

AN ABSTRACT OF THE THESIS OF

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With the need to integrate renewable energy sources into the current energy portfolio and the proximity of many population centers to an ocean coastline, it is pressing that marine energy systems, specifically wave energy converters (WECs), are evaluated as potential solutions for meeting energy needs. In order to best understand power development, economics, grid integration requirements, and other aspects prior to installation, the ability to model these systems computationally is vital to their eventual deployment. However, the research area of WEC array optimization is young, and as such, results from previously implemented optimization methods are both few in number and preliminary in nature. The goal of this research is to investigate the economics of implementing WEC arrays, determine viable cost models, create an optimization framework for WEC arrays that will enable developers to - for the first time - understand the tradeoff between power development and cost for potential WEC arrays, and to explore preliminary systems-level issues, such as WEC layout and device spacing. A genetic algorithm approach that utilizes an analytic hydrodynamic model and introduces the use of an array cost model is presented. The resulting optimal layouts for two studies are then discussed. This work is integral in providing an understanding of device layout and spacing and is a foundational starting point for subsequent and more advanced WEC array optimization research.

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Wave Energy Converter Array Optimization: Array Economic Analysis and
Preliminary Results of a Genetic Algorithm Approach
Introducing Cost Factors

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Christopher J. Sharp, Author

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To my Dad for making me learn the power rule in our Suburban on a family road trip
and to my Mom for still ensuring I am keeping up with my homework.

Chapter 1: Introduction

As demand for electricity increases, and as communities seek to continue or improve the quality of life and affluence of the growing population, the development and optimization of new, clean energy sources is of paramount importance. Of potential sources, ocean waves have a vast amount of energy and, for the last few decades, the research and development of the harnessing of this energy has been ongoing. However, the economics of developing, implementing and maintaining wave energy converters (WECs) is lacking, particularly considering sea state volatility over the lifetime of WECs. As the industry moves towards ocean deployment of full-scale, grid connected WECs, an *a priori* optimization of the theoretical power system – including contributing factors such as power development, cost, and system parameters – is required, especially when demonstrating viability to stakeholders.

An important consideration for these systems is the placement of devices on a farm in relation to one another – this placement influences the power production, economics, and environmental impact. With current WEC array layout research considering only power, and evaluating scenarios lacking the necessary realism to use in real deployment situations [1]–[6], research is needed in the area of optimizing WEC arrays, specifically in the consideration of more realistic array design parameters such as the inclusion of array economics.

Much of the research in array configuration draws upon lessons learned from the wind industry – particularly the effect of a device on its neighbors. However, unlike wind turbines, where nearby devices negatively affect the power production of surrounding turbines, WEC interactions have the capability of positively affecting the electricity produced by an array [7]. Achieving an interaction factor, q , greater than one has been the driving goal of current array optimization work. This demonstrates power production of an array that is greater than the combined power production of the same number of devices acting in isolation.

Optimizing WEC arrays is essential to those in the wave energy industry and such optimization will reduce implementation barriers by providing layout configurations that take into account the many factors that influence the cost and power development of the array. The primary information lacking in current optimization work is that of the economics

associated with a wave farm. At this early stage of development, with limited economic information, it is important that array optimization work allows for the inclusion of available economic information, but also allows for the updating of such information as accuracy improves. Despite the current limitations, incorporating cost is vital to give developers relevant, effective information to aid in decision making.

The costs associated with WECs and WEC arrays are complex and involve a plethora of cost attributes, including device cost, mooring and cabling costs, and operations and maintenance costs. It is necessary to the success of wave energy that these costs are well researched and understood in order to provide developers with the most accurate information possible as siting and layout decisions are made. The purpose of the chapter on array economics is to centralize the research regarding wave energy costs and available WEC array cost models. First, several countries interested in wave energy as well as groups involved in the field are considered. Next, potential cost factors and methods of reduction are discussed. Following the discussion of cost reduction possibilities, feasibility studies and grid integration considerations are presented. Finally, current WEC economic models are evaluated and their potential implementation into array optimization evaluated.

The challenge of finding an array configuration that optimizes each of the objectives previously mentioned provides a prime opportunity for the use of multi-objective optimization methods. This research will first discuss the previous approaches, driven by power maximization, used to generate WEC array layouts and will then consider optimization methods that can or have been used to create WEC layouts. Next, an analysis of WEC array economics will be investigated followed by a description of the power and cost models utilized in this work. Following, the results of two test cases will be shown and discussed. Both of the studies involve five devices in a random unidirectional sea state using a binary genetic algorithm. The first study is a preliminary WEC array optimization study and the second is a further explored spacing study. To conclude, ongoing research will be presented.

Chapter 2: Previous Approaches

Where previous research concerning WEC array optimization has focused solely on the maximization of power, our novel approach includes the addition of cost in the objective function. With the challenge of creating a device to both survive and harness the ocean's energy, maximizing power generation is important in demonstrating the potential of these devices, but there are clear trade-offs between an array's ability to develop power and the cost of installing and maintaining the devices. One metric employed in existing WEC array literature is the interaction factor, q , given in Eq. 2.1.

$$q = \frac{P_{array}}{N \cdot P_{isolated}} \quad (2.1)$$

where N is the number of devices, P_{array} is the power extracted from the array, and $P_{isolated}$ is the power extracted from one device in isolation. Just as wind turbines affect the power extraction of turbines in the nearby vicinity, when WECs are placed in relative close proximity to each other the power output is affected due to the fluid interaction of the device and the water. Interestingly (and in contrast to our understanding of wind turbine interaction), the radiated and scattered waves caused by devices have been found to create an interaction factor greater than one [8]. In short, a WEC array has the capability of producing more power than an equivalent number of devices acting in isolation.

When considering arrays of wave energy converters there are many factors that can influence the value of q . Recently, Andrés et al. summarized these factors, which include the number of WECs, distance between the WECs, arrangement of WECs, incident wave direction, and wave climate [9]. They found that, given limited layout designs with between two and four WECs, a triangular shape gave best results for a wave field of different directions and a square shape was best for a unidirectional wave field with the waves running parallel to the diagonal of the square [9]. Cruz et al. and Ballard et al. found that in addition

to the layout, control of the WEC's power take-off characteristics could also cause an increase in q [2], [6]. Fitzgerald and Thomas note that while it is possible to achieve a value of q greater than one when there is little variation in the incident wave direction, the variability of this direction will affect the interaction factor in a manner that is currently unknown [1]. Balitsky et al. found that implementing a global control scheme on an array could vastly improve the power produced by a WEC array, especially when compared to the array's passive response. They proposed that the utilization of control schemes for maximizing power could be more influential than array configuration. The authors also noted that developers would need to evaluate the costs associated with device layout and with control implementation [10]. In their configuration study off the coast of Portugal, Ricci et al. report that the interaction effects experienced between devices may become negligible at certain distances based on device geometry. They suggest this distance to be roughly four times the device radius [4].

Of the layout optimization approaches found, only the work of Vicente et al. mentions the potential effect that physical implementation costs could have on device configuration [11]. Without performing a cost optimization, it is suggested that layout cost could be affected, and potentially reduced, if the devices are placed in such a way that mooring, electrical transfer and grid connection could be shared [11].

Without the use of optimization methods to better account for all the factors influencing an array's configuration, many current proposed layouts have been chosen solely based on a researcher's educated judgment and then evaluated for power and interaction effects. As an example, Vicente et al. consider several configurations of WECs – single line, hexagonal, triangular, square and offset line [11]. Through evaluating these different arrangements and applying waves from different directions, the authors conclude that an increase in the interaction factor will not drive the design of array layouts, but rather factors such as cost and mooring will most influence layout configuration decisions.

Currently, introductory research utilizing optimization methods for WEC layout design has been conducted. The primarily referenced research is that of Child and Venugopal [5],

which considers the case of five truncated WEC cylinders (similar to Figure 6.1) that are attached to the ocean floor via taught tethers – restricting device movement to the vertical (heave) direction. Assuming linear wave theory, three cases are considered – maximizing power development using real-tuned devices, maximizing power development using reactively tuned devices, and minimizing power development using reactively tuned devices. The difference between real-tuning and reactive tuning is whether scattered waves or radiated waves are considered to be more dominant and thus affects the coefficients involved in the power take off parameters. Additionally, the arrays were created assuming a regular sea state and incident wave direction of zero (due east). To find potential layouts, Child and Venugopal utilized two optimization methods – a Parabolic Intersection (PI) method, and MATLAB’s Genetic Algorithm (GA) toolbox. The PI method placed devices such that they are affected by the parabola-shaped scattered waves generated by device(s) closer to the oncoming wave. Figure 2.1 shows an example array achieved by this method.

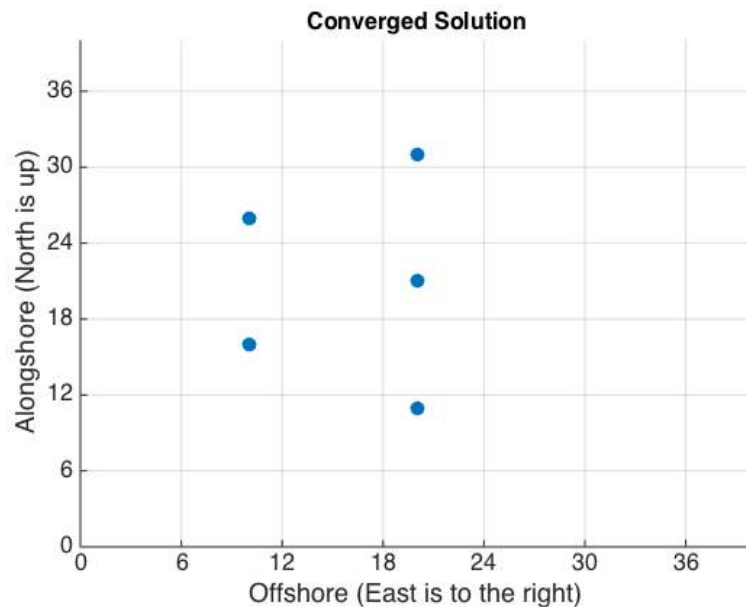


Figure 2.1: Array Achieved Using Parabolic Intersections

In addition to the parabolic intersection method, the genetic algorithm toolbox of MATLAB was utilized as well. This method, limited to 50 generations, achieved configurations such as the layout shown in Figure 2.2 [5].

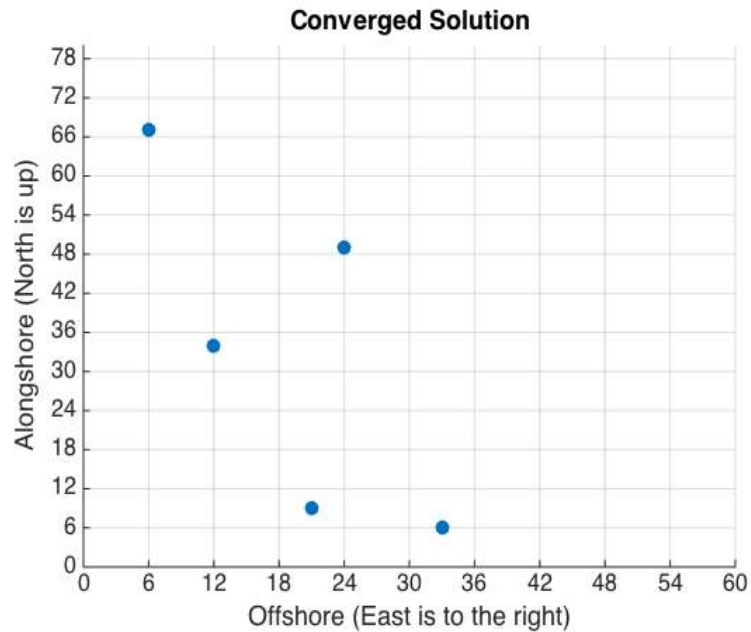


Figure 2.2: Array Achieved Using MATLAB's Genetic Algorithm Code

Both methods resulted in relatively similar layouts, where the five WECs were positioned in the shape of a 'W', with the bottom two points pointed towards the oncoming wave and the three upper points located down-wave. In this manner the down-wave devices were affected by the scattered and radiated waves of the up-wave devices. The results from the GA using reactive tuning gave the greatest increase in the interaction factor; however, the computational effort of the PI method was much less and gave comparable results.

Garrad Hassan (now DNV-GL), the creator of WindFarmer (a wind farm optimization tool), is also working on developing WaveFarmer to optimize WEC arrays [12]. In

discussing the development of WaveFarmer, two optimization cases were presented involving point absorbers – an array with four devices and an array with ten devices. Both of these case studies, evaluated at a unidirectional incident wave, attempted to maximize the array power produced. The first case study, involving an array of four point absorbers, set the placement of the devices at the corners of a square and then optimized based on adjusting the power take off characteristics of each individual WEC. In case two, the ten devices were allowed to arrange themselves given certain constraints. The minimum center-to-center distance between devices was three times the WEC diameter and the maximum separation distance was ten diameters. The arrangement that maximized the power was that of two lines almost orthogonal to the incident wave with five WECs in each line, where the rows were offset from one another. Figure 4.3 shows the resulting array layout.

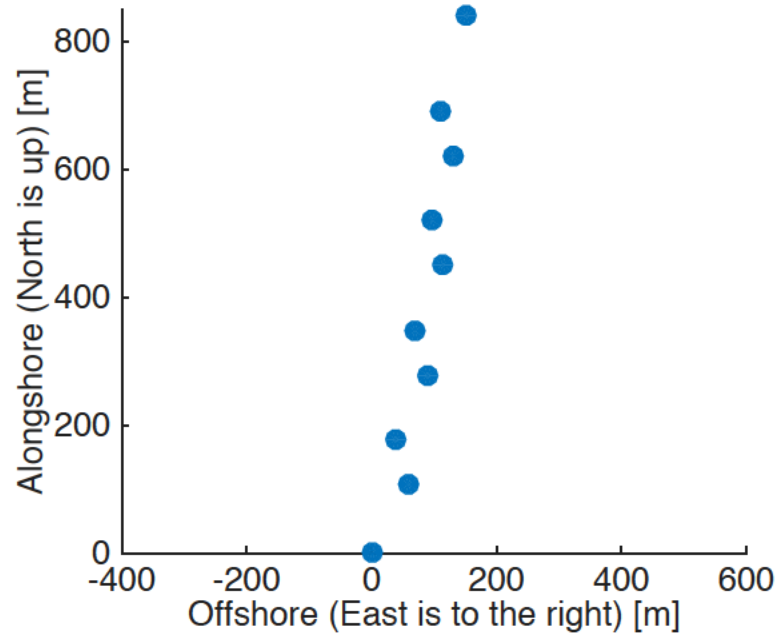


Figure 4.3: Layout Generated by DNV-GL in [6]

Both results demonstrated an increased interaction factor. An advancement that this work makes over the previously mentioned work of Child and Venugopal is the inclusion of an irregular wave set generated using a Bretschneider spectrum [6]. This allows for a more realistic optimization scenario. Unfortunately, DNV-GL has not disclosed their method for optimization.

The layout that is most often utilized for comparative evaluation is similar to those created by Child and Venugopal and DNV-GL, involving rows of devices perpendicular to the incident waves with each row offset from its up-wave neighbor. Examples of this method can be seen in the development of Sandia National Lab's SNL-SWAN [13], the experimental observations of array effects on regular waves in Porter et al. [14], and the basin tests concerning mooring loads done by Krivtsov and Linfoot [15].

Current research involving how WECs should be placed in relation to each other in arrays solely incorporates the array's power development without including other aspects such as physical cost, which could affect the proposed layout since cost is an inhibiting factor to the utility-scale implementation of WEC devices [16]. Given the multi-objective nature of the WEC array optimization problem, and the complexity of the resource, it is advantageous to design and implement a Genetic Algorithm. The current state-of-the-art in array optimization uses MATLAB's GA toolbox [5], [17], [18], but the application of this black-box method precludes both the ready introduction of problem-specific parameters and the incorporation of real-world complexity in modeling and objective evaluation.

While the referenced work serves as a starting point for WEC array optimization research, the goal of the current work is to expand the capability of the WEC array optimization methods and to increase fidelity of models employed, specifically through the consideration of cost and advanced input parameters. The following chapters discuss how the authors used a genetic algorithm to find optimal arrays and show preliminary results using a similar problem formulation to that of Child and Venugopal.

Chapter 3: Analysis of WEC Array Economics

This chapter presents an in depth examination of WEC array economics. At this stage in the wave industry, developers are looking towards ocean deployment of WECs and WEC arrays; however, information on costs associated with such deployments is not well established. The purpose of this chapter is to gather and investigate that which affects and should be included in a WEC economic model in order to allow the influence of cost as accurately as possible on an array configuration design.

3.0 Overview

The costs associated with WECs and WEC arrays are complex and include a plethora of cost attributes, including device cost, mooring and cabling costs, and operations and maintenance costs. It is vital to the success of wave energy that these costs are well-researched and understood in order to provide developers with the most accurate information possible as siting and layout decisions are made. The purpose of this paper is to centralize the research regarding wave energy cost (including discussing current WEC array cost models) First, several countries interested in wave energy as well as groups involved in the field are considered. Next, potential cost factors and methods of reduction are discussed. Following the discussion of cost reduction possibilities, feasibility studies and grid integration considerations are presented. Finally, current WEC economic models are evaluated and their potential implementation into array optimization evaluated.

3.1 Future of Wave Energy

With the amount of attention energy portfolios are experiencing around the world, several national governments have recognized that energy from the ocean has potential to serve as a significant resource in the pursuit of renewable energy portfolios. This section will present roadmaps that three countries have developed for implementing marine and hydrokinetic energy (MHK), including ocean waves, ocean tides, ocean currents, and river currents.

3.1.1 United States of America

The U.S. roadmap, constructed by the Ocean Renewable Energy Coalition, presents the many factors involved in the process of taking MHK technologies from their current state of development to being grid compatible on a large scale by 2030 [16]. These include research and development of all aspects of MHK devices as well as research into external factors, such as siting and environmental studies. Additionally, the report notes how wave energy has the potential to grow in a similar manner to the wind and solar sectors. The report specifies three phases which MHK development would undergo – demonstration (100 kW) to pilot (5 MW), pilot to small arrays (50 MW), and small arrays to commercial utility-scale arrays (100 MW) [16]. In light of this report's nature, the roadmap does note that reducing cost is a priority, but does not discuss in detail how this can or should be done.

Ocean waves have been presented as a potential resource that could provide more than 50% of the United State's needed energy [19]. A preliminary predicted range of the cost of energy (COE) for wave energy is between 0.18 USD/kWh and 0.34 USD/kWh [19]. This is a large span, but this is consistent with the relative immaturity of WEC development (the authors point out that wind energy at a similar developmental stage to current WECS was about 0.22 USD/kWh, by comparison) [19]. It is supposed that as the technology improves, the cost of WECS will drastically decrease – theorized to be to a competitive 0.6 USD/kWh [16].

3.1.2 Ireland

Ireland is attempting to reduce its carbon footprint by the year 2050 and consequently, Sustainable Energy Authority of Ireland created a roadmap for incorporating renewable energy from the water surrounding its shores [20]. The roadmap introduces four phases: 1/4-scale technology deployment, full-scale devices, pre-commercial arrays (<10 MW), and commercial scale arrays (>100 MW) [20]. The report predicts that up to 70,000 jobs could be created and that the country could experience an economic benefit of 120 billion euros [20]. Ireland is in a good position to pursue this energy source due to several marine energy

companies operating in country. The report notes that devices need further development to lower costs.

3.1.3 United Kingdom and Scotland

At a national government level, The United Kingdom (UK) has committed to lowering carbon emissions by 2050 [21]. To achieve their energy portfolio goals, the UK Energy Research Center and the Energy Technologies Institute separated and then prioritized different developmental activities by theme. The activities that are considered the highest priority are economic installation and recovery, design for maintenance, device structure, techno-economic analysis tools, sub-sea electrical system, and offshore umbilical. While these are only a few of those mentioned with high priority, they are some of the primary activities that would have a direct noticeable effect on the associated cost [19].

The Forum for Renewable Energy Development of Scotland (FREDS) Marine Energy Group (MEG) set out to expand the capability of Scotland to become a global leader in marine renewable energy (estimated to provide 10% of Scotland's power by 2020) in 2004 [22], and later assessed the state of marine renewable energy in Scotland in 2009 [21]. Through these roadmaps, Scotland has become a global leader in marine renewable energy, culminating in multiple test- and grid-scale projects [23]. An update to the roadmap issued in 2012 outlines current and future wave energy projects, along with provisions for updating the Scottish power infrastructure to handle marine renewable grid integration [24].

The roadmaps all recognized the need to lower costs in order to achieve marine energy viability, but did not thoroughly discuss cost factors involved throughout the process.

3.2 Primary Groups

With the increasing interest in wave energy and the need for economic assessment and cost reduction, there are several groups who are actively pursuing avenues to quantify and reduce cost. This section of the paper will introduce interested parties, both in the U.S. and abroad, which surfaced when researching existing information on wave energy economics.

Primarily the focus of this paper tends towards that of research being conducted in the U.S. with the understanding that research in Europe is several years advanced.

3.2.1 U.S. Department of Energy

In the United States, the Department of Energy (DOE) provides oversight concerning federal support of MHK technologies. The Wind and Water Power Technologies Office is designed to “improve the performance, lower the costs, and accelerate the deployment of innovative wind and water power technologies” [25]. The 2014 Water Power Program Peer Review provides a summary of the funding supplied to MHK technologies, as well as pointing out goals developed with existing energy sources in mind. In another report, it is noted that MHK technologies could enter the energy market in a similar manner to wind and as such the wind industry should be used for comparison at these early stages [25], [26].

3.2.2 Electricity Power Research Institute

The Electricity Power Research Institute (EPRI) is a conglomerate of several individuals from different organizations working on “[defining] offshore wave energy feasibility demonstration projects” [27]. EPRI has located several potential sites in the U.S. Using the Pelamis WEC as an input, the group runs simulations for power, cost and environmental issues of proposed arrays at the sites [27]. The simulations are preliminary and require many functional assumptions, but still provide a baseline for subsequent research. These findings will be discussed in section 3.5.

3.2.3 U.S. National Laboratories

Several of national laboratories are researching different cost aspects of MHK technologies. Sandia National Laboratories (SNL) has developed a tentative outline using Technology Readiness Levels (TRLs) to describe the development of WEC arrays [28]. TRLs provide a consistent framework for discussing the advancement of different technologies towards grid connection. SNL is working with RE Vision Consulting, LLC on

developing a reference model that includes the economics associated with WEC arrays [29]. Additionally, the National Renewable Energy Laboratory has constructed a preliminary Jobs and Economic Development Impact (JEDI) model for predicting the cost of a WEC farm [30], [31].

3.2.4 Europe

In Europe there are several groups concerned with analyzing wave energy economics; a selection of these groups will be discussed here. First, the Carbon Trust is focused on reducing carbon outputs in the UK and consequently promotes and aids the development of energy sources with low- to no-carbon emissions, such as marine energy [30]. The Carbon Trust is concerned about the economic survivability of MHK technologies and includes risk into as party of their cost formulation. Also, the Carbon Trust has developed a spreadsheet tool for calculating array cost [30], [32].

The Strategic Initiative for Ocean Energy (SI Ocean) was a European Union (EU) funded project designed to create a plan that maximizes the amount of ocean energy by 2020 [33]. As a part of this process, SI Ocean evaluated the current state-of-the-art and noted the primary aspects of development that needed consideration for cost minimization. These aspects consist of the structure and prime mover, foundations and moorings, power take-off, installation, electrical connection, operations, and maintenance [33].

A recent and ongoing EU funded collaborative project, DTOcean, is designed to accelerate the development of marine energy [34]. Consequently, DTOcean is creating a tool for analyzing WEC farm life cycle logistics and returning a LCOE. A major component of this would involve determining accurate costs associated with WEC arrays; however, this work is ongoing.

3.3 Cost Factors

In order to achieve a consumer cost of energy that is competitive with current energy sources (or at least current renewable energy sources), the capability of accurately modeling and predicting marine energy system performance is necessary. In the early phases of WEC

system research, the primary concern was the design of devices and methodologies that could extract energy from the waves. With the creation of many types of WECs, the next step in wave energy development is to ensure the methodologies can be integrated into the grid at an effective cost. The devices themselves are only one facet of the cost when it comes to grid scale implementation. As can be expected, in this early stage of wave energy's economic consideration there are many different opinions as to what will or should be included in cost calculations and how to accurately formulate the costs for comparison.

In 2002, Leijon et al. presented the opinion that "degree of utilization" should be a key component in cost calculations [35]. Degree of utilization refers to the ratio of yearly-generated power over the unit's rated power and involves the inclusion of components such as a site's wave climate as well as a unit's availability. In a simplistic assessment, where no subsidies are considered and fuel cost is assumed to be zero, the components of a plant's cost are said to be investments (including interest rate), maintenance, and supervision. Examining present values of several of Sweden's [then] current energy sources, the authors demonstrate that higher utilization yields correlate to an increased value of power. An interesting result of this study is that, based on particular wave climates and considering a utilization factor, smaller devices would be more economical than large devices [34]. While the research is preliminary where specific cost factors are considered, it notes that maintenance and fuel minimization are important considerations.

With the further development of WEC's since 2002, Bedard, working with the EPRI, presents the comparison of energy types using cost of energy (COE) [36]. It is assumed that acquiring energy offshore will be more difficult and thus more expensive than onshore energy sources. Additionally, the reliability of offshore energy is assumed to be similar to wind turbines and that the operation and maintenance (O&M) can be reduced by advances in WEC operation. Bedard also predicts that wave energy, once operating on a larger scale, will be comparable with wind energy, but also notes that estimating costs is challenging and should be done with caution [35].

In a study by Stallard et al., developers are questioned concerning economic appraisal methods [37]. In the study, cost components are broken down into capital and operating

costs. Capital costs are considered to primarily include construction, installation, station keeping, and equipment. Operational costs consist of replacement parts, personnel, vessels/transportation equipment, and insurance. It is proposed that utilizing COE is a common method when evaluating and comparing WEC costs. Though, while COE is widely used in the energy sector, the authors note that this method varies greatly with changes in discount rates and doesn't include factors such as the revenue side of investment or investment scale. The authors also note that the consideration of risk is an important factor to consider at this stage in WEC economics [36].

The Oregon Wave Energy Trust (OWET) utilizes an IMPLAN (Impact Analysis for PLANing) input-output model in their study of the economic impact of implementing WECs off Oregon's coast. Some major assumptions by OWET include a 500 MW farm with a capacity factor of 30% [38]. Components included in the construction costs are onshore transformers and grid connections, cables, mooring, power conversion modules, concrete structures, building/facilities, and installation work. A set value is assumed for the annual overhead costs. OWET concludes that, based on their many assumptions, commercial WEC industry in Oregon would provide a vast number of new jobs, but recognizes that cost barriers exist throughout the many facets that need to be addressed [37].

The Carbon Trust breaks down the capital and O&M costs a bit further by assigning a percentage to each cost attribute. The report shows that the device makes up a vast majority of the capital cost. O&M costs are comprised primarily of maintenance (57%) and retrofitting the device (24%) [39]. The report notes that while initial pilot projects and farms will have higher costs, future costs will likely reduce due to greater development, device optimization, and economy of scale. It is also stated that the greatest chance for cost reduction comes from device components, installation, O&M, and next generation concepts [38]. In a later report compiled by the Carbon Trust, the previously mentioned cost components are reexamined. The costs found in this report are actually higher than what was projected in 2006 and the conclusion drawn is that initially, developers were focused on demonstrating devices, but in the five years between reports, the industry moved forward

with a better understanding of the costs involved and began focusing on reducing those costs [39].

An interesting aspect of cost that most literature fails to explore is that of environmental siting and permitting. The Pacific Northwest National Lab (PNNL) evaluated the costs associated with this facet of MHK technologies. They found that environmental costs include regulatory drivers, siting, scoping, pre-installation studies, and post-installation studies. The report considered pilot size arrays (1-10 devices), scaling up to large commercial arrays (>50 devices), and predicted that initially the costs would be higher, but would taper down once baseline studies are completed since these would supply a better understanding of the environmental impacts [40]. There are several areas for uncertainty in these costs, primarily associated with the monitoring, mitigation, and regulatory requirements.

The operational costs are difficult to accurately determine due to the stage of the industry; however research is being conducted in the area. O'Connor et al. recently published a paper on operational expenditure costs where factors accounting for access and availability of the WECs are included [41]. The authors find that for early stage development these factors could greatly impact the economic benefit of arrays by decreasing the amount of energy produced.

SI Ocean also incorporates an availability factor into their levelized cost of energy work [42]. Input groupings consist of capital costs (devices, foundation, mooring, connections, installation, projects costs, decommissioning), operating costs (maintenance, operations, insurance, seabed rent, transmission charges), and annual energy production (site resource, device energy capture, availability). In SI Ocean's report they note that in the early stages of WEC development an aspect of cost requiring vital consideration is perceived risk. The risks are defined as being primarily project and technical risk. The report suggests that once reliability and operational expenditure is demonstrated in the early stages, costs will decrease accordingly [43].

There are several considerations that should be noted from the research presented above.

- It could be, depending on sea condition, that using a greater number of smaller devices might be more economical than a fewer number of larger devices
- It is predicted that the economics of the wave energy industry, once operational on a larger scale, will follow those of the wind industry
- Alternative economic evaluations (including but not limited to COE) should be utilized when evaluating and comparing WEC array economics
- Environmental siting, permitting and monitoring should be included as cost factors
- Device optimization, installation and O&M appear to provide the greatest opportunities for array cost minimization
- Device access and availability will affect the O&M costs and should be included in economic evaluations

The factors that contribute to the costs associated with an array are very similar across current research – as are their percentages of the total cost. While this is positive, the values assigned to each of these factors vary across research and are based on many assumptions.

3.4 Cost Reduction

With many assumptions currently required to predict the cost of grid connecting a WEC array, there are several methodologies to help improve the accuracy of these cost predictions.

In regards to MHK technologies, determining the economics of tidal energy is often a bit more straightforward due to design similarities with the wind industry and because the devices are usually submerged [44]. That said, the WEC industry can learn from work done in tidal energy concerning cost. For example, SNL has produced several cost-reduction pathway options for axial-flow turbines. Their top findings include optimizing the structural design as well as an improving deployment, maintenance, and recovery [42].

The Offshore Renewable Energy (ORE) Catapult project suggests that an important factor in reducing cost is helping investors “get comfortable with marine energy” [45].

Additionally, standardization of technology development, assessment, and better investor coordination between the public and private sectors is necessary for minimization of cost [44].

Using the wave resource of Australia as a case study, Haward et al. presents two theoretical wave energy models [46]. The authors conclude that emission trading is necessary for the success of most renewable energy forms in order to ensure cost competitiveness with other energy sources. Also, wave energy is at a disadvantage compared to solar energy and wind energy due to its early stage of development [46].

RE Vision, a group leading the economic assessment of the WEC reference model (RM3) with SNL [46], presents two economic methods – early adopter and commercial. The early adopter method involves implementing marine energy at the current moment. This method is useful for determining what policies need changing to assist implementation. Comparatively, the commercial method compares MHK technologies against existing more mature technologies while leaving the assumed risks equivalent. This commercial method highlights developmental gaps that exist between technologies [47].

RE Vision has also worked with EPRI in to assess the economics of wave power. In this work, a utility generator (UG) method and a non-utility generator (NUG) method are utilized [48]. The primary difference between these two methods is their obligation to serve (a UG is generally required to provide power if capable and necessary), rates/prices (a NUG sets prices at the allowable limit), and risks/benefits (a UG is more dependable investment with lower return). This report also presents two alternative methods to COE for determining and comparing costs – net present value and internal rate of return [49].

In the paper by Beels et al. an array of wave topping devices, Wave Dragon Wave Energy Converters, are evaluated based on power and cost [50]. For this specific case it is found that the driving factor would be the power produced when compared against the cost. The authors found that the increase in cost when the array was designed such that the cables were not optimized was minuscule in comparison to the increase in power [48].

3.5 Feasibility Studies

Several studies have been done that evaluate the costs and power output of realistic, theoretical arrays.

One such operational simulation, conducted by Teillant et al., involves an array of 100 axisymmetric oscillating 2-body devices off Ireland's west coast [51]. The purpose is to test a productivity and economic assessment method. The novelty of this method is the ability to return cost information at different phases throughout the lifecycle as well as the ability to evaluate the sensitivity of different cost factors [50].

EPRI also performed several feasibility analyses at different locations with theoretical arrays [52]. The process involved an assessment of current WECs and sites, selection of the site and WEC, evaluation of a pilot scale array, and evaluation of a commercially scaled array. This process can be repeated several times by considering factors such as environmental impact or policies and regulations. The device chosen by EPRI is the OPD Pelamis because a small array had previously been physically tested off the coast of Portugal. The locations chosen were Oregon, San Francisco, Hawaii, and Massachusetts [51].

Of the locations evaluated, Oregon achieved the cheapest COE at 9.7 cents/kWh and San Francisco was the highest at 11.2 cents/kWh [52]. EPRI concluded that at all the locations more research and development needs to be done to bring down the COE, but each location has potential as an array site [52]–[55]. Completing this study involved creating and following several guidelines: 1) analyzing designs 2) comparing power and 3) cost estimation. Concerning the O&M parameters, guidelines were borrowed from the experience of the offshore oil and gas industry. EPRI concludes that the ocean as an energy resource is definitely worth pursuing, but at the current stage of development, devices are only ready for demonstration [56].

3.6 Grid Integration

An important aspect that must be considered regarding the cost of WEC arrays is grid integration. While some arrays may operate in isolation powering remote islands or

coastlines, the primary goal of wave energy is to input the ocean power into the larger utility-scale power grid.

In a general sense, Angevine et al. shows that in the U.S. there are primarily renewable portfolio standard targets, which are non-binding renewable goals, and Federal tax-based incentives, which mostly support wind [56]. Unlike most countries, the U.S. doesn't usually utilize feed-in-tariffs because of restrictions by the Federal Power Act and Public Utility Regulatory Policies Act (PURPA) (under select cost based circumstances, the Federal Energy Regulatory Commission (FERC) does allow feed-in-tariffs). Barriers that could affect wave energy's grid connection include public opposition, capital costs, poor access to the transmission system, a regulated market, and frequently changing policies and regulations [56].

In a case study performed in Ireland, Blavette et al. suggest that integrating wave power into the grid could negatively affect the power quality [57]. To test this theory a model was run which included a variable source of power. They show that the efficiency of the grid does decrease, but continues on to evaluate several smoothing methods that can alleviate the problem [57]. Blavette et al. conducted another case study about the grid effects of a medium sized WEC array at different sites [58]. The demonstrated problems arise due to the fluctuations and unpredictability of the power. For the case study, oscillating water columns were used with a combined power capacity of 19.4 MW [59]. The study showed that control at a common coupling was enough to keep the voltage with an acceptable bound for a majority of networks.

Based on the nature in which WECs generate power, there will have to be methodologies implemented into the grid along with the array in order to ensure an efficient and dependable grid. For instance, a power compensation unit will need to be used offshore near the location of the WEC. This unit will ensure that the reactive power produced by the WEC is absorbed or created as needed. Ahmed shows that when several devices are placed in an array the power variation is lessened but can still be an issue and as such would need power compensation units [59].

As has already been noted, integrating a wave farm into the grid has challenges. O’Sullivan and Dalton separate these challenges into grid-side (shore) challenges and generator-side (ocean) challenges [60]. Grid-side challenges include building the infrastructure necessary to physically connect to the grid as well as dealing with costs accrued from charging regimes and use-of-system charges. On the generator-side, the primary issue has already been discussed – variable power. Electricity from the ocean must be handled in such a way that it meshes well with the grid’s electricity. The existing grid has distribution codes for the technical performance of generators, reactive power requirements, and fault ride-through requirements. The last requirement is relative new and stipulates that a power source of a certain size remain connected to the grid during a fault [61].

In Oregon, OWET recognizes the need to determine the requirements for grid integration [62]. As such, several years ago, they set tasks to determine interconnection guidelines, integrated system analysis, forecasting requirements, scheduling requirements, technical and operational barriers, and integration and balancing of wave energy [61]. Since then, OWET has released another report that discusses the issues associated with integration [62]. Wave energy is limited similarly to other renewable energy forms in its variable power output. Availability of wave energy is more predictable than wind or solar energy, but still has stochastic tendencies. Due to this potential issue, reserves must be kept to supplement or extract from the WEC’s supplied power as needed. The method in which this occurs can be a complicated task. Factors that must be considered include types of reserves available, market structure, how the balancing authority area interacts with its neighbors, price of fuel, and wholesale electric market prices [61].

While this section may seem slightly removed from the economics of WECs, it is fact very necessary as each of the issues must be solved and the solution will affect the economics of WECs. Therefore, a robust cost model should include these components. Unfortunately, at this point, existing cost models are not this detailed – the tendency is to assume that costs associated with grid connecting conclude once the cable is brought to shore. While this may be true depending on the locality, it should be included in the model as a tunable option.

3.7 Current Models

Currently, several cost models exist in the form of interactive spreadsheets. Carbon Trust released the first WEC cost model in 2006 [63]. The Carbon Trust model divides cost into two large categories, capital costs and O&M costs, and uses a present value method to calculate the energy cost. A primary limitation to this model is its age. Since 2006, the cost values utilized in this model have been found to be inaccurate [32], [39], [63].

A more recent cost model, produced by NREL and RE Vision in 2010, is the MHK version of the Jobs and Economic Development Impact (JEDI) model [31]. A valuable aspect of this model is the added functionality of outputting the jobs, income, and economic activity that would result from a farm being used in a certain state. The MHK Jedi model incorporates on-site labor and professional services impacts, local revenues and equipment, and supply chain impacts, and induced impacts. NREL's model is useful for getting an overview of the different aspects that are incorporated into cost calculations and seeing what the economic impact might be, but unfortunately the model only has values for a 10 MW array. As such, unless one is an expert in knowing how to scale the inputs for different sized arrays the model is very limited in its usability regarding array optimization [30], [31].

More recently, as part of the reference model project, SNL, with RE Vision, created a spreadsheet that contains many cost factors involved in a WEC array calculations as well as reporting many of the assumptions involved [29]. This spreadsheet is admittedly low in accuracy due to the lack of good data at this stage in WEC development. However, it can easily be updated as new information is acquired [29].

The most recent cost model was developed in the spring of 2014 at Aalborg University in Denmark [64]. This model allows quite a bit of customization. For example, the user has the ability to input the specific device information of the WEC. Additionally, the spreadsheet grants the ability to either choose from list of predetermined common sea states or to input the power matrix of a defined sea state. These are important features in that they will ensure that the WEC won't be falsely generating revenue. Another useful feature is the ability to scale the WEC up and down in the spreadsheet if a different size is desired. And finally the spreadsheet outputs both COE and net present value (in addition to other interesting

information). There are some drawbacks to this tool that should be noted. First of all uncertainty still exists – while the spreadsheet allows for customization, the values being utilized aren't definite and as such the results should be treated as reasonable suggestions. The largest drawback is that it can only calculate the economics of a single WEC – not an array [64], [65].

Table 3.1: Available Cost Models

Carbon Trust	NREL JEDI	SNL RMP	Aalborg
+ Utilizes present value approach - Released in 2006 - Outdated values	+ Includes job information - Released in 2010 - Limited to 10 MW arrays	+ Simple to update + Plethora of data + Released in 2012 - Does not perform calculations	+ Highly tunable + Includes net present value + Released 2014 - Only for singular devices

3.8 Implementation into Optimization Work

As developers move closer to array implementation of wave energy converters, it is vital that stakeholders have a solid understanding of the economics associated with WEC arrays. To assist developers in reducing costs, it is important that the process from device design to grid integration is optimized. Research in the wind industry has demonstrated that array optimization tools can provide helpful information for developers. However, for the tools to be useful, the information on which the tools are based must be as accurate as possible.

As such, the models that currently exist are a preliminary foundation, but need to be developed further and need to potentially utilize different methodologies for reporting the cost – rather than solely exploring COE.

Due to the volatility of the ocean and the uncertainty of costs that may be accrued in connection to WEC array development, computational array optimization will assist in the implementation of WEC arrays by predicting the project costs and power development prior

to development. For this information to prove useful, however, the development of a realistic cost model is fundamentally necessary.

3.9 Conclusions

The costs associated with wave energy converters are vast and difficult to accurately discern at this stage in the developmental process due to the lack of congruency amongst technologies. Over the last decade, there have been significant research advancements in understanding the many factors that affect wave energy COE. However, there are still many holes that need filling regarding WEC array cost research.

- Data sharing between industry members
- Standardization
- Better understanding of economic inputs and values
- Specifically better understanding of O&M expenditures
- How to improve the efficiency of a device

In the Pacific Northwest of the US, there are several companies, such as M3 and Columbia Power Technologies, which are at the stage where they can begin to isolate and solidify the costs associated with their devices as they move towards grid connection. Additionally, with the number of developers thinking about and preparing for grid connection, an aspect of research which would be helpful would be to determine the steps that are necessary and the costs associated with these steps. While devices still differ in general design, there are enough similarities for standards to be determined, and with standards in place, up to the point of mooring, cost would be much simpler to determine. Finally, better understanding of WEC device and array economics is vital for the survival of the industry as developers seek to find investors and make accurately informed decisions.

Chapter 4: Modeling

Power has been the driving consideration for determining the optimal arrangement of devices when connecting to the grid as a primary power source. The reason for this emphasis is due to the possibility of arrays of devices being able to produce more power than the same number of devices in isolation. Specifically arrays are being designed to maximize the interaction factor, q , as shown in Eq. 2.1 [9]. Due to the nature in which a majority of WECs affect, and are affected by, their incident ocean waves, the interaction factor, q , has been theoretically found to be greater than one [8], indicating that devices can positively impact farm power development when placed in arrays.

4.1 Power

When an incident wave encounters a floating body (in this case, a WEC) there are two primary results that affect the value of q . First, the object will begin to bob and, similar to the ripples formed from throwing a stone into a pond, waves will radiate away from the object. Second, the incident wave will be forced to “bend” around the device and consequently the waves will increase in height. If devices can be placed so as to benefit from the radiated and diffracted waves generated by up-wave or nearby devices, the device can generate more power than in isolation [7].

There is software that exists, such as the linear wave-body software WAMIT [66], for calculating the power produced by an array of devices in a given sea state, but this software is prohibitively computationally expensive for employment within an iterative optimization method. Alternatively, McNatt et al. has created a novel method for calculating power produced by an array of WECs which utilizes WAMIT for a given device geometry and then calculates the power produced for different array configurations analytically [7]. First the damping, added mass, and hydrostatic matrices of a WEC in isolation are determined using WAMIT. These hydrodynamic properties are found for a specific device geometry and water depth, as well as for a range of wave periods and directions. Figure 4.1 shows an example of the effect that a single device has on a wave field.

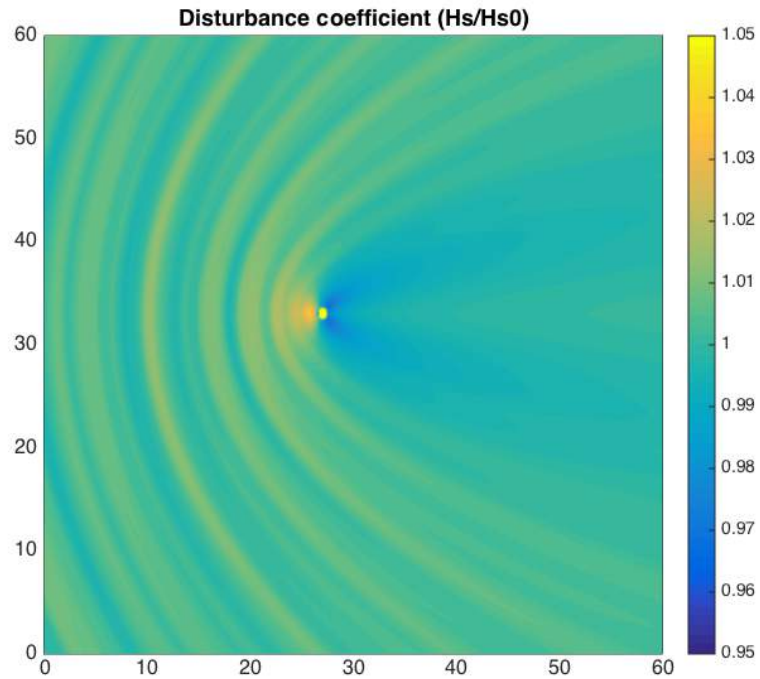


Figure 4.1: Change in Wave Height (m/m) Caused by an Isolated Device

Using the hydrodynamic properties generated in WAMIT for a single device, an analytical model can be used to extrapolate these effects for multiple devices in an array. Accounting for the orientation of each device, the complex excitation force and damping of the entire array is found using the scattered waves of a plane incident wave and the radiated wave coefficients [7]. With this information, the power development of an array can be found using Eq. 4.1 [67].

$$P = \frac{1}{8} \mathbb{X}^* \mathbb{B}^{-1} \mathbb{X} \quad (4.1)$$

In Eq. 4.1, \mathbb{X} is the complex excitation force and \mathbb{B} is the damping of the array [67].

4.2 Cost

Optimizing array layouts while considering only power development as a system objective lacks the realism necessary for wave energy industry's success; the cost associated with developing, deploying, and maintaining a WEC array must also be allowed to influence an array's configuration, but has been neglected up to this point in WEC array optimization work.

The cost model used in the optimization work presented in this article is Sandia National Lab's Reference Model Project (RMP) [29]. While not a calculating tool specifically, the RMP is a collection of costs involved in different WEC array nameplate capacities. As with the other models, there are many assumptions involved, but the RMP is updated as new information becomes available. Figures 4.3 and 4.4 show examples of information provided by the RMP.

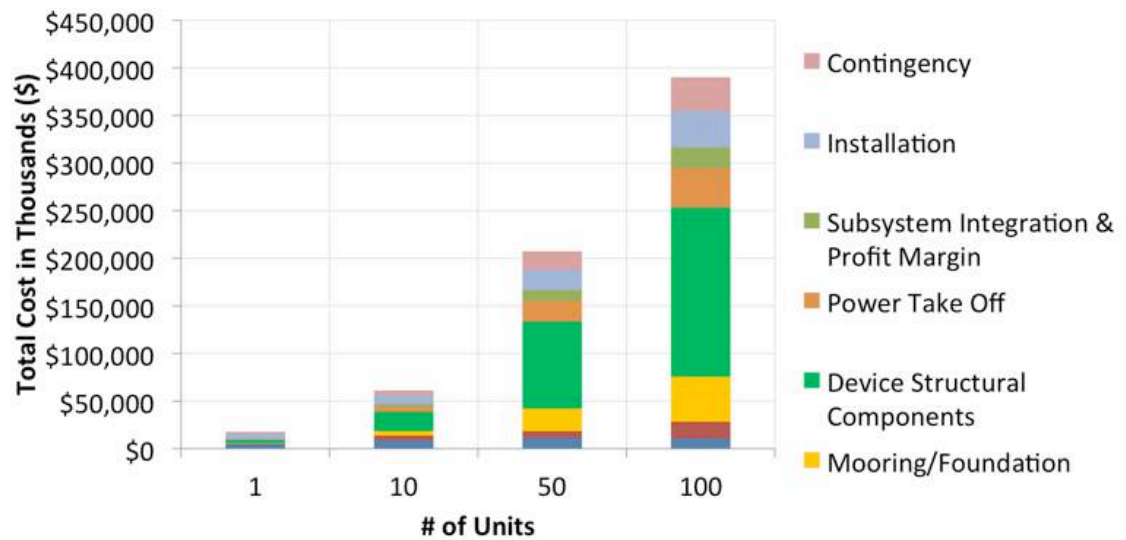


Figure 4.2: Capital Costs for Four Different Sized Arrays from SNL's RMP [29]

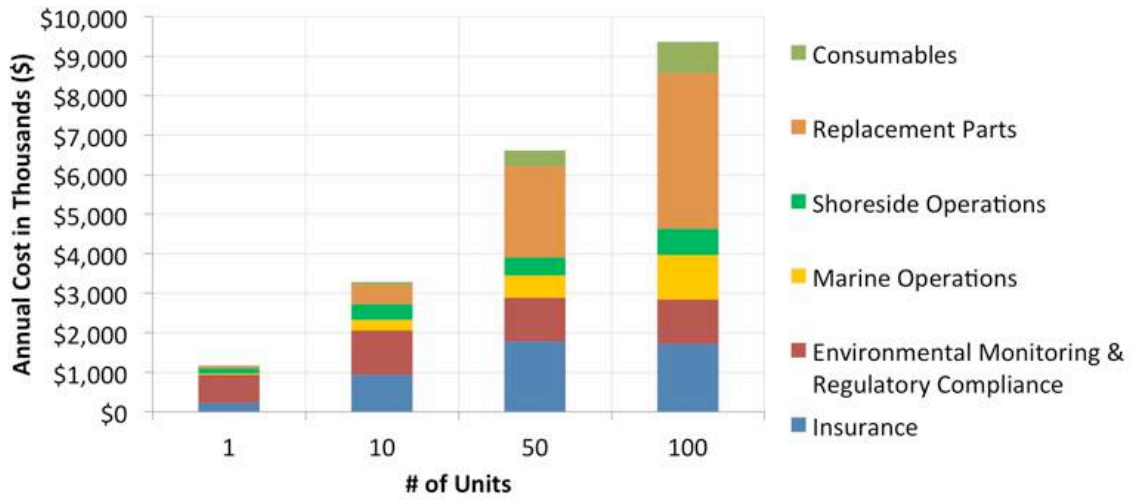


Figure 4.3: O&M Costs for Four Different Sized Arrays from SNL's RMP [29]

For the optimization method developed as part of the presented work (preliminary results will be presented in Chapter 7) the cost equation was formulated by fitting a polynomial to the information provided by SNL's RMP and is shown in Eq. 4.2.

$$Cost = 3(10)^7 * N^{0.6735} \quad (4.2)$$

In Eq. 4.2, the cost of an array is based solely on N , the number of devices in an array. Considering only the number of devices, this formulation serves as a placeholder, to be updated with new information as it is developed, while still allowing cost to influence array configuration.

Chapter 5: Genetic Algorithm Approach

In order to account for the economic influence on WEC arrays, we developed an optimization approach that utilizes a binary Genetic Algorithm (GA) to generate suggested layouts. The GA is used because of its ability to efficiently converge upon an objective function's optimal solution while considering an array of continuous and discrete factors. Including cost as a contributing component to the optimal arrangement of WECs in an array, the multi-objective equation chosen to reflect the trade-off between cost and power is shown in Eq. 5.1.

$$\text{Objective Function} = \frac{\text{Cost}}{P_{20}} \quad (5.1)$$

In this objective function *Cost* is the value found using Eq. 5.1 and P_{20} represents the power generated by an array over a 20-year lifetime. Throughout the search this objective function is being minimized. The unit of this objective is cents per kilowatt-hour - this means that once the cost models attain accuracy, the value of Eq. 5.1 will represent a lifetime averaged cost of energy and could be used for comparison against energy sources such as wind or solar.

A GA is an evolutionary optimization algorithm that mimics how chromosomes are passed from parents to children while allowing for mutations to prevent converging on local optima. The function of the GA is improved by utilizing such stochastic attributes, including the generation of a random population of parents. In the implemented algorithm there are several tunable parameters – elitism, crossover, and mutation. An individual parent represents a unique array solution. Figure 6 shows how the arrays are turned into strings for the GA.

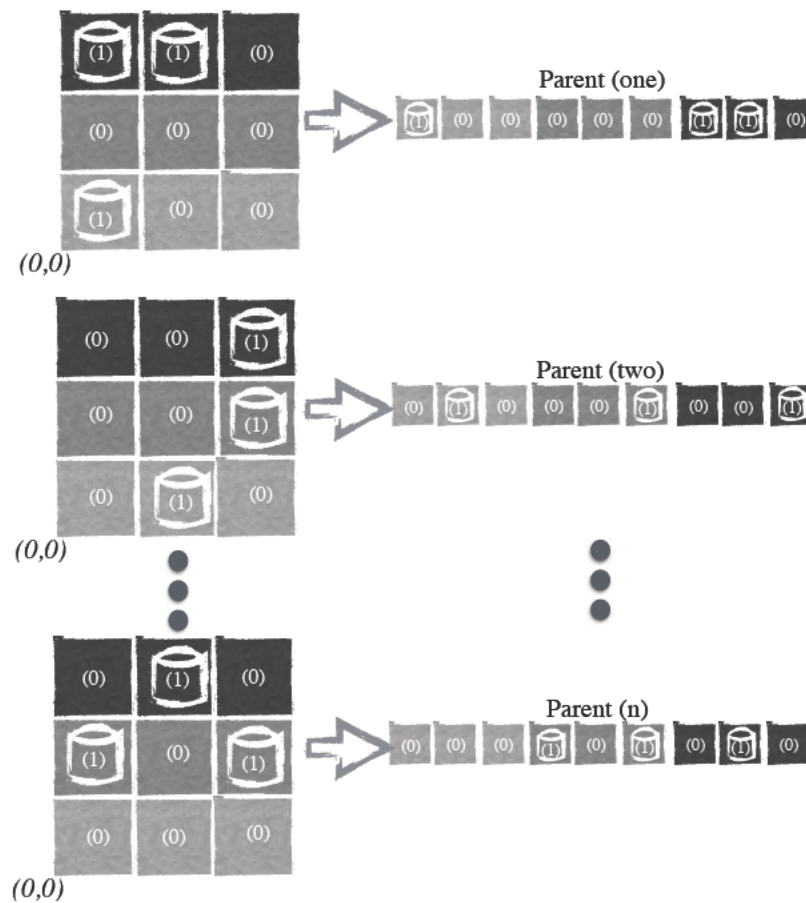


Figure 5.1: Example of the Relationship Between Arrays and Parent Strings

Each cell in an individual parent string represents a section of the ocean and includes either a one, representing a WEC, or a zero, representing empty ocean. The binary GA is strategically chosen such that the minimum separation distance between devices – an aspect of array design that has been previously unexplored – can be readily explored (the effects of the minimum separation distance are shown in Chapter 8).

Once the initial parents are generated, they are evaluated according to the objective function (Eq. 5.1) and ranked. The elitism function, which clones an upper percentage of the

parent population, copies potential solutions directly to the children set. To balance this elitism, the same percentage of the worst solutions, based on objective function evaluation, is also removed from the set. After elitism, crossover is performed on the parent population. Because the WECs are located sparsely throughout the space and because the number of devices is initially constrained to a set value, multi-point crossover is not employed. Instead, the integrated method of crossover involves selecting a WEC or WECs from parent (n) and placing that WEC or WECs in parent (n+1). Likewise the same number of WECs is selected from parent (n+1) and placed in parent (n). Figure 5.2 demonstrates the crossover method.

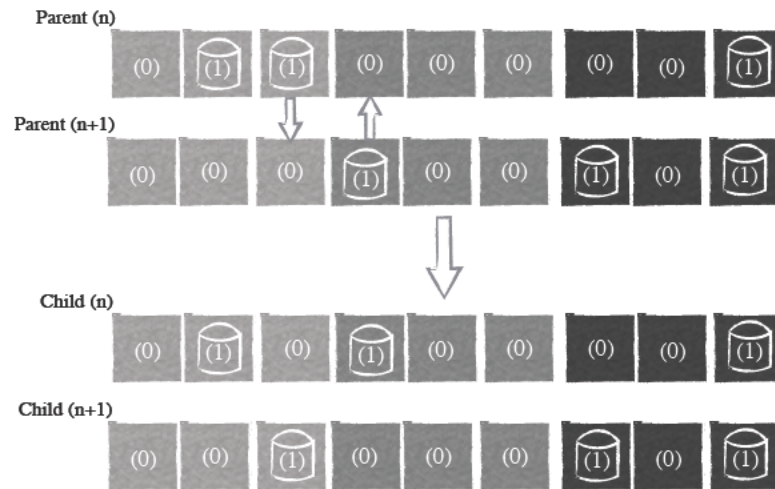


Figure 5.2: Illustration of Implemented Crossover Method

Crossover is performed on a defined percentage of the parent population and the selection of which WEC or WECs to swap is both tunable (by selecting the number of WECs to swap) and random (choosing which of the devices will be swapped). Next, mutation is performed on the children created from crossover. For mutation, a very small percentage of cells are randomly selected throughout the space and the value changed from

either a one to a zero or a zero to a one. Once the children set is complete it is evaluated and ranked.

After ranking, the population is checked for convergence. Convergence is defined as identical layouts and objective evaluations amongst a defined upper percentage of the population. Once convergence is attained the algorithm returns the converged solution as the reported optimal array layout. If convergence isn't attained the process continues. Figure 5.3 shows the pseudocode for the GA used in this work.

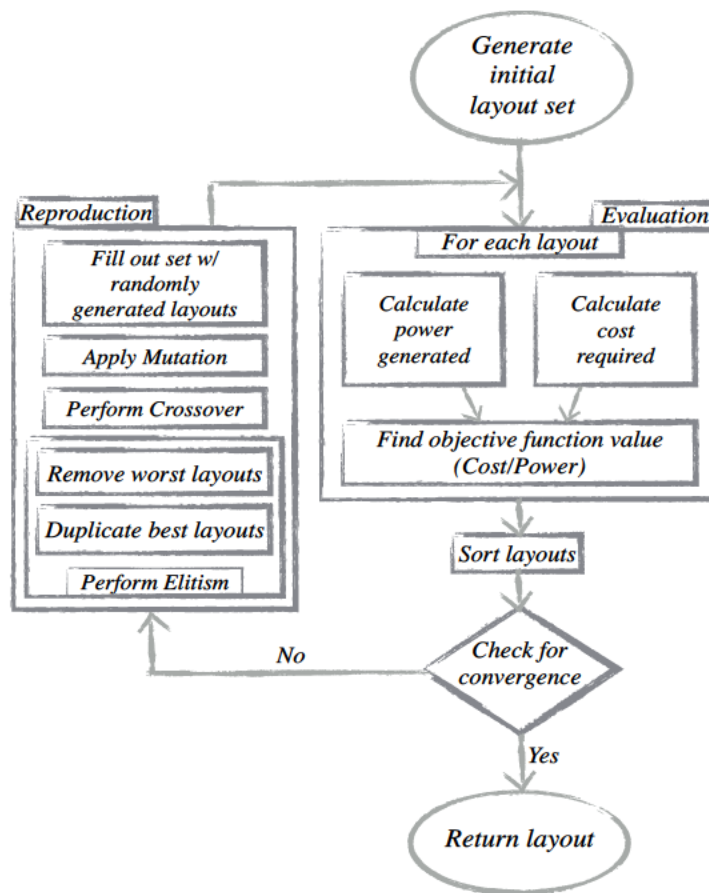


Figure 5.3: Genetic Algorithm Flowchart

Chapter 6: Problem Formulation

To demonstrate the code we developed and to achieve the results presented in the following chapter, five truncated cylinders (Figure 6.1), constrained in heave, were placed in a Bretschneider spectrum with unidirectional waves. The heaving, truncated cylinders utilized for this work represent point absorber type WECs acting in the vertical direction, and the unidirectional waves mean that the waves are only coming from a single cardinal direction. The Bretschneider spectrum had a modal frequency of 0.2 Hz, a significant wave height of 2m, and periods ranging from 4 seconds to 8 seconds. These parameters were chosen to better compare our results, using a novel genetic algorithm implementation, with the results of Child and Venugopal [5].

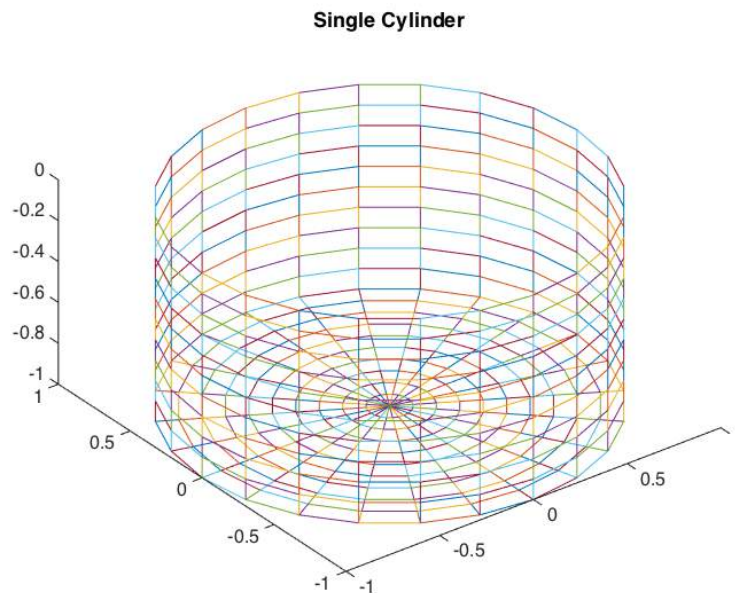


Figure 6.1: Truncated Cylinder Utilized in the Optimization Method

The space utilized for both studies was a 10x10 grid allowing for one hundred different locations to place five WECs. The unidirectional wave field and single degree of freedom WEC are meant as a test case to prove the efficacy of the GA method.

6.1 Parameters for Preliminary Study

Multiple preliminary trial runs of the binary GA were conducted in order to empirically derive appropriate parameter values for two different minimum separation distances. A minimum distance was used to replicate the need to minimize physical device interaction. This minimum separation value is the center-to-center distance of neighboring cells and with devices placed in the center of these cells is the closest center-to-center distance that WECs are allowed to get to each other. The primary case, Case (A), has a minimum separation distance of three times the device diameter, or six meters, which is based on the work of DNV-GL [6]. In addition to the six-meter case, an alternative case, Case (B), was run at which the minimum separation distance was three meters. There are two aspects of parameters that can be tuned – the physical space and the genetic algorithm.

Table 6.1: Preliminary Study Tunable Space Parameters

Space Parameters			
Case	# Of WECs	Resolution ($l \times w$)	Minimum Separation Distance
(A)	5	10 x 10	3*diameter [6] = 6 m
(B)	5	10 x 10	3 m

Table 6.2: Preliminary Study Tunable GA Parameters

GA Parameters					
Case	# Of Parents	Elitism Rate	Crossover Rate	Mutation Rate	Convergence Requirement
(A)	100	10%	80%	0.2%	50%
(B)	100	8%	84%	0.2%	50%

In Table 6.1, ‘*l*’ refers to the alongshore direction, South-North, and ‘*w*’ refers to the offshore direction, West-East. The resolution refers to how many potential locations a WEC could be located in an array (e.g. In a space with resolution 10x10, there are 100 potential locations to place the 5 WECs). Consideration was given to the resolution so as to avoid limiting the space and missing potential optimal configurations. For the crossover step, two WECs were chosen, at random, to crossover between parents.

6.2 Parameters for Spacing Study

To better understand the effect that the minimum separation distance has on the layout configuration, the spacing study takes the preliminary study and adds two more cases. In addition to the three-meter and six-meter minimum separation distance cases, a four-meter and five-meter case was completed. Tables 6.3 and 6.4 show the parameters used for each of these cases. From the preliminary study, Case 1 is the same as Case (B) and Case 4 is the same as Case (A).

Table 6.3: Spacing Study Tunable Space Parameters

Space Parameters			
Case	# Of WECs	Resolution ($l \times w$)	Minimum Separation Distance
1	5	10 x 10	3 m
2	5	10 x 10	4 m
3	5	10 x 10	5 m
4	5	10 x 10	6 m

Table 6.4: Spacing Study Tunable GA Parameters

GA Parameters					
Case	# Of Parents	Elitism Rate	Crossover Rate	Mutation Rate	Convergence Requirement
1	100	8%	84%	0.2%	50%
2	100	8%	84%	0.2%	50%
3	100	8%	84%	0.2%	50%
4	100	10%	80%	0.2%	50%

The following chapters will present and discuss the results found from the preliminary study and the spacing study.

Chapter 7: Preliminary Study Results and Discussion

For both of these cases, due to the stochastic nature of this GA and the constrained placement of each device, convergence on multiple comparably optimal layouts was implicated. The optimal configurations presented here are those achieved the most consistently which had the best objective evaluation. Concerning Case (A), two similar consistent layouts were converged upon. Layout (A) is the solution of Case (A) that has the lowest objective evaluation and is shown in Figure 7.1.

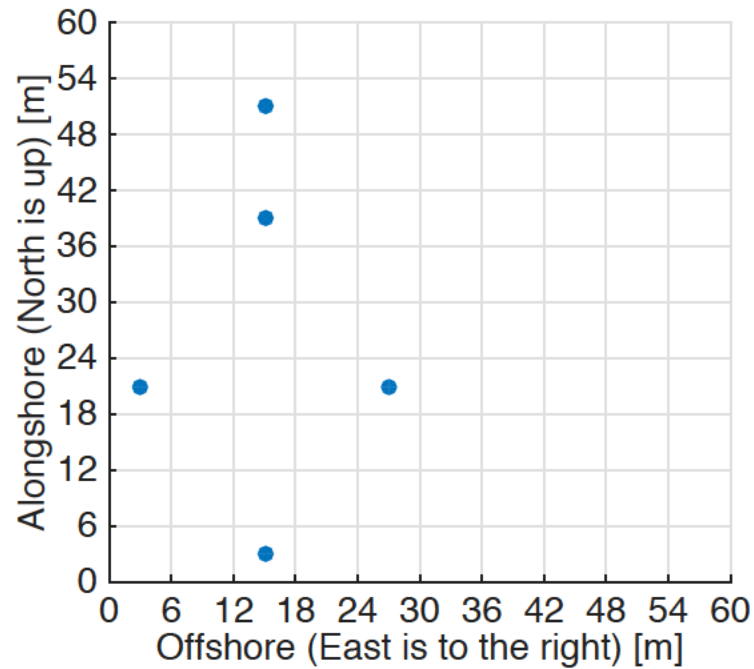


Figure 7.1: Optimal Solution of Case (A), Layout (A)

For the majority of the layouts develop from Case (A), the devices were offset from one another. Interesting, a slight variation of Case (A) was also obtained several times. This

alternative solution, Layout (A'), is shown in Figure 7.2. Layout (A') has the same diamond shape facing the oncoming wave, but doesn't have any WECs vertically next to each other. This Layout (A') does have a larger objective evaluation, but only by a very small amount. (See Table 7.1)

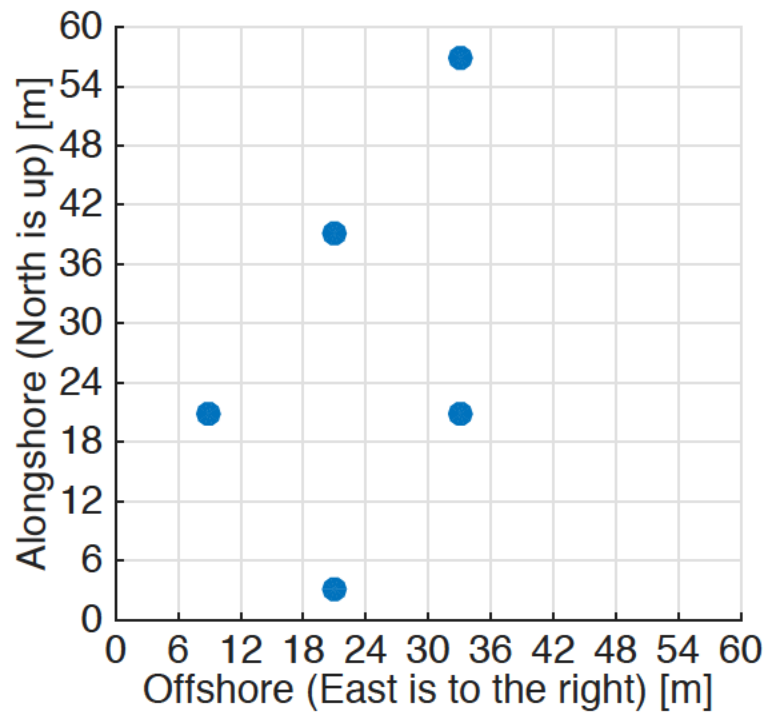


Figure 7.2: Optimal Solution of Case (A), Layout (A')

To better compare the results of Layouts (A) and (A') the wave field interactions with the layouts are examined. In both cases the devices appear to be lining themselves up to take advantage of the greater wave heights generated by the up-wave devices. Layout (A) also suggests that a WEC doesn't necessarily have to be down-wave from another in order to benefit.

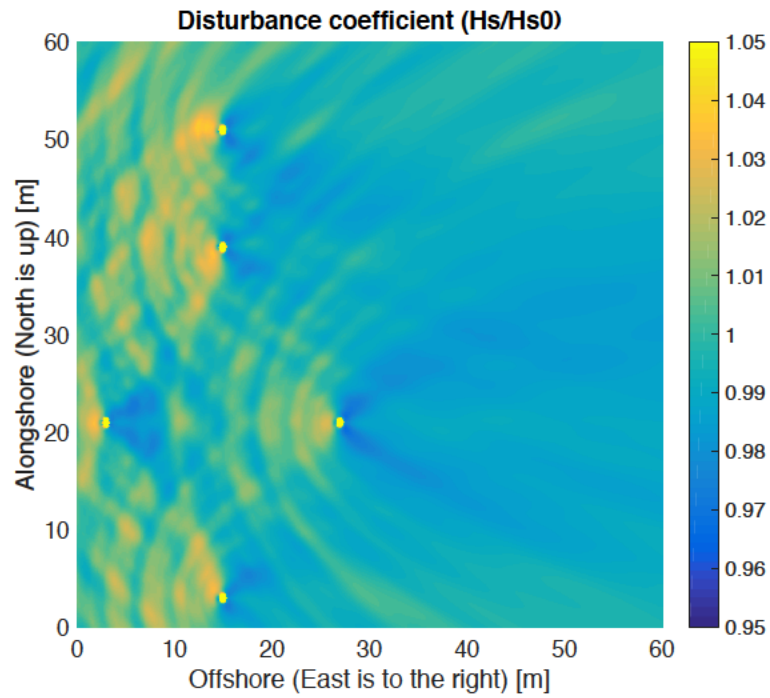


Figure 7.3: Case (A), Layout (A) Wave Field

The north most device in Figure 7.3 is both taking advantage of the waves scattered by the device below it as well as benefitting the device to the south. In contrast, the uppermost device in Figure 7.4 only minimally benefits any other devices with its scattered waves, which probably explains the higher objective function and lower interaction factor calculated for Layout (A') in and shown in Table 7.1.

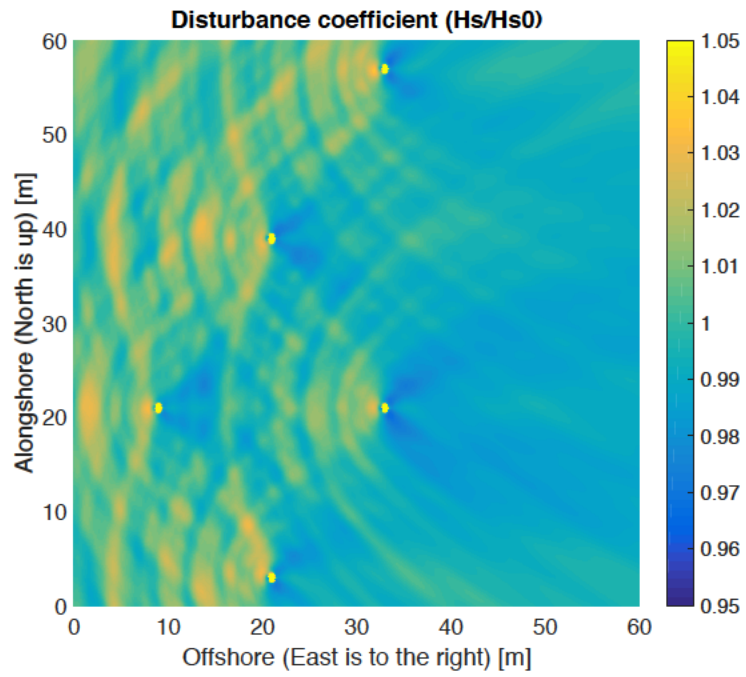


Figure 7.4: Case (A), Layout (A') Wave Field

In contrast to the Layouts (A) and (A') generated by Case (A), Case (B) obtained the result portrayed in Figure 7.5.

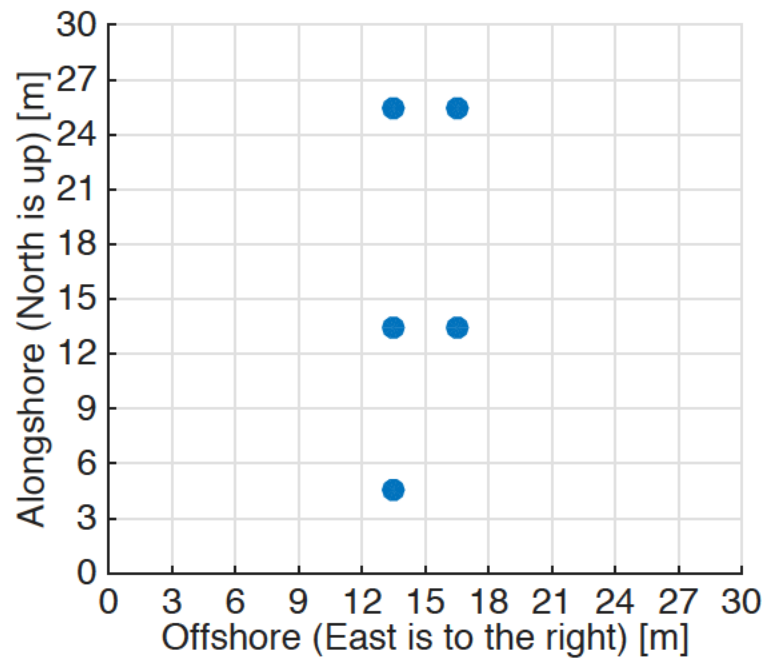


Figure 7.5: Optimal Solution of Case (B)

Interestingly, when the devices are allowed a smaller separation distance, the tendency is to line themselves up in pairs with one directly down-wave from another at the minimum allowable distance. Examining Figure 7.5 shows areas of increased wave heights between the devices that are inline with the incident wave. This increase in significant wave height behind the up-wave devices could be due to each device radiating waves for the other's benefit. It might seem that the south most device would line itself up with one of the pairs of devices, but when the algorithm attempted this configuration the objective function evaluation was higher than that of the converged layout – indicating that more than two devices inline loses the advantage found by radiated waves experienced with only pairs of inline devices.

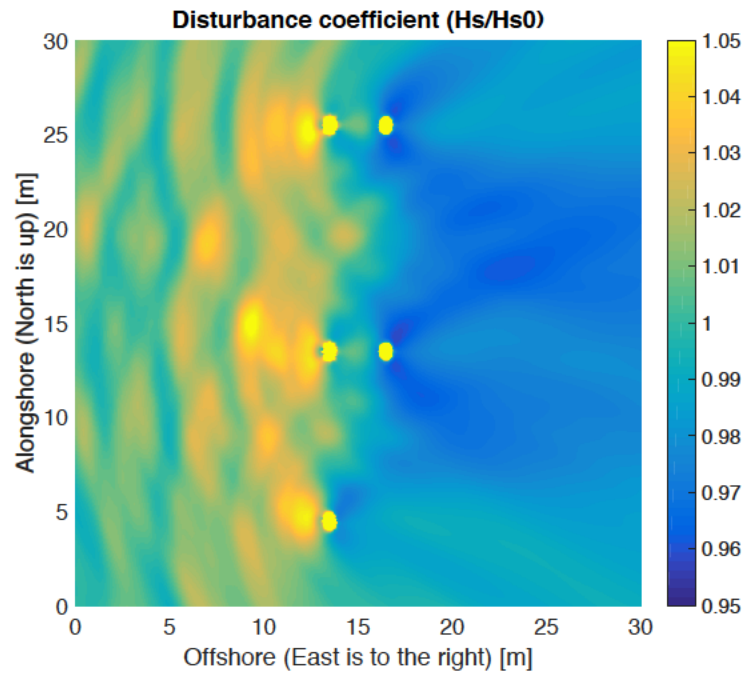


Figure 7.6: Case (B) Wave Field

Examining the objective function evaluations in Table 7.1 reveals a lower – and therefore more optimal – objective function value for Case (B) than for Case (A). This lower value would suggest that an increase in the interaction factor could be best achieved through radiated waves rather than via the diffracted waves. However, the objective function does not take into consideration the cost which could be associated with potentially damaging a device by placing it too close to its neighbor. As the cost and power models gain fidelity in the future, it will be interesting to see which, if either, of the radiated or scattered waves dominates in regards to interaction effect. Given the information available now the objective function evaluations and interaction factors found for the cases are summarized in Table 3.

Table 7.1: Objective Function and Interaction Factor Results from Case (A), Layouts (A) & (A') and Case (B)

Case	Objective Function	Interaction Factor (q)
(A)	3.7920	1.019
(A')	3.7994	1.017
(B)	3.7737	1.024

Now that the results from the developed genetic algorithm have been presented and evaluated, they will be compared against the results found by [5]. As was presented in Chapter 2, Child and Venugopal utilized two methods to optimize a layout. Figures 2.1 and 2.2 demonstrated a representation of the results achieved. Both results have a similar 'W' shape with the waves approaching towards the side of the 'W' that has two points. The PI method gives similar results as what was generated by the presented GA, but despite the similar nature of device placement, this method is limited both in its ability to account for different wave directions and the lack of cost objective. The following Table, Table 7.2, compare the objective function evaluations of Case (A), Layout (A) with those of the layouts shown in Figures 2.1 and 2.2. To ensure a more equivalent comparison, the layouts of Child and Venugal were represented by the author and their objective function evaluation calculated using the method used to find Case (A), Layout (A).

Table 7.2: Comparison of the Objective Function and Interaction Factor of Case (A), Layout (A) with Presented Layouts of Child & Venugopal

Method		Objective Function	Interaction Factor (q)
Presented Genetic Algorithm	Case (A), Layout (A)	3.7920	1.019
Child & Venugopal [5]	Parabolic Intersection	3.8793	0.9961
	MATLAB'S Genetic Algorithm	3.8864	0.9942

What is observed when comparing these results is that the WEC arrangement found by the method presented here achieves a lower objective function evaluation and performs much better than the example layouts from Child & Venugopal. It should be noted that the interaction factor found for the results from Child & Venugopal when using the method presented in our research differ from the reported interaction factors – 0.9961 versus 1.787 for the Parabolic Intersection (PI) method and 0.9942 versus 2.1010 for the MATLAB GA method [5]. This indicates that the power is being calculated in a different manner than what is presented in our work. The values reported for the PI and MATLAB GA method seem to be high, but without knowing how the power is calculated for these methods, it is difficult to determine their validity. Additionally, the referenced results from the PI and MATLAB GA methods use a regular wave set rather than the Bretschneider spectrum utilized by our presented optimization method. These differing wave fields would also affect the power developed.

Chapter 8: Spacing Study Results and Discussion

For the results presented here the optimization algorithm was employed for four different cases where the minimum separation distance was adjusted – three meters, four meters, five meters, and six meters. The three-meter and six-meter cases are the same as Case (B) and Case (A), Layout (A) discussed in Chapter 7 respectively. Due to the stochastic qualities inherent in a GA, the same layout was not achieved with every run; however, the results presented were the most common and displayed the lowest objective function evaluation.

The results obtained from each case are presented in Figure 8.1 – 8.8. 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.

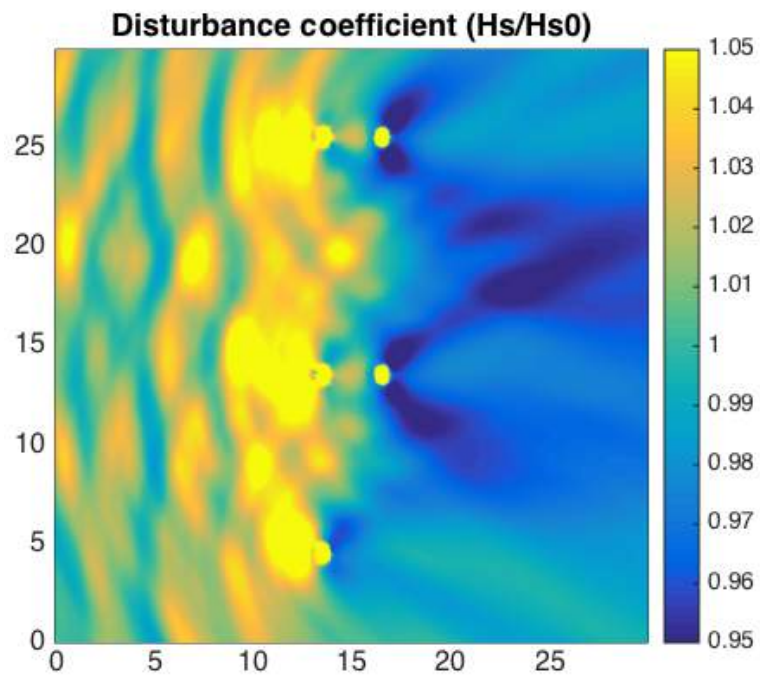
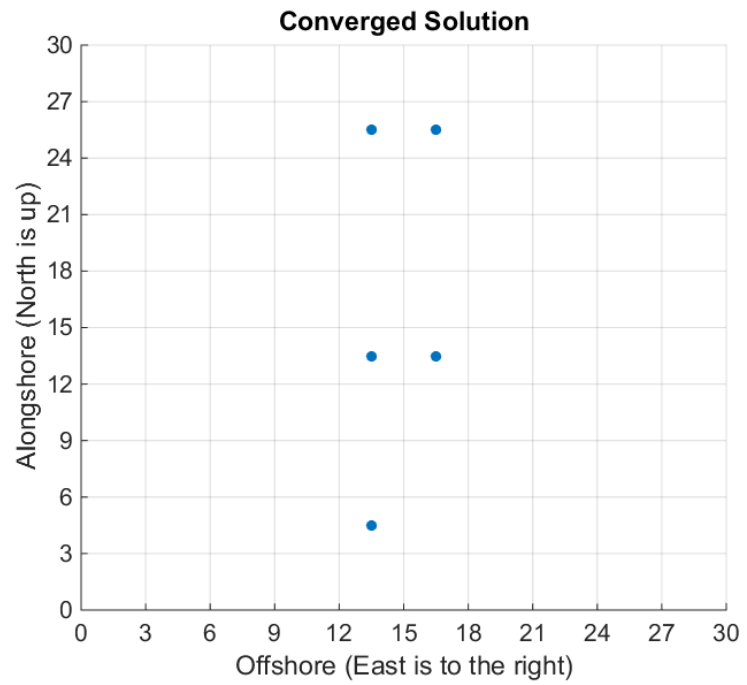


Figure 8.1/8.2: Case 1 (3-meter Minimum Separation Distance) Layout and Wave Field

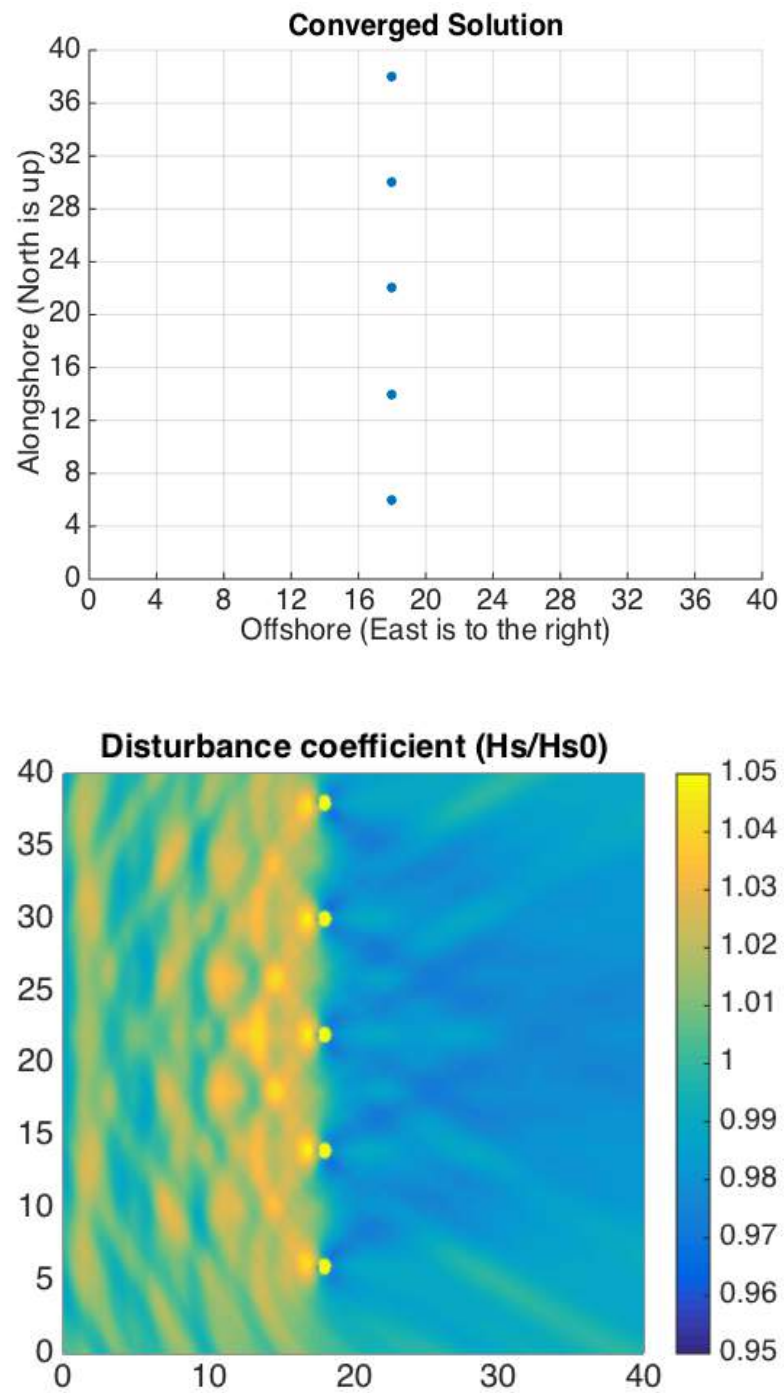


Figure 8.3/8.4: Case 2 (4-meter Minimum Separation Distance) Layout and Wave Field

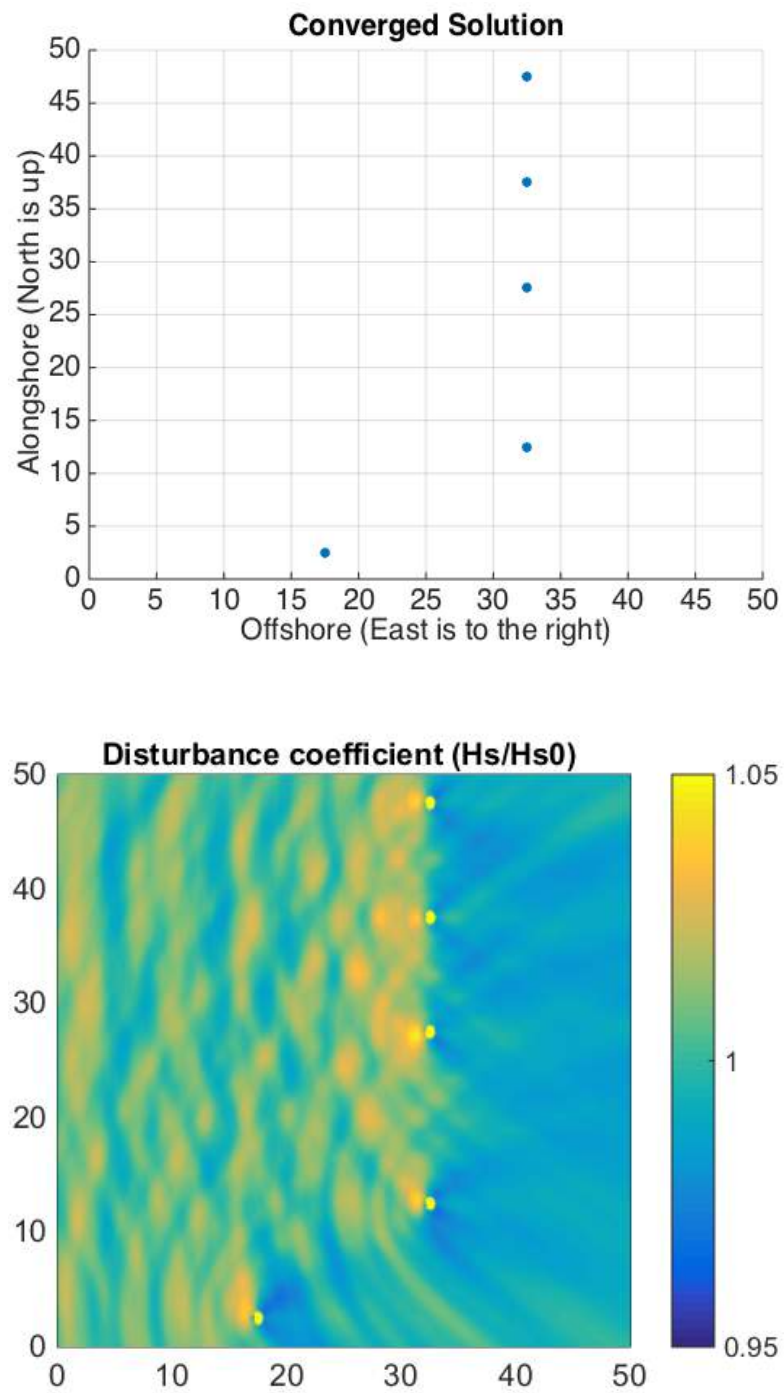


Figure 8.5/8.6: Case 3 (5-meter Minimum Separation Distance) Layout and Wave Field

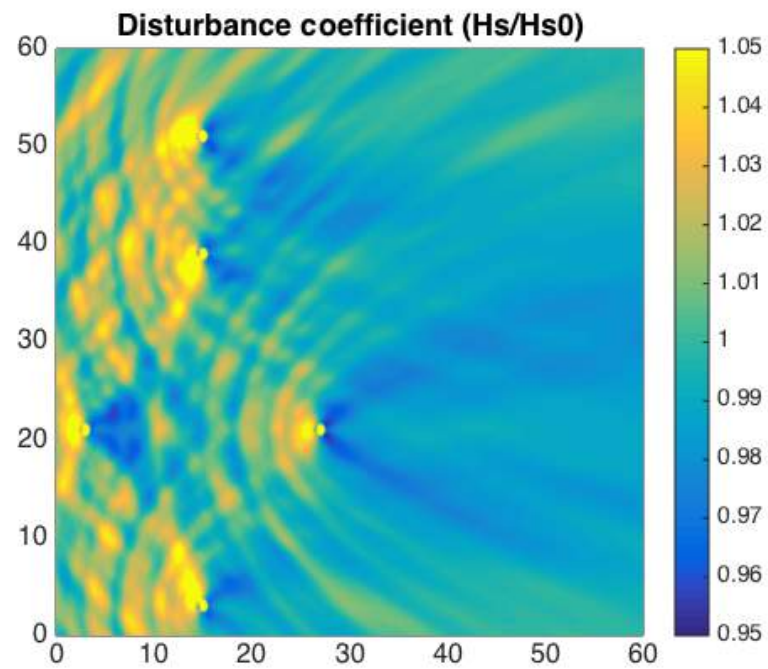
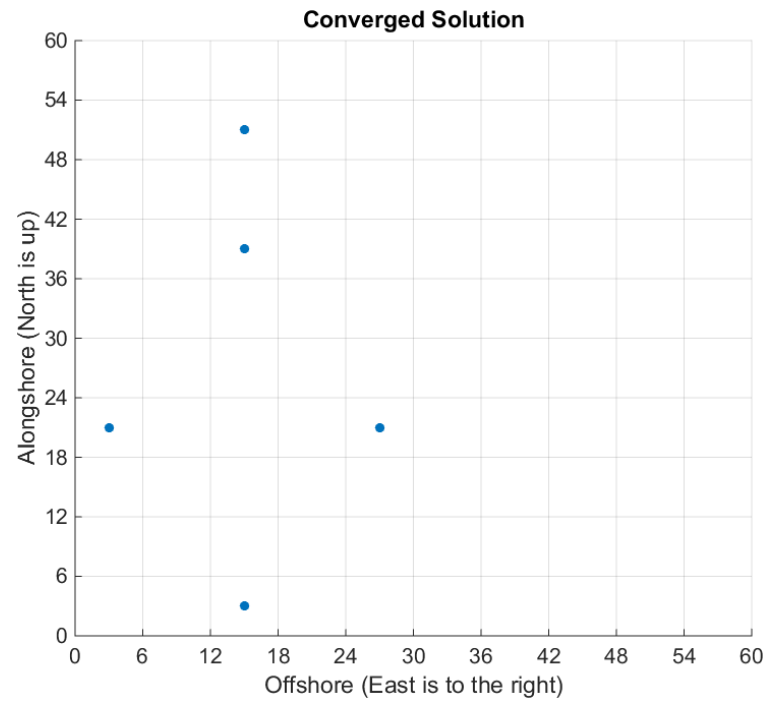


Figure 8.7/8.8: Case 4 (6-meter Minimum Separation Distance) Layout and Wave Field

The interaction factor, q , as defined in Eq. 2.1, obtained for all of cases evaluated in the spacing study is shown below in Table 8.1.

Table 8.1: Interaction Factor Comparison between all Four Cases

	Case 1	Case 2	Case 3	Case 4
Interaction factor	1.024	1.021	1.016	1.019

It can be observed that the best resulting shape found from 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 likely 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.

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.

Chapter 9: Conclusions

With the volatility and power that is found in ocean waves it is paramount for the success of the wave energy industry that developers are supplied with the most realistic and informative data regarding the deployment of arrays of WECs in real sea conditions. If designed well, the layout of WEC devices in an array scenario has the opportunity to increase power production through device interaction as well as to minimize the cost of the array through shared infrastructure. Prior to the completion of this research, WEC array design research has only considered maximizing an array's power production without considering economics. Utilizing a test case scenario, the work presented here shows the optimal results generated through the development and application of a binary genetic algorithm. When WECs are placed in the ocean, two primary types of waves are generated by the device that can then be utilized by neighboring devices for producing power – radiated waves and diffracted waves.

In Case 1, when restricted to a three-meter minimum separation distance, the devices line up in pairs parallel to the oncoming wave. These pairs of WECs are taking advantage of the radiated waves. However, when the minimum distance is increased to six meters, the converged layouts place themselves in a diamond shape with one corner pointing towards the oncoming incident wave such that the devices take advantage of nearby device's diffracted waves. This change is due to the dissipation of radiated waves. When considering the deployment of devices in real sea scenarios it is doubtful that devices would be placed close enough to take advantage of the radiated waves and achieving an interaction factor greater than one due to array layout would likely depend on diffracted waves.

The variability of optimized arrays shown in Figures 8.1 – 8.8 demonstrate the need for further research regarding multi-directional wave profiles, and also indicates a connection between an optimized layout and the local sea conditions. An optimized array configuration will likely differ depending on the section of ocean in which a developer is interested. To assist the promotion of the wave energy industry, the creation of a tool that develops WEC

layouts given a type of device and section of the ocean would be helpful in increasing investor confidence by predicting system performance prior to implementation. Further research that should be pursued includes improving cost models, creating environmental impact models, using accurate and variable device designs, and incorporating real sea conditions.

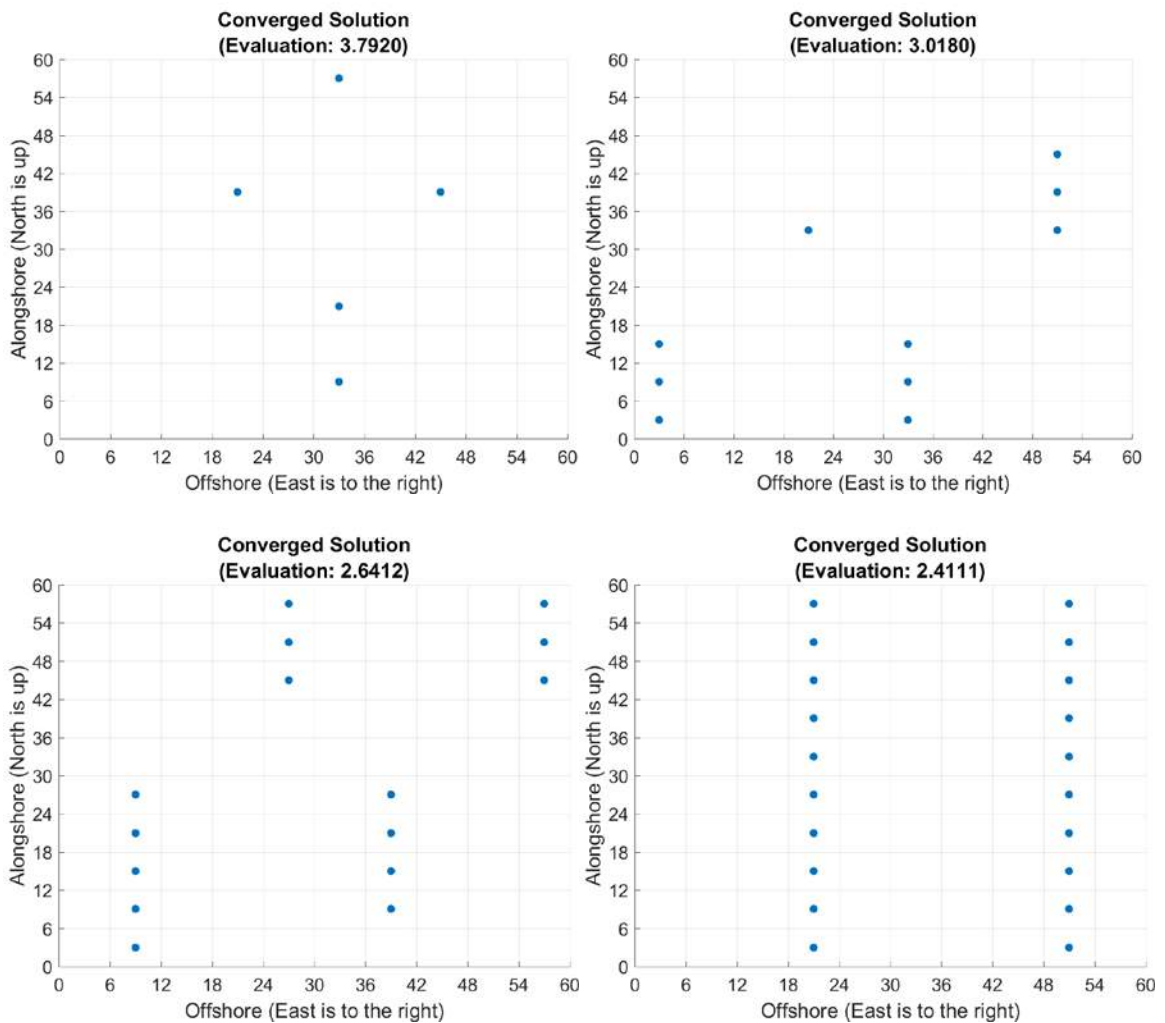
In WEC array development, the optimal layout for devices is determined to be dependent on the local sea state, device design and geometry, the minimum distance between devices, and costs based on local information. Given a heaving point-absorber type WEC and a unidirectional wave, an optimal configuration can be deduced. However, once realistic inputs are included, optimization methods (such as the GA work presented here), capable of handling the plethora of inputs necessary for supplying useful array suggestions to industry, must be utilized. Additionally, in order for array optimization work to help break down barriers to implementation in industry, all factors that affect the WEC array system should be accurately modeled. Currently, power is the driving factor in regards to array configurations. While the challenge of arranging WECs with an interaction factor greater than one is interesting from a power development standpoint, incorporating cost is necessary for allowing WEC array optimization to be used by industry stakeholders. With these added objectives, optimization methods such as genetic algorithms are shown here to be useful for generating suggested arrays of WECs. The preliminary GA results presented in this work show the capability of the method for learning about optimal arrangements where economic influence is included in addition to that of power. Future work will involve removing the simplification factors of wave direction and number of devices. Also, as cost models are improved and environmental impact models created the algorithm can be updated accordingly.

Chapter 10: Continuing Research

The presented research has provided a basis for continuing research. This chapter will discuss avenues of that continuing work and will display several early results. Primarily, the ongoing work is divided into several categories – using the GA to find the optimal number of devices to put into a defined section of the ocean, and implementing a real-coded GA instead of a binary GA to more precisely search the solution space.

10.1 Optimal Number of Devices

Up to this point, the number of devices used in array configuration design research and array design optimization research has been defined, and no research has been done to determine how many devices would be optimal for use in a given section of the ocean. It is important that developers determine how to best utilize the section of ocean they have access to, whether through policy or leasing. The absence of research in which the number of devices is varied has been due to the lack of an objective that counteracts the power. If only power is considered then the most power generated would occur when the entire space is flooded with as many devices as is physically allowable. However, when cost is introduced as an objective to appose power, the optimal number of devices is that which maximizes power while minimizing cost. To that end, the algorithm described in Chapter 5 is run for different numbers of devices. For each set number of devices, the space is a 10 x 10 grid with a minimum separation distance of six meters. This equates to a sixty-meter by sixty-meter section of the ocean. The number of devices explored range from 5 devices to 20 devices in increments of 5. At each set number of devices, 10 trials were performed. The best result for each set of devices from these trials can be seen in Figure 10.1 – 10.4.



Figures 10.1-10.4: The Best Layout, Based on Objective Function Evaluations, for 5, 10, 15 & 20 Devices

After finding the objective function evaluations for all 10 trials at each defined number of devices, a second-order polynomial fit was applied to these results. The minimum of this polynomial fit will point to the number of devices that is optimal in the given space. Figure 10.2 shows the polynomial fit when applied to the results shown in Figure 10.1.

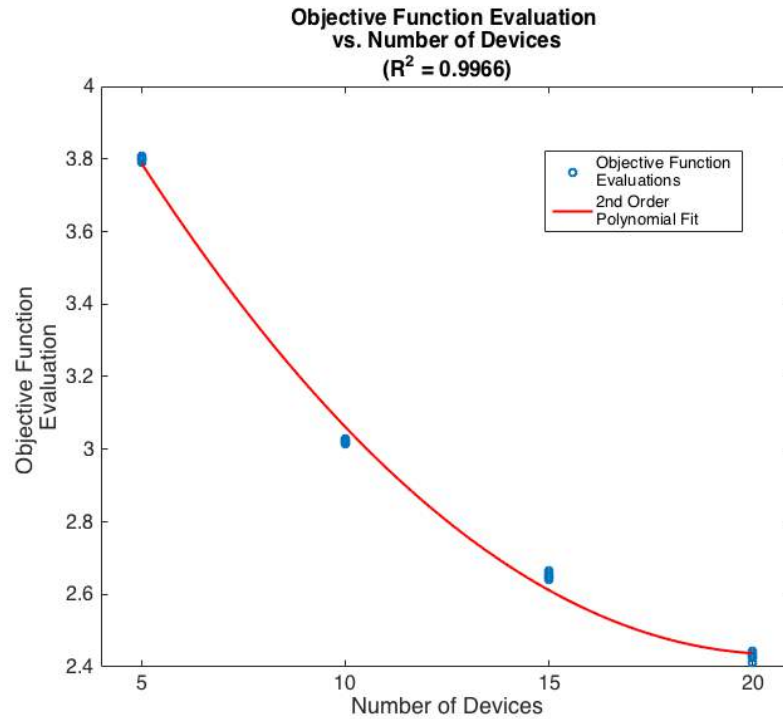


Figure 10.5: The 2nd Order Polynomial Fit when Applied to the Objective Function Evaluations of 5, 10, 15 & 20 Devices – 10 Trials Each

With an R^2 value of 0.9966, there is a definitive trend in the data that corresponds to a second-order polynomial. Based on the fit, it is apparent that the optimal number of devices has not been found yet, and will occur for a layout with a higher number of devices. At the time this research was conducted, runs with higher number of devices were still being attained.

10.2 Real-coded Genetic Algorithm

The work presented here is that of a binary genetic algorithm which was useful for exploring and understanding the effect that spacing has on layout's objective function

evaluation. However, when the space is discretized and devices constrained to the center of cells (as with a binary GA) there is the chance that the optimal configuration may be between tested discrete values. As such it is advantageous to allow the algorithm to determine the optimal spacing rather than depend on user input that, especially at this stage of array development, is limited in its knowledge.

10.3 Introducing a Variable Number of Devices into a Real-coded GA

The next primary research goal is to combine the previously mentioned areas – create an algorithm that is able to determine the optimal spacing between devices as well as the optimal number of devices and their arrangement. When adjusting the algorithm described in Chapter 2 to account for a varied number of devices in a discretized space, it was observed that with the current objective function, cost divided by power, the space was being filled with as many devices as possible. Consequently, it was decided that rather than continue to use a single objective function that combines cost and power, the objectives would be left separate and Pareto front approach implemented. The new objective will be to find the number of devices and their arrangement such that the shortest distance to the Pareto point representing the lowest cost and the highest power is found. This work is currently ongoing and will be implemented into the real-coded GA when it is created.

10.4 Final Thoughts

The research presented here has provided a solid basis in regards to ongoing work and we are excited to continue to pursue these facets as well as to explore new areas of research within the realm of WEC array optimization as they arise.

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