID and NBDC are close to shore and are susceptible to being influenced by surrounding ocean obstacles. The datasets taken from this source were used to compare the results of the SWAN modeled run. Some sources off the California coast were not used because they were deemed unreliable or didn’t have a complete set of data. The buoy ID, shown in Table 4.3, can be used to find historical data, location, depth and years of available data for a buoy. A visual representation of the location of the buoys used can be seen in Figure 4.3 [54]. The wave data from the CPID and NDBC sources were processed in excel to give the average wave height, period and direction for each month of a given year.

Table 4.3. CPID/NDBC - Buoy Locations and Years of Data Used

<table>
<thead>
<tr>
<th>Cell</th>
<th>ID</th>
<th>Location</th>
<th>Year</th>
<th>Lat (deg N)</th>
<th>Lon(deg W)</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>93</td>
<td>Mission Bay</td>
<td>89, 08, 11</td>
<td>32.75</td>
<td>117.37</td>
<td>192</td>
</tr>
<tr>
<td>1</td>
<td>46047</td>
<td>Tanner Banks</td>
<td>08, 11</td>
<td>32.43</td>
<td>119.53</td>
<td>1399</td>
</tr>
<tr>
<td>2</td>
<td>28</td>
<td>Santa Monica Bay</td>
<td>08, 11</td>
<td>33.85</td>
<td>118.63</td>
<td>363</td>
</tr>
<tr>
<td>2</td>
<td>63</td>
<td>Harvest Platform</td>
<td>89</td>
<td>34.47</td>
<td>120.68</td>
<td>204</td>
</tr>
<tr>
<td>2</td>
<td>71</td>
<td>Harvest</td>
<td>08, 11</td>
<td>34.45</td>
<td>120.78</td>
<td>549</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>Santa Cruz Canyon</td>
<td>89</td>
<td>33.92</td>
<td>119.73</td>
<td>320</td>
</tr>
<tr>
<td>2</td>
<td>107</td>
<td>Goleta Point</td>
<td>08, 11</td>
<td>34.33</td>
<td>119.8</td>
<td>183</td>
</tr>
<tr>
<td>2</td>
<td>111</td>
<td>Anacapa Passage</td>
<td>08, 11</td>
<td>34.17</td>
<td>119.43</td>
<td>114</td>
</tr>
<tr>
<td>2</td>
<td>46053</td>
<td>Santa Barbara</td>
<td>08, 11</td>
<td>34.24</td>
<td>119.85</td>
<td>450</td>
</tr>
<tr>
<td>2</td>
<td>46054</td>
<td>Santa Barbara W</td>
<td>08, 11</td>
<td>34.27</td>
<td>120.45</td>
<td>460</td>
</tr>
<tr>
<td>2</td>
<td>46063</td>
<td>Point Conception</td>
<td>08</td>
<td>34.25</td>
<td>120.66</td>
<td>980</td>
</tr>
<tr>
<td>3</td>
<td>46011</td>
<td>Santa Maria</td>
<td>89, 08, 11</td>
<td>35</td>
<td>120.99</td>
<td>411.5</td>
</tr>
<tr>
<td>3</td>
<td>46023</td>
<td>Pt. Arguello</td>
<td>89, 08, 11</td>
<td>34.71</td>
<td>120.97</td>
<td>384.1</td>
</tr>
<tr>
<td>3</td>
<td>76</td>
<td>Diablo Canyon</td>
<td>89, 08, 11</td>
<td>35.203</td>
<td>120.86</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>46028</td>
<td>Cape San Martin</td>
<td>89, 08, 11</td>
<td>35.74</td>
<td>121.89</td>
<td>1158</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>Santa Cruz Harbor</td>
<td>89</td>
<td>36.95</td>
<td>122</td>
<td>13</td>
</tr>
<tr>
<td>5</td>
<td>61</td>
<td>Marina</td>
<td>89</td>
<td>36.7</td>
<td>121.82</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>46012</td>
<td>Half Moon Bay</td>
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<td>37.36</td>
<td>122.88</td>
<td>209</td>
</tr>
<tr>
<td>5</td>
<td>46042</td>
<td>Monterey</td>
<td>89, 08, 11</td>
<td>36.78</td>
<td>122.47</td>
<td>2098</td>
</tr>
<tr>
<td>6</td>
<td>29</td>
<td>Point Reyes</td>
<td>08, 11</td>
<td>37.95</td>
<td>123.47</td>
<td>550</td>
</tr>
<tr>
<td>6</td>
<td>47</td>
<td>Farallon</td>
<td>89</td>
<td>37.51</td>
<td>122.87</td>
<td>102</td>
</tr>
<tr>
<td>6</td>
<td>46013</td>
<td>Bodega Bay</td>
<td>89, 08, 11</td>
<td>38.24</td>
<td>123.3</td>
<td>116.4</td>
</tr>
<tr>
<td>6</td>
<td>46026</td>
<td>San Francisco</td>
<td>89, 08, 11</td>
<td>37.75</td>
<td>122.84</td>
<td>53</td>
</tr>
<tr>
<td>7</td>
<td>46014</td>
<td>Pt. Arena</td>
<td>89, 08, 11</td>
<td>39.24</td>
<td>123.97</td>
<td>256</td>
</tr>
<tr>
<td>8</td>
<td>94</td>
<td>Cape Mendocino</td>
<td>08, 11</td>
<td>40.29</td>
<td>124.74</td>
<td>325</td>
</tr>
<tr>
<td>8</td>
<td>46030</td>
<td>Blunts Reef</td>
<td>89</td>
<td>40.42</td>
<td>124.53</td>
<td>82.3</td>
</tr>
<tr>
<td>9</td>
<td>46022</td>
<td>Eel River</td>
<td>89, 08, 11</td>
<td>40.72</td>
<td>124.57</td>
<td>674.8</td>
</tr>
<tr>
<td>10</td>
<td>46027</td>
<td>St Georges</td>
<td>89, 08, 11</td>
<td>41.85</td>
<td>124.38</td>
<td>48</td>
</tr>
</tbody>
</table>

4.1.2 Bathymetry

The bathymetric data were taken from the U.S. Coastal Relief Model (CRM) and ETOPO1 global relief model distributed by NOAA through the National Geophysical Data Center. The ETOPO1 has a 1 arc-minute resolution and covers the entire surface of the earth. This bathymetry data was used in the coastal simulations, as seen in Figure 4.2. The CRM has a three arc-second resolution and covers the U.S. East and West coasts, the northern coast of the Gulf of Mexico, Puerto Rico, and Hawaii. This model has bathymetric data taken from the following sources: the U.S. National Ocean Service Hydrographic Database, the U.S. Geological Survey, the Monterey Bay Aquarium Research Institute, the U.S. Army Corps of Engineers [56]. The CRM was used in the individual cell simulations as seen in Figure 4.2.
4.1.3 Wind

Each cell also has its own wind input for the same month and year from which the wave statistics were used. The wind data was taken from NOAA’s Multiple-Satellite Blended Sea Surface Winds located in NOAA’s NOMADS Live Access Server [57]. Subsampling aliases and random errors are reduced through blending data from multiple satellites [57]. The wind direction was interpolated onto the blended sea grids with the help of the National Centers for Environmental Prediction Reanalysis 2. This database is able to give wind vectors and stresses on a quarter degree grid resolution every six hours, daily, or monthly.

4.2 Computer Modeling

Mathematical models of wave propagation endeavor to simulate the development of waves through space and time. Several phenomena must be accurately modeled including energy transfer from the wind, interaction between waves, bottom friction, breaking, reflection due to obstacles, diffraction, vegetation and currents [58]. A few of the modeling software considered were:

- Simulating WAVes Nearshore (SWAN)
- REF/DIF

REF/DIF is a phase resolved model based on flow analysis while SWAN is a phase averaging model based on energy balance. REF/DIF solves the mild slope equation but is restricted in domain size, directional and slope size. SWAN solves the action balance equation and is the wave modeling software used for these simulations.

SWAN was developed by the Delft University of Technology and was chosen for its ability to handle:

- large domains
- non-linearity and spectral applications
- reflection
- wave generation and whitecapping from wind

As an open source software SWAN is a highly accessible and adaptable software with the ability to couple with other ocean models such as WAM and WAVEWATCH III.
4.2.1 SWAN

SWAN is a third generation wave model that calculates the evolution of waves from deep water conditions to near shore wave characteristics for coastal waters by the user inputting the bathymetry, wind field and wave aspects at the boundary. SWAN takes into account all relevant sources and sinks such as:

- wind generated waves
- wave-wave interactions
- bottom friction
- whitecapping
- depth induced breaking
- shoaling
- current
- refraction

SWAN was run using monthly wave characteristics for three different scenarios to determine the wave energy available off of the California coast. The three circumstances were selected to address a range of possible sea states along the coastline. The three situations being 1989, 2008, and 2011 representing a calm year, an El Nino year and a recent year respectively.

4.2.2 Governing Equations

All information about the sea state is contained in the wave energy density $E(\sigma, \theta)$, which distributes wave energy over $\sigma$ frequency and propagates in $\theta$ direction [58]. Since wind generated waves have a highly irregular nature, the energy density is described as a spectrum in order to incorporate all variances. First, the elevation of the sea surface, $\eta$, at one point as a function of time is defined as [58]:

$$\eta(t) = \sum_i a_i \cos(\sigma_i t + \alpha_i)$$  \hspace{1cm} (4.1)

where $a_i$ is the $i^{th}$ wave’s amplitude, $\sigma_i$ is the circular frequency of the $i^{th}$ wave and $\alpha_i$ is the phase of the $i^{th}$ wave. The energy density spectrum $E(\sigma)$ is derived through the autocovariance function of the sea surface height and the time lag, $\tau$, [58].
\[ E(\sigma) = 2 \int_{-\infty}^{+\infty} (\eta(t)\eta(t+\tau))e^{-2\pi i \sigma \tau} d\tau \]  \hspace{1cm} (4.2)

The sea surface elevation variation can now be given as [58]:
\[ \eta^2 = \int_{0}^{+\infty} E(\sigma) d\sigma \]  \hspace{1cm} (4.3)

Using the n-th moment of the variance density spectrum Eq.16 is derived [58].
\[ m_n = \int_{0}^{\infty} \sigma^n E(\sigma) d\sigma \]  \hspace{1cm} (4.4)

Now specific wave parameters can be found. Since \( m_0 = \eta^2 \), the significant wave height is now:
\[ H_s = 4\sqrt{m_0} \]  \hspace{1cm} (4.5)

The total energy of the waves per unit surface area and the surface variation are equal [58]:
\[ E_{tot} = \frac{1}{2} \rho_w g \eta^2 \]  \hspace{1cm} (4.6)

However, energy density is not conserved during propagation, whereas the action density \( N \) is conserved [58]. The action density is defined as \( N = E/\sigma \). The progression of the action density is described by the action balance equation,
\[ \frac{dN}{dt} + \frac{dc_x N}{dx} + \frac{dc_y N}{dy} + \frac{dc_\sigma N}{d\sigma} + \frac{dc_\theta N}{d\theta} = \frac{S}{\sigma} \]  \hspace{1cm} (4.7)

where the action density, \( N(\sigma, \theta; x, y, t) \), is a function of frequency \( \sigma \), direction \( \theta \), coordinates \( x \) and \( y \) and time \( t \) [58]. The first term, \( \frac{dN}{dt} \), represents the local rate of change of action density with respect to time while the second and third parameters, \( \frac{dc_x N}{dx} \) and \( \frac{dc_y N}{dy} \), designates the propagation in geographic space \( x \) and \( y \), respectively [58]. The forth variable, \( \frac{dc_\sigma N}{d\sigma} \), represents the change in relative frequency due to depth and current variations in \( \sigma \) space [58]. The fifth term, \( \frac{dc_\theta N}{d\theta} \), denotes the refraction induced by depth and current in \( \theta \) space [58].

The \( c \) parameter in these equations are the velocities of propagation within their respective space. These variables are found from linear wave theory [58].
\[(c_x, c_y) = (\overline{c}_d + \overline{u}) = \frac{1}{2} \left( 1 + \frac{2|\vec{k}|h}{\sinh 2|\vec{k}|h} \right) \overrightarrow{k} + \overline{u} \]

\[c_\sigma = \frac{\partial \sigma}{\partial \overrightarrow{d}} \left( \frac{\partial h}{\partial t} + \overrightarrow{u} \cdot \nabla \overrightarrow{h} \right) - c_g \overrightarrow{k} \cdot \frac{\partial \overrightarrow{u}}{\partial \overrightarrow{s}} \]

\[c_\theta = -\frac{1}{k} \left( \frac{\partial \sigma}{\partial \overrightarrow{r}} \overrightarrow{k} + \overrightarrow{k} \cdot \frac{\partial \overrightarrow{u}}{\partial \overrightarrow{r}} \right) \]

where \( h \) is the depth, \( s \) is the co-ordinate in the wave propagation direction of \( \theta \), \( r \) is the co-ordinate perpendicular to \( s \), \( \overrightarrow{c}_d \) is the group velocity, \( \sigma^2 \) is the dispersion relation and \( \overrightarrow{k} \) is the wave number vector [58].

\[ \overrightarrow{k} = (k_x, k_y) = (|\vec{k}| \cos \theta, |\vec{k}| \sin \theta) \]

\[ \overrightarrow{u} = (u_x, u_y) \]

\[ \sigma^2 = g k \tanh(kh) \]

where \( g \) is the acceleration due to gravity. Also note that in Equation 4.7 the term at the end, \( S \), is the source/sink term which represents the generation, dissipation or redistribution of wave energy [58]. SWAN takes into account six different processes that contribute to the \( S \) term. These six processes are wind generated waves, wave energy transfer through three and four wave interaction, wave decay due to whitecapping, bottom friction and depth-induced wave breaking [58].

### 4.2.3 Computation

Before any computations could be done, SWAN must first be validated. Two studies have previously validated how this wave simulation program computes the wave characteristics for several types of ocean phenomena such as shoaling and diffraction [59, 60]. In these studies it was shown that SWAN has the ability to get within 10% of the expected values.

For the current study, the validation of SWAN was a two-step process. The first of which is validating the installation of SWAN. This was accomplished by running three different test cases that were provided on the programs website [61]. These test cases, testing
refraction, currents and diffraction, were supplied to ensure that SWAN was correctly installed and all features were working correctly.

The second step is to validate how the boundary conditions are contrived and which terms in the action balance equation to activate. This was accomplished by taking data from the WIS buoy database. These buoys are in a location that is sufficiently far away from shore, ensuring that no interferences have occurred. This data was then processed and organized in a way that allowed the average wave statistics for a given month to be easily read and entered as the boundary conditions for the entire California coast. The wave parameters for the individual cell computations were compiled from the coastal calculations, see Figure 4.1. and Figure 4.4 for further explanation.

![Diagram of wave computations](image)

**Figure 4.4. Origination of data for wave computations.**

The wind boundary conditions for both the coastal and individual cell computations were gathered from NOAA’s NOMADS LAS. This source gives the wind vectors and magnitudes at a 10 meter height for a user selected time, latitude and longitude.

The bathymetry for the coastal computation was taken from NOAA’s ETOPO1 because it was the only model that would work for such a large area. NOAA’s CRM was used for the individual cell runs since the area under consideration was small enough to use the finer grid resolution of the CRM.
Figure 4.4 shows the two different types of computational runs and where the boundary conditions for each originated. Once all three aspects were entered, SWAN was run.

The end result of these computations is ten individual cells along the California coast that have specific wave height, period and direction for all 12 months of the 3 scenario years. These outputted parameters were compared with the buoy measured CPID and NDBC wave characteristics. For a more thorough visualization see Figure 4.2. Once both parameters were within the expected range of values, the validation of the boundary conditions and activated terms in the action balance equation was completed.

All the default commands were used unless otherwise noted. For this study the maximum wind drag coefficient used was $2.5 \times 10^{-3}$ and all outputs from SWAN are based on true energy with a nautical convention for wind and wave directions. Since all buoy data was in spherical coordinates, SWAN was also run in spherical coordinates. The wave program was run in the third-generation mode with triads and bottom friction activated. The BSBT scheme was used for all wave computations to decrease computation time and alleviate the garden sprinkler effect. The number of meshes used in the computational grid of the costal setup for both x-direction and y-direction was 700 while the individual cells have a mesh size of 500 for both directions.

The mesh size for the coastal runs and the cells were found by locating the mesh size that produced a consistent output while minimizing the computational power and time needed. Figures 4.5 and 4.6 show several runs in which the mesh size was increased until the computed wave parameter remained fairly constant. Figure 4.5 shows this for a coastal run while Figure 4.6 shows this process for a cell run. From these figures one can easily see why the mesh sizes used were chosen.

In both cases the resolution used for theta-space was 72. Once the computations were completed, SWAN outputted several key parameters, the most important of which were the:

- longitude
- latitude
- wind velocity (m/s)
- significant wave height (m)
- mean absolute wave period (s)
Figure 4.5. Mesh size calculation for the coastal run.

Figure 4.6. Mesh size calculation for the individual cell runs.

- mean wave direction (degree)
- transport of energy (W/m).

SWAN also outputted specific wave characteristics at several of the NDBC/CPID buoy locations. The outputted wave attributes and the recorded NDBC/CPID wave characteristics were then compared and can be seen in Chapter 5. With the use of the transport of energy parameters, the total wave energy resource is known and can be converted to kW/m. Using Equation 2.1, an air density of 1.2298 kg/m$^3$ and the wind data from NOMADS LAS, the available wind energy was computed. The wind energy is also
converted to kW/m and then combined with the wave energy, thus arriving at the combined energy off of the California coast.

This process was performed for each month of the selected 3 years. Once the utilization of SWAN was completed, MATLAB was used as a post processing tool. The data from SWAN was converted and organized so figures of the total energy can be easily complied. The figures were made using the worldmap function built into MATLAB. This enables the energy data to be mapped according to the longitude and latitude. Several of the MATLAB codes as well as the SWAN command files for the coastal and individual cell runs can be found in Appendix A.
CHAPTER 5
RESULTS AND DISCUSSION

To find the objectives mentioned in Chapter 3, three scenarios were examined: 1989, 2008 and 2011 which represents a relatively low energy year, an El Nino year and a recent year respectively. A closer look into each year is taken to fully understand the variations undergone by each region as well as the energy contribution that each energy source provides.

5.1 PRESENTATION OF THE FINDINGS

Each of the three years are broken into their monthly variations, the results of which are located in Tables 5.1-5.9. Tables 5.1-5.9 compare the SWAN computed and buoy measured wave characteristics for every month. Most of the computed wave aspects fall within the range of the buoy measured data with the exception of Cell 2. Cell 2 is not well modeled due to inadequate boundary conditions as well as the blockage by Pt. Conception. However, from previous studies [10, 29], it is known that Cell 2 has a low energy density which would disqualify the area from consideration. On a whole, the parameters outputted by SWAN come very close to those measured by the buoys, thus the wave energy calculated by SWAN will be in the ballpark of the true value. In Tables 5.1-5.9 there are some boxes filled with “#Div/0!” or “#VALUE!”. This means that the buoy in comparison did not record data for that month.

Tables 5.1-5.9 show how the wave characteristics change every month and how the years compare to each other. On a whole, the El Nino year and the recent year are very close in energy density. As expected, the energy density for 1989 is far lower than the other two years. This is further proven when Figures 5.3 (pp. 50), 5.4 (pp. 50), and 5.5 (pp. 51) are compared. From Tables 5.1-5.9 the following average parameters can be assembled:
Table 5.1. Comparison of SWAN Computed Wave Height and Measured Buoy Height for 2011

<table>
<thead>
<tr>
<th>Cell</th>
<th>Buoy</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>93</td>
<td>(1.13 ± 0.33)</td>
<td>(1.18 ± 0.39)</td>
<td>(1.36 ± 0.49)</td>
<td>(1.29 ± 0.31)</td>
<td>(1.38 ± 0.49)</td>
<td>(1.05 ± 0.26)</td>
<td>(1.06 ± 0.18)</td>
<td>(1.1 ± 0.2)</td>
<td>(1.08 ± 0.26)</td>
<td>(0.95 ± 0.29)</td>
<td>(1.04 ± 0.32)</td>
<td>(1.04 ± 0.31)</td>
</tr>
<tr>
<td></td>
<td>SWAN</td>
<td>0.987</td>
<td>0.404</td>
<td>2.152</td>
<td>0.999</td>
<td>1.066</td>
<td>0.723</td>
<td>0.711</td>
<td>0.765</td>
<td>0.741</td>
<td>0.620</td>
<td>1.059</td>
<td>0.802</td>
</tr>
<tr>
<td>2</td>
<td>4047</td>
<td>#DIV/0!</td>
<td>#DIV/0!</td>
<td>(1.4 ± 1.47)</td>
<td>(0.46 ± 0.99)</td>
<td>(0.4 ± 0.78)</td>
<td>(0.6 ± 0.85)</td>
<td>(0.57 ± 0.8)</td>
<td>(0.29 ± 0.62)</td>
<td>(1.14 ± 0.99)</td>
<td>(1.86 ± 0.69)</td>
<td>(1.9 ± 0.73)</td>
<td>(2.11 ± 0.66)</td>
</tr>
<tr>
<td></td>
<td>SWAN</td>
<td>2.691</td>
<td>0.781</td>
<td>3.226</td>
<td>2.455</td>
<td>1.941</td>
<td>1.201</td>
<td>1.427</td>
<td>1.523</td>
<td>1.975</td>
<td>2.260</td>
<td>3.091</td>
<td>1.456</td>
</tr>
<tr>
<td>3</td>
<td>111</td>
<td>(1.14 ± 0.4)</td>
<td>(1.2 ± 0.43)</td>
<td>(1.36 ± 0.51)</td>
<td>(1.31 ± 0.45)</td>
<td>(1.32 ± 0.56)</td>
<td>(0.91 ± 0.3)</td>
<td>(0.93 ± 0.27)</td>
<td>(0.96 ± 0.24)</td>
<td>(0.86 ± 0.25)</td>
<td>(0.87 ± 0.29)</td>
<td>(1.11 ± 0.35)</td>
<td>(0.96 ± 0.27)</td>
</tr>
<tr>
<td></td>
<td>SWAN</td>
<td>0.153</td>
<td>0.004</td>
<td>0.367</td>
<td>0.010</td>
<td>0.005</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.021</td>
<td>0.019</td>
<td>0.042</td>
<td>0.006</td>
</tr>
<tr>
<td>4</td>
<td>71</td>
<td>(2.37 ± 0.71)</td>
<td>(2.39 ± 0.75)</td>
<td>(2.87 ± 0.92)</td>
<td>(2.61 ± 0.96)</td>
<td>(2.33 ± 0.63)</td>
<td>(1.88 ± 0.44)</td>
<td>(1.71 ± 0.36)</td>
<td>(1.9 ± 0.49)</td>
<td>(1.97 ± 0.6)</td>
<td>(2.5 ± 0.83)</td>
<td>(2.38 ± 0.7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SWAN</td>
<td>1.551</td>
<td>0.164</td>
<td>1.321</td>
<td>0.309</td>
<td>0.109</td>
<td>0.007</td>
<td>0.012</td>
<td>0.000</td>
<td>0.325</td>
<td>0.346</td>
<td>0.816</td>
<td>0.218</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>(2.35 ± 0.93)</td>
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Table 5.4. Comparison of SWAN Computed Wave Height and Measured Buoy Height for 2008

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Table 5.6: Comparison of SWAN Computed Wave Direction and Measured Buoy Direction for 2008
Table 5.7. Comparison of SWAN Computed Wave Height and Measured Buoy Height for 1989

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Table 5.8. Comparison of SWAN Computed Wave Period and Measured Buoy Period for 1989

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- Cell 1’s average: wave height of 1.5 meters, period of 12.6 seconds, direction of 214 degrees
- Cell 2’s average: wave height of 1.55 meters, period of 11 seconds, direction of 270 degrees
- Cell 3’s average: wave height of 2 meters, period of 12 seconds, direction of 290 degrees
- Cell 4’s average: wave height of 2.3 meters, period of 11.6 seconds, direction of 292 degrees
- Cell 5’s average: wave height of 2.1 meters, period of 12 seconds, direction of 285 degrees
- Cell 6’s average: wave height of 2.2 meters, period of 11.5 seconds, direction of 220 degrees
- Cell 7’s average: wave height of 2.2 meters, period of 11 seconds, direction of 290 degrees
- Cell 8’s average: wave height of 2.3 meters, period of 11 seconds, direction of 290 degrees
- Cell 9’s average: wave height of 2.3 meters, period of 10.8 seconds, direction of 290 degrees
- Cell 10’s average: wave height of 2 meters, period of 10.5 seconds, direction of 290 degrees

Figure 5.1 shows a slight decrease in the average monthly wave height from February to August and then a slight increase from August to January. This trend is the same for each of the three years. Overall, the wave height only marginally varies having a maximum around 2.5 meters and a minimum around 1.5 meters.

Now that the temporal relationships of waves have been observed, the time-based relationship of wind must be ascertained and compared. Tables 5.10-5.12 contain the wind velocities, measured at a height of 10 meters, are found at the same locations listed in Tables 5.1-5.9. In these tables the wind velocity, in m/s, is entered for every month of the three years under consideration. These tables are then used to determine the temporal relationship of wind which is summarized in Figure 5.2.

Figure 5.2 shows that the average wind velocity steadily increases from February to June, decreases from June to November and stays consistent for the months of December and January. The wind velocity ranges from about 7 m/s to 2 m/s, showing a large variance. It should be noted that all wind velocities are at a height of 10 meters.
Figure 5.1. Averaged monthly wave height.

Table 5.10. Wind Velocity (m/s) for Each Cell for 2011

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<td>6.87</td>
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</tbody>
</table>

### Table 5.12. Wind Velocity (m/s) for Each Cell for 1989

<table>
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<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
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<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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<tbody>
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<td>4.8</td>
<td>4.3</td>
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<td>5.8</td>
<td>6.9</td>
<td>2.9</td>
<td>3.9</td>
<td>2.5</td>
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<tr>
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<td>6</td>
<td>4.9</td>
<td>7.6</td>
<td>4.3</td>
<td>4.4</td>
<td>2</td>
</tr>
</tbody>
</table>
A complementary relationship between wave and wind can be detected from Figures 5.1 and 5.2. When one resource decreases over the span of the year, the other increases.

### 5.1.1 Coastal Runs

Buoys used as the boundary conditions for the wave grid on the coastal runs were selected from the WIS database. The coastal computations were done to acquire:

- an overall energy profile for the coast of California for comparison with other studies
- the boundary conditions for the individual cell runs

The boundary conditions were found in this manner because buoys are sparse in some cells and can be influenced by ocean obstructions, leading to unreasonable boundary conditions.

Figures 5.3-5.5 show the yearly combined wave and wind energy averages for the coast of California. Figure 5.3 shows the average for 1989 and displays a maximum value around 35 kW/m located in the northern part of California. Figure 5.4 shows the median for 2008 and presents a peak value around 50 kW/m, also found in the northern part of
California. Figure 5.5 shows the average for 2011 and shows an extreme of 60 kW/m, situated in the northern part of California. Most of these values are located far from land.

Note that the total energy has the unit of kW/m. For a wave device, this translates into the rate of energy conversion (kW) per meter of ocean surface and for a wind turbine, this signifies the rate of energy conversion per turbine diameter in meters.
Figures 5.3-5.5 gives a visual representation of how the combined energy changes as it approaches shore as well as a general understanding of how the energy density changes along the California coast. Figure 5.6 shows a quantitative way of viewing the yearly combined energy in each cell along the California coast for each of the three years. In all three years, the combined energy generally increases as you travel north.
When calculating the total energy for California’s coast, it was noted that wave energy contributed an average of 99% of the energy while wind contributed only 1% in locations exceedingly far from shore. It should be noted that the wind energy was calculated from a velocity measured at a height of 10 meters. If this height is increased the available wind energy will increase and contribute more to the overall energy.

### 5.1.2 Individual Cells

Three representative cells distributed along California’s coast were chosen to investigate the total wind and wave energy near shore. The cells chosen were Cell 1 for southern California, Cell 5 for central California and Cell 9 for northern California. The yearly combined wave and wind energy averages for these three cells and all three years are presented in Figures 5.7-5.15. Figures 5.7-5.15 give a visual representation of the integrated energy throughout each representative cell. These figures clearly show that the energy changes significantly depending on the geographic location along the coast and the location within an individual cell.

![Figure 5.7. Yearly calculated wind and wave energy average for Cell 1, (1989).](image)

It should be noted that in Figures 5.7 and 5.9 there are two square areas which are not representative of the energy at that location. This was caused by the wind data not being available at this location. This also happens in Cell 2 which may further explain the anomalies observed in Figures 5.7-5.15. However, these irregularities should not take away from the overall meaning of these figures which is that these cells have relatively low energy density close to shore compared to other parts of the coast.
Figure 5.8. Yearly calculated wind and wave energy average for Cell 1, (2008).

Figure 5.9. Yearly calculated wind and wave energy average for Cell 1, (2011).

Figure 5.10. Yearly calculated wind and wave energy average for Cell 5, (1989).
Figure 5.11. Yearly calculated wind and wave energy average for Cell 5, (2008).

Figure 5.12. Yearly calculated wind and wave energy average for Cell 5, (2011).
Figure 5.13. Yearly calculated wind and wave energy average for Cell 9, (1989).

Figure 5.14. Yearly calculated wind and wave energy average for Cell 9, (2008).
Figures 5.16-5.27 display the combined energy for a specific month for all three years. These figures also compare how each year compares to the other years under consideration for a given month. The quantitative nature of these figures gives a valuable insight into the amount of integrated energy that can be utilized at any location along the California coast for the given month.

Figure 5.15. Yearly calculated wind and wave energy average for Cell 9, (2011).

Figure 5.16. Average yearly integrated energy for the month of January.
Figure 5.17. Average yearly integrated energy for the month of February.

Figure 5.18. Average yearly integrated energy for the month of March.

Figure 5.19. Average yearly integrated energy for the month of April.
Figure 5.20. Average yearly integrated energy for the month of May.

Figure 5.21. Average yearly integrated energy for the month of June.

Figure 5.22. Average yearly integrated energy for the month of July.
Figure 5.23. Average yearly integrated energy for the month of August.

Figure 5.24. Average yearly integrated energy for the month of September.

Figure 5.25. Average yearly integrated energy for the month of October.
From Figures 5.7-5.27 it is noticed that the northern part of California has a high energy resource while the southern part has a relatively low resource. This is consistent with other studies [10, 29]. As one gets closer to the shore, the wind energy contributes a larger amount to the overall energy density. Near shore wind provides about 10% of the energy while wave contributes 90% of the total energy. The reason behind this is that as a wave gets closer to shore it starts to lose its energy, due to the interaction with the sea floor. It should be noted that the wind energy is computed from a wind velocity at 10 meters height. If this height increases, the wind velocity will also increase thus increasing the amount of wind energy available.
Tables 5.13-5.15 show the total energy resource of the three cells under consideration for each month of the representative three years. From these tables, it can be gleaned that as one moves up the coast of California, the total energy resource increases. The total energy does vary on a seasonal basis with the peak being from November to March. Figure 5.17 shows the average monthly energy for Cell 9 for all months of the 3 years as well as the seasonal variation.

**Table 5.13. Average Monthly Integrated Energy for Selected Cells 2011**

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
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<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
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<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
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<td>17</td>
<td>9</td>
<td>35</td>
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<td>60</td>
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**Table 5.14. Average Monthly Integrated Energy for Selected Cells 2008**

<table>
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<th>May</th>
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<td>18</td>
<td>12</td>
<td>36</td>
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<td>62</td>
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</table>

**Table 5.15. Average Monthly Integrated Energy for Selected Cells 1989**

<table>
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<tr>
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<th>Jan</th>
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<th>Mar</th>
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<td>2</td>
</tr>
<tr>
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<tr>
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<td>12</td>
<td>20</td>
<td>31</td>
<td>35</td>
<td>48</td>
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</tbody>
</table>

Figures of the combined energy of each cell for every month of the three years considered can be found in Figures B.1 - B.361 in Appendix B. A summary of the average combined offshore wave and wind energy, in kW/m, for each of the cells can be found in Table 5.16 with a visual representation in Figure 5.28. Table 5.16 and Figure 5.28 show that northern California has more energy resource than any other location along the coast. Cells 8, 9 and 10 are areas that will be the main concentration when selecting a location for an integrated platform since these cells have the highest average energy for all three years.
Table 5.16. Yearly Average Integrated Energy in kW/m for Each Cell

<table>
<thead>
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<th>Cell 2</th>
<th>Cell 3</th>
<th>Cell 4</th>
<th>Cell 5</th>
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<th>Cell 10</th>
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<td>25</td>
<td>25</td>
<td>17</td>
<td>21</td>
<td>27</td>
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<td>40</td>
<td>42</td>
</tr>
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<td>27</td>
<td>33</td>
<td>40</td>
<td>48</td>
<td>41</td>
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</tbody>
</table>

Figure 5.28. Cell 9 seasonal variation for all 3 years.

5.2 LOCATION SELECTION

The location that would be the best is the one that has the highest energy density throughout the entire year for both resources - wave and wind. The location cannot be too far from shore or in deep water for economic reasons [31]. From the collected data, it is known that the majority of the energy at a location comes from the waves. Cells 8, 9 and 10 are all strong candidates. Cell 8 has some blockage and the wave energy decreases before reaching a location near shore. However, the northern most part of Cell 8, near Eureka, would be an excellent location. Cell 10’s energy resource is also quite high but the wave energy significantly decreases before reaching a location near shore. Cell 9 is the most promising of the three cells. Most of Cell 9 has a large energy resource and the energy does not significantly decrease before reaching a location close enough to shore for a platform.

For optimal performance, the platform should be designed to handle the averages of Cell 9 which has an average wave height of 2.3 meters, period of 10.8 seconds and wave direction of 290 degrees. This gives the platform a rated wave capacity of 24 kW/m. With the suggested design parameters, the platform will be outputting its rated capacity for 10 out of
the 12 months. For the other two months, the platform will only be producing around half of its rated capacity. It would behoove the designers to come up with a way in which the design parameters of the platform can be altered depending on the current conditions. If the above design parameters are followed, the platform would miss out on a great deal of energy from October to March.

A more comprehensive analysis of the wind conversion aboard the platform needs to be done. Without data on the limits of the platform, in term of acceptable load levels, it is difficult to suggest a rated wind capacity. Therefore a conservative height estimate will be made and is detailed in Section 5.2.1. The rated capacity will go up the higher the wind turbine is located but this must be balanced with the additional load on the platform.

### 5.2.1 Platform Design

This studies conceptual interpretation of an integrated platform would consist of a 30 meter WEC device with two VAWT’s on top, Figure 5.29. The wind turbines as well as the WEC device would be connected to a single generator which would then transmit the electricity converted to shore. A VAWT was chosen as the wind turbine to be integrated with a WEC device because the generator for this type of turbine can be placed near the base. This is significant because the center of mass will be lowered which is vital to the stabilization of such a platform.

Previously it was stated that wind conversion devices have about a 40% efficiency and wave conversion devices have about a 80% efficiency. The rated wave capacity, $P_{WC}$, of such a platform can be calculated as:

$$P_{WC} = (WC) (LC) (Eff_w)$$

(5.1)

Where

- $WC$ = wave capacity, 24 kW/m
- $LC$ = length of wave conversion device, 30 meters
- $Eff_w$ = efficiency of wave conversion device, 80%

Therefore

$$P_{WC} = (24) (30) (0.80)$$

$$= 576 \text{ kW}$$

This means that a 30 meter WEC device would have a rated capacity of 576 kW.
For this study having a VAWT with an overall height of 25 meters, a diameter of 10 meters and a blade length of 15 meters will be considered, Figure 5.30. The wind speed will be taken at the center of the blade, Figure 5.30 point A. This will give a measured wind speed height of 17.5 meters. For Cell 9, the average wind speed is around 4.5 m/s measured at 10 meters. The wind speed at the new height is found using Equation 5.2:

\[ V_i = (V_0) \left( \frac{Z_i}{Z_0} \right)^\alpha \]

\[ = (4.5) \left( \frac{17.5}{10} \right)^{0.9} \]

\[ = 4.74 \text{ m/s} \quad (5.2) \]

This states that the wind speed at a height of 17.5 meters is 4.74 m/s. Using Equation 2.1, an air density of 1.2298 kg/m³ and a turbine cross sectional area of 150 m², the average available wind power, \( AWP \), is calculated:

\[ AWP = \frac{1}{2} (\rho) (A) \left[ (V_i)^3 \right] \]

\[ = \frac{1}{2} (1.2298) (150) \left[ (4.74)^3 \right] \]

\[ = 9.8 \text{ kW} \quad (5.3) \]

The rated wind turbine capacity, \( WTC \), is calculated as:

\[ WTC = (AWP) (Eff_A) \quad (5.4) \]
Where

\[ \text{Eff}_A = \text{efficiency of wind conversion device, 40\%} \]

Therefore

\[ WTC = (9.8) (0.40) \]

\[ = 3.92 \text{ kW} \]

Consequently, the total wind turbines capacity of the platform, \( TWTC \), would be:

\[ TWTC = (2) (WTC) \] \hspace{1cm} (5.5)

\[ = (2) (3.92) \]

\[ = 7.84 \text{ kW} \]

The total capacity of the platform, \( TCP \), would be:

\[ TCP = \text{PWC} + TWTC \] \hspace{1cm} (5.6)

\[ = 576 + 7.84 \]

\[ = 584 \text{ kW} \]
5.2.2 Economic Analysis

According to the simulations performed, the WEC device would produce its rated capacity for 10 of the 12 months or 7,300 hrs/yr. For the other two months, the platform would produce 60% of its rated capacity or 1,460 hrs/yr. The wave platform energy production, WAEP, would be:

\[
WAEP = (PWC) (OH_F) + (PWC) (RF) (OH_P)
\]

(5.7)

Where

- \(OH_F\) = wave device time of operating at full capacity, 7,300 hrs/yr
- \(RF\) = capacity reduction factor, 60%
- \(OH_P\) = wave device time of operating at part capacity, 1,460 hrs/yr

Therefore

\[
WAEP = (576) (7,300) + (576) (0.60) (1,460)
\]

\[
= 4,204,800 + 504,576
\]

\[
= 4,709,376 \text{kWh/yr}
\]

It is estimated the wind turbines will be producing their rated capacity for 8 months of the year or 5,840 hrs/yr. For the other 2,920 hrs in the year, the turbines will be experiencing a wind speed around 3.2 m/s which translates to a partial wind turbine capture, PWTC, of 2.5 kW. The wind energy production, WIEP, would be:

\[
WIEP = (TWTC) (OH_{FW}) + (PWTC) (OH_{PW})
\]

(5.8)

Where

- \(OH_{FW}\) = wind turbine time of operating at full capacity, 5,840 hrs/yr
- \(OH_{PW}\) = wind turbine time of operating at part capacity, 2,920 hrs/yr

Therefore

\[
WIEP = (7.84) (5,840) + (2.5) (2,920)
\]

\[
= 45,786 + 7,300
\]

\[
= 53,086 \text{kWh/yr}
\]
The total electricity produced by the platform, \( TEP \), would be:

\[
TEP = WAEP + WIEP
\]

\[= 4,709,376 + 53,086 \]

\[= 4,762,462 \text{ kWh/yr} \]

The electricity to reach the shore, \( ES \), is calculated by:

\[
ES = (TEP) (1 - TL)
\]

Where

\[TL = \text{transmission loss, 5\%} \]

Therefore

\[
ES = (4,762,462) (1 - 0.05) \]

\[= 4,524,339 \text{ kWh/yr} \]

All of the electricity produced will be sold to California at an average retail price, \( RP \), of $0.1324/kwh [53]. Therefore the total earnings per year, \( TE \), from this platform would be:

\[
TE = (ES) (RP)
\]

\[= (4,524,339) (0.1324) \]

\[= $599,022/yr \]

One benefit of an integrated platform is that there will be a lower structural and erection cost per kW [7]. A study by the National Renewable Energy Laboratory calculates the levelized cost of an offshore wind platform to be $5,600/kW [62]. The levelized cost includes the annual operating expenses, the installed capital cost and many other factors which can be seen in Figure 5.31 [62]. A different study by Black and Veatch calculates the cost of a wave conversion device to be $9,240/kW [63]. Figure 5.32 [63] breaks down the different costs associated with a wave energy conversion device such as the WEC device, operation and maintenance cost and many other factors. Figures 5.31 [62] and 5.32 [63] have some factors which are colored red, indicating that these costs will overlap, thus reduce the cost when building an integrated platform. Some of these costs are the anchoring cables, overall infrastructure, project management and transportation.

Figure 5.32. Capital cost breakdown for a wave conversion device. Source: Black & Veatch Holding Company. “Cost and Performance Data for Power Generation Technologies” Prepared for NREL. Feb 2012.
If each platform was constructed separately the cost would be the addition of the WEC device cost and the wind turbine cost. An additional cost would be the cost of the subsea transmission line which is about $164,958/mi [64]. It is estimated that these platforms would be 3 miles from shore. The individual cost of the WEC, $ICWEC$, device would be:

$$ICWEC = (TWTC) (WAPC) + (TLC) (MI)$$  \hspace{1cm} (5.12)

Where

$WAPC = \text{wave platform cost, } $9,240/kW$

$TLC = \text{transmission line cost, } $164,958/mi$

$MI = \text{miles from shore, } 3$

Therefore

$$ICWEC = (576) (9,240) + (164,958) (3)$$

$$= 5,322,240 + 494,874$$

$$= 5,817,114$$

In similar regards, the individual cost of the wind turbine, $ICWT$, device would be:

$$ICWT = (PWC) (WIPC) + (TLC) (MI)$$  \hspace{1cm} (5.13)

Where

$WIPC = \text{wind platform cost, } $5,600/kW$

Therefore

$$ICWT = (7.84) (5,600) + (164,958) (3)$$

$$= 43,904 + 494,874$$

$$= 538,778$$

The total cost of these two platforms, $TCTP$, would be:

$$TCTP = (ICWT) + (ICWEC)$$  \hspace{1cm} (5.14)

$$= 5,817,114 + 538,778$$

$$= 6,355,892$$

However, the sum of these costs should not be used because some costs are duplicated and can be eliminated. A study by Beyene and MacPhee sites that a combined
platform would cost about 55% of the total cost [63]. Therefore, the cost of an integrated platform, $C_{IP}$, can be calculated as:

$$C_{IP} = [(W_{APC}) + (W_{IPC})] (CR) \quad (5.15)$$

Where

$$CR = \text{cost reduction percentage of an integrated platform, 55\%}$$

Therefore

$$C_{IP} = [(9,240) + (5,600)] (0.55)$$

$$= 8,162/\text{kW}$$

The total capital cost for the platform, $T_{CC}$, would be:

$$T_{CC} = (C_{IP}) (TCP) + (TLC) (MI) \quad (5.16)$$

$$= (8,162) (584) + (164,958) (3)$$

$$= 8,162 \times 584 + 164,958 \times 3$$

$$= 5,261,481$$

The cost savings from integrating both platforms, $CS$, will be:

$$CS = (T_{CTP}) - (T_{CC}) \quad (5.17)$$

$$= 6,355,892 - 5,261,481$$

$$= 1,094,411$$

The simple act of integrating both the wave and wind platform will save over $1,000,000. This is vital to the financial success of such an endeavor. The simple payback period, $SPP$, for the integrated platform would be:

$$SPP = (T_{CC}) / (TE) \quad (5.18)$$

$$= (5,261,481) / (599,022)$$

$$= 8.8 \text{ yrs}$$

### 5.2.3 Sensitivity Analysis

The following section takes a look at how the simple payback period and annual cost savings are affected by varying electricity prices. The study currently uses an average retail
price of $0.1324/kwh to calculate a total earning of $599,022. Figure 5.33 shows how the total earning will increase or decrease depending on the average retail price.

![Figure 5.33. Sensitivity analysis to electrical prices and total earning.](image)

As the retail price of electricity increases the total earnings from the platform will increase and thus decrease the simple payback period as seen in Figure 5.34.

![Figure 5.34. Sensitivity analysis to electricity prices for simple payback period.](image)

### 5.2.4 Incentive Analysis

California has several programs that offer incentives to qualified programs to help pay for the startup costs of the system. Incentives could drastically reduce the total capital
cost and the payback period. Several incentive and tax programs currently exist such as Self-Generation Program (SGIP) and the Renewable Electricity Production Tax Credit (PTC). Another attractive feature is that the company will be a part of California’s Renewable Portfolio Standard, which states that California must get 33% of its electricity from renewable sources by 2020 [65].

This list does not represent an exhaustive search for all incentives that would apply to this case. The considered technology of an integrated platform is something that most incentive programs do not cover. Therefore, the incentives given to similar renewable energy technologies, such as wind turbines, will be used.

5.2.3.1 SGIP

Eligibility for participation in this incentive program is based on greenhouse gas emission reduction. This program can only be taken advantage of if the company is supplied energy by PG&E, SCE, SoCal Gas or SDG&E [66]. Table 5.17 shows the different technologies that the program covers and the related incentive for each technology. For this report we assume that the device will be eligible for the wind turbine incentive. This program also specifies that for projects larger than 30 kW, only 50% of the incentives will be paid up front and the other 50% will be covered under performance-based criteria over the first five years. The SGIP does not incentives electricity generation from wave energy.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Incentive $/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine</td>
<td>1,190</td>
</tr>
<tr>
<td>Waste Heat to Power</td>
<td>1,190</td>
</tr>
<tr>
<td>Internal Combustion Engine</td>
<td>480</td>
</tr>
<tr>
<td>Gas Turbine</td>
<td>480</td>
</tr>
<tr>
<td>Advanced Energy Storage</td>
<td>1,800</td>
</tr>
<tr>
<td>Biogas</td>
<td>1,800</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td>2,030</td>
</tr>
</tbody>
</table>

5.2.3.2 PTC

This tax credit program provides per kWh based tax credit for companies that generate electricity. Among those qualified generation technologies are wind turbines which receives ≤2.0/kWh [67].
With these incentives taken into account the new capital cost, $NCC$, would be:

\[
NCC = (TCC) - (TCP) (I) - (ES) (TC)
\]  

(5.19)

Where

\( I \) = incentives from SGIP, $1,190/kW
\( TC \) = tax credit from PTC, $0.02/kWh

Therefore

\[
NCC = (5,261,481) - (584) (1,190) - (4,524,339) (0.02)
\]

\[
= 5,264,481 - 694,960 - 90,487
\]

\[
= 4,479,034
\]

The new simple payback period, $NPP$, would be:

\[
NPP = \frac{NCC}{TE}
\]  

(5.20)

\[
= \frac{4,479,034}{599,022}
\]

\[
= 7.5 \text{ yrs}
\]

The time frame in which this platform pays back has many variables which could increase or decrease the number of years such as:

- the price electricity is being sold at
- the rated capacity of the platform
- the distance from land
- the wave and wind characteristics for that year
CHAPTER 6

CONCLUSION

The aim of this study was to develop a map of the coast of California which displayed the combined wave and wind energy potential. This was accomplished by using various sources such as the NOMADS LAS, NDBC, CPID and WIS databases in conjunction with the wave modeling software SWAN. Once all relevant data was coupled with SWAN, computations were run to model the California coast. Two different types of runs were performed: coastal and individual cells. The coastal run was performed in order to get an overall picture of the coast and to generate boundary conditions for the individual cells. The individual cells were then simulated with SWAN to get a more detailed understanding of the near shore resource available in each cell. This computational process was repeated for every month of the three representative years; 1989, 2008 and 2011. Once the wave modeling software was completed, MATLAB was used as a post processing tool. With this software, the overall energy computations and averages took place as well as the mapping of each cell.

As a secondary goal, the study analyzed the data to determine the temporal correlation between waves and wind. It was found that the wave height and wind velocity have a complementary relationship. When one decreases over the course of the year, the other rises. Finding this association was done in part to help determine how the platform should be built. Once both goals were met, a location for an integrated device was found. The best position for a platform was in Cell 9 where the energy does not dissipate until close to shore, thus minimizing the transmission and construction costs. It was found that the incorporated apparatus should be built to handle an average wave height of 2.3 meters, period of 10.8 seconds and wave direction of 290 degrees giving the platform a rated capacity of 24 kW/m.

An integrated platform 30 meters long with two 25 meter tall wind turbines would have a rated capacity of 584 kW and would cost an estimated $5,261,481 to implement and run. Integrating both wave and wind devices saves $1,094,411 compared to if each platform was constructed separately. If some incentives are considered, the integrated platform’s
original capital would drop by $785,447 to $4,479,034. The proposed platform would produce about 4,524,339 kWh/yr in electricity and make $599,022/yr. This leads to a simple payback period of around 8.8 years when incentives are not considered and 7.5 years when incentives are considered. Several factors, such as the price that electricity is being sold at, play a huge role in this estimation. Any change in these factors could lead to an increase or decrease in the simple payback period.

6.1 Possible Sources of Errors

This study was designed to have as little error as possible; however, there are still some factors which have the potential of producing errors. Errors can be derived from the fact that:

- the full wave spectrum was not used for the boundary conditions on the coastal simulations
- the data used as the boundary conditions are point data which means that SWAN had to calculate the wave parameters between each data point
- there are errors inherent in SWAN
- the changing air density due to temperature fluctuations was not taken into account when calculating the wind energy
- the wind data used for this study had a course grid resolution compared to the computational grid used
- some wind data along the California coast was missing

6.2 Future Research

For future studies several things can be done to improve the accuracy and completeness of this study. The most prominent of which is to get the hourly variations for the promising areas listed above. This will ensure that the areas under consideration act as predicted as well as to better understand the design parameters needed for this location. On top of that, the wave model could be run with the spectral data if accessible. Once the design parameters are fully understood, the actual design of the platform and how it will be anchored to the bottom should be researched. Once deigned, computer modeled load and stress analysis can take place to begin the optimization of platform. Upon completion of the computer modeled simulation real world modeling and testing can begin.
REFERENCES


APPENDIX A

SWAN AND MATLAB COMMANDS
Example of a .m file for:

Making maps for individual cells

```matlab
worldmap([32 33.5], [-120.5 -116.5])
load coast
whos -file coast.mat
surf(double(Yp), double(Xp), double(E))
colorbar
caxis([0 60])
setm(gca,'MlabelLocation', 1)
set(gca, 'Visible', 'on')
xlabel({'','Longitude'})
ylabel({'Latitude',''})
saveas(gcf, '1Apr2011','fig')
saveas(gcf, '1Apr2011','jpg')
```

Combining cells

```matlab
filelist = dir('*.mat');
fprintf('Processing %sn', filelist(5).name);
fopen(filelist(5).name,'r');
load(filelist(5).name);
E1(1:501,:)=E;
Wind1(1:501,:)=windE_kw;
Wave1(1:501,:)=transp_magkw;
X1(1:501,:)=Xp;
Y1(1:501,:)=Yp;
Depth(1:501,:)=Depth;
...
Etotal=(E1+E2+E3+E4+E5+E6+E7+E8+E9+E10+E11+E12)/12;
Windyavg=(Wind1+Wind2+Wind3+Wind4+Wind5+Wind6+Wind7+Wind8+Wind9+Wind10+Wind11+Wind12)/12;
Waveavg= mean(Waveavg);
Waveavg=(Wave1+Wave2+Wave3+Wave4+Wave5+Wave6+Wave7+Wave8+Wave9+Wave10+Wave11+Wave12)/12;
Waveavg= mean(Waveavg);
percentwind=Windyavg./Etotal;
percentwave=Waveavg./Etotal;
save('cell21989.mat', 'Windavg','Waveavg','percentwind','Depth','percentwave','X1', 'Y1' ,'Etotal','E1','E2','E3','E4','E5','E6','E7','E8','E9','E10','E11','E12','Windavg','Wave1','Wave2','Wave3','Wave4','Wave5','Wave6','Wave7','Wave8','Wave9','Wave10','Wave11','Wave12');
```

Finding a wind value at known location

```matlab
filelist = dir('*.mat');
fprintf('Processing %sn', filelist(2).name);
fopen(filelist(2).name,'r');
load(filelist(2).name);
w93=wmag(266,405);
```

Coastal SWAN command file

```bash
PROJECT 'CA coast' '1' 'Jan 11' 'title 2'
SET 0 90 .05 200 1 9.81 1025 .0025 1 .05
```
SET NAUT
MODE TWODIMENSIONAL
COORDINATES SPHE
CGRID -125.425 30.793 0 9.98 11.274 700 700 CIRCLE 36.03 .5 30
INPGRID BOTTOM -125.425 30.7926666666666667 0 598 677 .01666666666667 .016666666667
INPGRID FRICTION -125.425 30.7926666666666667 0 700 700 .0143 .01611
INPGRID WIND -125.425 30.8 0 40 45 .25 .25
READINP BOTTOM -1 'CAcoast.bot' 1 5
READINP WIND 1 'CAcoastJanwind.wnd' 3
FRICTION
TRIAD
BOUNDPAR1 SHAPESPEC JONSWAP 3.3 MEAN
BOU SEGM -124.5 42.6666666666666667 -125.425 42.6666666666666667 -125.425 30.8 VAR PAR 0 2.75 14.08 282 30 1.007 3.2 13.9 259 &
1.257 3.15 13.89 261 30 1.507 3.11 13.9 263 30 1.757 3.07 13.94 266 30 2.007 3.04 13.95 269 30 &
5.257 2.68 14.52 305 30 6.607 2.68 14.52 305 30
GEN3
PROP BSBT
NGR 'cell1' -120.6 32 0 4 1.6
NGR 'cell2' -121.7 33.4 0 4 1.2
NGR 'cell3' -122.2 34.4 0 2.7 1.2
NGR 'cell4' -123 35.4 0 2.2 1.2
NGR 'cell5' -124 36.4 0 2.3 1.2
NGR 'cell6' -124.7 37.4 0 1.8 1.2
NGR 'cell7' -125 38.4 0 2 1.2
NGR 'cell8' -125.3 39 0 1.3 1.2
NGR 'cell9' -125.4 40 0 1 1.2
NGR 'cell10' -125.3 41.4 0 1.3 .6
NESTOUT 'cell1' 'cell1.dat'
NESTOUT 'cell2' 'cell2.dat'
NESTOUT 'cell3' 'cell3.dat'
NESTOUT 'cell4' 'cell4.dat'
NESTOUT 'cell5' 'cell5.dat'
NESTOUT 'cell6' 'cell6.dat'
NESTOUT 'cell7' 'cell7.dat'
NESTOUT 'cell8' 'cell8.dat'
NESTOUT 'cell9' 'cell9.dat'
NESTOUT 'cell10' 'cell10.dat'
BLOCK 'COMPGRID' NOHEAD 'everythingelse.mat' TRANSP PDIR TDIR RTM01 RTP TPS RPER RTMM10 DSPR QP VEL FRCOEF PROPSY PROPTHETA PROPSIGMA GENERAT GENWIND DISSIP QB FORCE
BLOCK 'COMPGRID' NOHEAD 'CAJan2011.mat' XP YP HSIGN HSWELL DIR PER TM01 TM02 TMM10 DEPTH WIND PROPA
COMP
STOP

Individual SWAN command file

PROJECT 'Cell1' '1' 'Jan 11' 'title 2'
SET 0 90 .05 200 1 9.81 1025 .0025 1 .05
SET NAUT
MODE TWODIMENSIONAL
COORDINATES SPHE
CGRID -120.6 32 0 4 1.6 500 500 CIRCLE 72 .003 0.5 30
INPGRID BOTTOM -120.6 32 0 4800 1920 .000834 .000834
INPGRID FRICTION -120.6 32 0 400 400 .01 .004
INPGRID WIND -120.5 32 0 16 7 .25 .25
READINP BOTTOM -1 'cell1.bot' 1 1
READINP WIND 1 'cell1_2011_Jan.wnd' 3 1
TRIAD
FRICTION
BOUNDPAR1 SHAPESPEC JONSWAP 3.3 MEAN
BOUNDnest1 NE 'cell1.dat'
GEN3
PROP BSBT
BLOCK 'COMPGRID' NOHEAD 'everythingelse.mat' TRANSP PDIR TDIR RTM01 RTP TPS RPER
RTMM10 DSPR QP VEL FRCOEF PROXPY PROPTHETA PROPSIGMA GENERAT GENWIND DISSIP
QB FORCE
POIN '93' -117.37 32.75
POIN '46047' -119.53 32.43
TABLE '93' 'Buoy93.dat' XP YP HSIGN HSWELL DIR PER TM01 TM02 TMM10 DEPTH WIND
TABLE '46047' 'Buoy46047.dat' XP YP HSIGN HSWELL DIR PER TM01 TM02 TMM10 DEPTH WIND
BLOCK 'COMPGRID' NOHEAD 'cell1Jan2011.mat' XP YP HSIGN HSWELL DIR PER TM01 TM02
TMM10 DEPTH WIND PROPA
COMP
STOP
APPENDIX B

MONTHLY SWAN RESULTS
Figure B.1. Cell 1 January 1989.

Figure B.2. Cell 1 February 1989.

Figure B.3. Cell 1 March 1989.

Figure B.4. Cell 1 April 1989.
Figure B.5. Cell 1 May 1989.

Figure B.6. Cell 1 June 1989.

Figure B.7. Cell 1 July 1989.

Figure B.8. Cell 1 August 1989.
Figure B.9. Cell 1 September 1989.

Figure B.10. Cell 1 October 1989.

Figure B.11. Cell 1 November 1989.

Figure B.12. Cell 1 December 1989.
Figure B.13. Cell 2 January 1989.

Figure B.14. Cell 2 February 1989.

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Figure B.75. Cell 7 March 1989.

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Figure B.268. Cell 3 March 2011.

Figure B.269. Cell 3 April 2011.

Figure B.270. Cell 3 May 2011.

Figure B.271. Cell 3 June 2011.
Figure B.272. Cell 3 July 2011.

Figure B.273. Cell 3 August 2011.

Figure B.274. Cell 3 September 2011.

Figure B.275. Cell 3 October 2011.
Figure B.276. Cell 3 November 2011.

Figure B.277. Cell 3 December 2011.

Figure B.278. Cell 4 January 2011.

Figure B.279. Cell 4 February 2011.
Figure B.280. Cell 4 March 2011.

Figure B.281. Cell 4 April 2011.

Figure B.282. Cell 4 May 2011.

Figure B.283. Cell 4 June 2011.
Figure B.284. Cell 4 July 2011.

Figure B.285. Cell 4 August 2011.

Figure B.286. Cell 4 September 2011.

Figure B.287. Cell 4 October 2011.
Figure B.288. Cell 4 November 2011.

Figure B.289. Cell 4 December 2011.

Figure B.290. Cell 5 January 2011.

Figure B.291. Cell 5 February 2011.
Figure B.292. Cell 5 March 2011.

Figure B.293. Cell 5 April 2011.

Figure B.294. Cell 5 May 2011.

Figure B.295. Cell 5 June 2011.
Figure B.296. Cell 5 July 2011.

Figure B.297. Cell 5 August 2011.

Figure B.298. Cell 5 September 2011.

Figure B.299. Cell 5 October 2011.
Figure B.300. Cell 5 November 2011.

Figure B.301. Cell 5 December 2011.

Figure B.302. Cell 6 January 2011.

Figure B.303. Cell 6 February 2011.
Figure B.304. Cell 6 March 2011.

Figure B.305. Cell 6 April 2011.

Figure B.306. Cell 6 May 2011.

Figure B.307. Cell 6 June 2011.
Figure B.308. Cell 6 July 2011.

Figure B.309. Cell 6 August 2011.

Figure B.310. Cell 6 September 2011.

Figure B.311. Cell 6 October 2011.
Figure B.312. Cell 6 November 2011.

Figure B.313. Cell 6 December 2011.

Figure B.314. Cell 7 January 2011.

Figure B.315. Cell 7 February 2011.
Figure B.316. Cell 7 March 2011.

Figure B.317. Cell 8 April 2011.

Figure B.318. Cell 7 May 2011.

Figure B.319. Cell 7 June 2011.
Figure B.320. Cell 7 July 2011.

Figure B.321. Cell 7 August 2011.

Figure B.322. Cell 7 September 2011.

Figure B.323. Cell 7 October 2011.
Figure B.324. Cell 7 November 2011.

Figure B.325. Cell 7 December 2011.

Figure B.326. Cell 8 January 2011.

Figure B.327. Cell 8 February 2011.
Figure B.328. Cell 8 March 2011.

Figure B.329. Cell 8 April 2011.

Figure B.330. Cell 8 May 2011.
Figure B.331. Cell 8 June 2011.

Figure B.332. Cell 8 July 2011.

Figure B.333. Cell 8 August 2011.
Figure B.334. Cell 8 September 2011.

Figure B.335. Cell 8 October 2011.

Figure B.336. Cell 8 November 2011.
Figure B.337. Cell 8 December 2011.

Figure B.338. Cell 9 January 2011.

Figure B.339. Cell 9 February 2011.
Figure B.340. Cell 9 March 2011.

Figure B.341. Cell 9 April 2011.

Figure B.342. Cell 9 May 2011.
Figure B.343. Cell 9 June 2011.

Figure B.344. Cell 9 July 2011.

Figure B.345. Cell 9 August 2011.
Figure B.346. Cell 9 September 2011.

Figure B.347. Cell 9 October 2011.

Figure B.348. Cell 9 November 2011.
Figure B.349. Cell 9 December 2011.

Figure B.350. Cell 10 January 2011.

Figure B.351. Cell 10 February 2011.
Figure B.352. Cell 10 March 2011.

Figure B.353. Cell 10 April 2011.

Figure B.354. Cell 10 May 2011.

Figure B.355. Cell 10 June 2011.
Figure B.356. Cell 10 July 2011.

Figure B.357. Cell 10 August 2011.

Figure B.358. Cell 10 September 2011.

Figure B.359. Cell 10 October 2011.
Figure B.360. Cell 10 November 2011.

Figure B.361. Cell 10 December 2011.