INTRODUCTION

The United States, along with many other countries around the world, is actively pursuing the expansion of its energy portfolio to include electricity that is locally sourced and environmentally friendly. As such, the ocean has attracted attention due to the vast amount of power contained in its waves and tides. According to the Department of Energy, marine and hydrokinetic energy sources could account for fifteen percent of the nations electricity needs in the next fifteen years [1]. Wave energy theoretically has enough extractable power for over one hundred million homes and, with over fifty percent of the U.S. population living within fifty miles of a coastline, the energy would have a minimal transmission distance before reaching areas of need [1]. However, in order for the energy in the waves to effectively reach these homes, the wave energy converters (WECs) must successfully integrate into the power grid.

A specific factor to consider in the process of grid integration is that of array layout – how the devices are placed in relation to one another. Affected by a farm’s total power output as well as initial and reoccurring costs, array layout must be considered as WEC development moves toward ocean deployment and grid integration. This paper will discuss the current state of WEC array optimization, the power and cost models utilized in this work, the methodology (and input parameters) implemented and finally show the results found when the minimum spacing distance is altered.

ARRAY OPTIMIZATION

An interesting phenomenon in the placement of WECs is the ability of an array to produce more power than devices placed in isolation. This interaction factor, \( q \), is calculated as follows.

\[
q = \frac{P_{array}}{N \cdot P_{isolated}}
\]

\( P_{array} \) is the total power generated by an array, \( N \) is the number of devices in the array, and \( P_{isolated} \) is the power generated by a single device in isolation [2]. Based on the ability to potentially gain a value of \( q \) greater than one, research on layout configuration has prioritized the maximization of generated power [3–6].

As developers approach implementing WEC arrays, the tools used for determining configuration need to consider more than just obtaining an interaction factor greater than one. The economics of a WEC farm should also be incorporated into the layout design. To be competitive with other energy sources, the costs need to be minimized while the power is maximized.

Power Modeling

The power is calculated in the following manner. First the linear wave body software, WAMIT [10], is used to find the damping, added mass, and hydrostatic matrices of a singular device, for a defined range of wave periods. These hydrodynamic properties are used to analytically find the force transfer matrix, diffraction matrix, and the radiated wave coefficients of the device. Given this information the device excitation force and the array’s added mass and damping can be found. This information is then used to find the
array’s power using Equation (2). Greater detail of the method used to determine array power can be found in McNatt et al \[7\].

\[
P = \frac{1}{8} \mathbf{x}^\top \mathbf{B}^{-1} \mathbf{x}
\]  

(2)

In Equation (2), \(\mathbf{x}\) represents the complex exciting force and \(\mathbf{B}\) represents the array damping \[8\].

**Cost Modeling**

If an array optimization tool is to be useful to developers, the cost of implementing, operating, and maintaining an array need consideration. Unfortunately, at this stage in the wave energy industry, the existing cost models are inaccurate due to the many assumptions that must be made. Of the existing models, Sandia National Lab’s Reference Model Project (RMP) is the most comprehensive and has the ability to be readily updated as more data is acquired \[9\]. From the information presented in the RMP an equation for cost is determined.

\[
\text{Cost} = 3 \times 10^7 \times N^{0.6735}
\]  

(3)

\(N\) is the number of WECs in the array.

Once power and cost are known, the objective function to be minimized is shown in the following equation.

\[
\text{ObjFunc} = \frac{\text{Cost}}{P_{20}}
\]  

(4)

In this objective function \(\text{Cost}\) is found in Equation (3) and \(P_{20}\) is the power generated over an assumed 20-year array lifetime.

**GENETIC ALGORITHM METHODOLOGY**

A binary genetic algorithm (GA) was utilized in this work to handle the many discrete factors involved in layout design. Genetic algorithms are evolutionary type algorithms in which parent solutions are mated to produce children that are comprised of aspects from each parent. Essentially, GAs mimic how chromosomes are passed from parent to offspring in nature while allowing for mutations throughout the generations.

To begin, the space where the WECs are to be placed is discretized into potential placement locations. In discretized form, a row vector represents an array where each cell is either a one (WEC) or a zero (empty). Figure 1 shows the process of putting a space array into vector form.

Once a random initial parent population has been created it is evaluated using the objective function and sorted. This sorted set of parent solutions then generates children solutions using several tunable processes – elitism, crossover, mutation, and random solution generation. The effect of theses parameters can be adjusted to aid in converging.

Elitism is when a set percentage of the best parents are kept between the parent solution set and children solution set. In concurrence with elitism the same number of the worst parents are removed.

Since this work only considered a set number of WECs in an array, crossover was performed by randomly selecting a WEC position(s) and then swapping the WECs at that (or those) position(s) between a parent pair. Figure 2 demonstrates this process.
Crossover is performed on a prescribed upper percentage of the parent set.

Upon completion of the crossover process, mutation is applied to the children created by crossover. Mutation occurs by randomly selecting a percentage of the cells throughout the space where the value will be changed (i.e. if the cell contains a ‘1’ then it will become a ‘0’ and vice versa). The introduction of mutation helps the GA avoid converging too quickly on a less than optimal solution.

Finally, after elitism and crossover the children set may be less than that of the original parent set. As a remedy, random arrays are generated to fill out the set. Introducing these random layouts, similar to mutation, aids in finding the optimal.

Once a children set has been formed, it is evaluated with the objective function, sorted and convergence is checked. Convergence is achieved when a defined upper percentage of the sorted children set is found to be identical.

If convergence is not found, the children set becomes the next parent set and the process repeats until convergence is found. Figure 3 visually demonstrates the process.

For the results presented here the process was run with four different cases where the minimum separation distance was adjusted.

Each of these cases utilized five devices and involved a 10×10-discretized space. Due to the utilization of randomness in a GA, for a specific case, the same result was not achieved every time; however, the results presented were the most common and displayed the lowest objective function evaluation. Table 2 displays the settings for each case.

<table>
<thead>
<tr>
<th>TABLE 1: TUNABLE PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>Minimum Separation Distance</td>
</tr>
<tr>
<td># Of Parents</td>
</tr>
<tr>
<td>Elitism Rate</td>
</tr>
<tr>
<td>Crossover Rate</td>
</tr>
<tr>
<td>Mutation Rate</td>
</tr>
<tr>
<td>Convergence Requirement</td>
</tr>
</tbody>
</table>

RESULTS

The results obtained from each case are presented in the following figures. For each case a figure was generated to demonstrate the layout shape and another figure generated to show the effect of the layout on the surrounding wave height.
The interaction factor, $q$, obtained for all cases is shown in Table 2.

<table>
<thead>
<tr>
<th>Case</th>
<th>$q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.024</td>
</tr>
<tr>
<td>2</td>
<td>1.021</td>
</tr>
<tr>
<td>3</td>
<td>1.016</td>
</tr>
<tr>
<td>4</td>
<td>1.019</td>
</tr>
</tbody>
</table>

**DISCUSSION**

It can be observed that the shape of each case changes as the separation distance increases. Case 1 has pairs of devices aligning themselves parallel to the oncoming wave. Case 2 shows the devices moving into a single line perpendicular to the oncoming wave. In Case 4, the WECs have realigned themselves such that four of the devices form a square shape with one corner pointing towards the oncoming wave.

The reason for this change is probably due to the sea state that the devices are experiencing. If the same number and type of device are placed in a sea state with a different modal period, the results will shift. For example, when the modal frequency used in the Bretschneider spectrum is changed from 0.17 Hz to 0.2 Hz, Case 3 achieves the layout seen in Case 1 and Case 4 achieves the layout demonstrated by Case 2.

In addition to altering array configuration, the change in separation distance also results in a change in $q$. A greater value can be obtained when the devices utilize radiated waves; however even when the devices are separated far enough that dispersed waves drive the configuration design, the value of $q$ is still found to be greater than one.

**CONCLUSIONS**

Currently array formation research only considers power in an attempt to find an array that yields an interaction factor, $q$, greater than one. While this is beneficial, developers are nearing the point of implementing arrays and as such an optimization tool that considers power as well as cost is necessary. The method introduced here attempts to minimize the objective function shown in Equation (4). When the input parameter of minimum separation distance is changed, the arrays that are achieved change as well. The variation in WEC array shape due to an altered minimum separation distance demonstrates the influence of sea state on an array's layout.

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**REFERENCES**


