Analysis of WEC Array Economics: Current State-of-the-Art and Future Needs

Chris Sharp[#1], Bryony DuPont[#2]

[#]*Department of Mechanical Engineering,*
Oregon State University
Corvallis, Oregon, USA

[1]sharpc@onid.oregonstate.edu
[2]Bryony.DuPont@oregonstate.edu

***Abstract*— Like the clustering of wind turbines on wind farms, many wave energy converters (WECs) must be installed close together in order for WECs to be commercially viable. Developers need computational methods for optimizing WEC placement in order to maximize power output while minimizing cost, environmental impact, and view-shed (the visibility of WECs in their environment). In order to accurately predict performance of WEC arrays, comprehension of the various costs involved - including installation, grid integration, and operations and maintenance costs - is of paramount importance. This paper will investigate factors affecting WEC array cost and state-of-the-art cost models as well as determining where the existing models need improvement. At this stage in wave energy technology, and with the importance of implementing ocean energy into the grid, the factors involved in the cost of WEC arrays are scattered and models that exist include different information based on varied assumptions and applicability. The purpose of this paper is to centralize the information that currently exists and to point out what gaps in the information need to be filled, with particular focus on comparing the US energy market to those of other countries, as offshore renewable technology faces significant barriers to implementation in the US.**

***Keywords* — Wave Energy, WEC Array Economics, Cost Factors, Cost Reduction, WEC Cost Models**

I. INTRODUCTION

As a vast and powerful component of this world, oceans have the potential to serve as a primary energy source in coastal regions by providing consistent, predictable power without producing the harmful byproducts associated with currently utilized energy sources. However, capturing the energy of the ocean in a cost effective manner presents a significant challenge. Over the last two decades, advancements have been made in the realm of wave energy conversion devices. These wave energy converters (WECs) are nearing the need to demonstrate their capability as a grid supportive energy source (Note: Throughout this paper 'array,' 'layout,' and 'farm' will be used interchangeably to refer to a grouping of WECs).

Like the clustering of turbines on a wind farm, for wave energy to produce utility-scale power, many WECs will likely be installed in close proximity to one another. There is a need for developers to be able to optimize WEC arrays computationally in order to determine how these arrays will function when deployed. While preliminary research has been done regarding such optimization, these approaches are simplistic – the arrays are optimized solely based on the power produced [48]. While this information is useful, developers are constrained by the cost needed to install arrays of WECs and as such an optimized layout should also consider the costs involved with a specific array configuration.

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.

II. 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 greener 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.

A. 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 [1]. 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) [1]. 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.

In a paper presented at the 2012 International Conference on Ocean Energy, ocean waves were presented as a potential resource that could provide more than 50% of the United State's needed energy [2]. A preliminary range of the cost of energy (COE) for wave energy is between 0.18 USD/kWh and 0.34 USD/kWh [2]. 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) [2]. 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 [1].

B. 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 [3]. The roadmap introduces four phases: ¼-scale technology deployment, full-scale devices, pre-commercial arrays (<10 MW), and commercial scale arrays (>100 MW) [3]. 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 [3]. 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.

C. United Kingdom and Scotland

The United Kingdom (UK) is legally committed to lowering carbon emissions by 2050 [4]. 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 affect on the associated cost [2].

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 [3], and later assessed the state of marine renewable energy in Scotland in 2009 [4]. Through these roadmaps, Scotland has become a global leader in marine renewable energy, culminating in multiple test- and grid-scale projects [5]. 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 [6].

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.

III. 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.

A. 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" [5]. 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 [5], [6].

B. 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" [7]. 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 [7]. The simulations are preliminary and require many functional assumptions, but still provide a baseline for subsequent research. These findings will be discussed in section VI.

C. 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 [9]. 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 [10]. 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 [11], [12].

D. Europe

In Europe there are several groups concerned with analyzing wave energy economics. Examples of a few 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 [12]. 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 [12], [13].

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 [14]. 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 [14].

A recent and ongoing EU funded collaborative project, DTOcean, is designed to accelerate the development of marine energy [15]. 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.

IV. Cost Factors

In the early phases of WEC system research, the primary hurdle concerned the creation of devices and methodologies that could extract energy from the waves. This problem has been demonstrated to be solvable and the next step in wave energy development is to ensure the methodologies can be integrated into the grid at an effective cost. 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.

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 thoughts as to what should be included in cost calculations and how the 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 [16]. Degree of utilization refers to the ratio of yearly-generated power over the unit's rated power. Using this factor would include 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 [15]. 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) [17]. In the presentation 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 advancements in WEC operation. Bedard also predicts that wave energy, once on a larger scale, will be comparable with wind energy, but also notes that estimating costs is challenging and should be done with caution [16].

In a study by Stallard et al., developers are questioned concerning economic appraisal methods [18]. 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 [17].

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% [19]. 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 [18].

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%) [20]. 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 [19]. 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 [20].

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 [21]. 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 [22]. 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 [24]. 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 [23].

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 on a larger scale, will follow that 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 the relative percentages of these different cost factors. While this is positive, the values assigned to of each of these factors vary across research and are based on many assumptions.

V. 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 [25]. 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 [24].

The Offshore Renewable Energy (ORE) Catapult project suggests that an important factor in reducing cost is helping investors "get comfortable with marine energy" [26]. Additionally, standardization of technology development, assessment, and better investor coordination between the public and private sectors is necessary for minimization of cost [25].

Haward et al. runs two theoretical wave energy models using the wave resource of Australia as a case study [27]. The authors conclude that emission trading is necessary for the success of most renewable energy forms in order to ensure cost competiveness 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 [26].

RE Vision, a group leading the economic assessment of the WEC reference model (RM3) with SNL [27], 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 [28].

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 [30]. 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 [29].

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 [31]. 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 [30].

VI. 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 [32]. 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 [31].

EPRI also performed several feasibility analyses at different locations with theoretical arrays [33]. 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 [32].

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 [33]. 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 [33]–[36]. 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 [7].

VII. 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 [38]. 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 [37].

In a case study performed in Ireland, Blavette et al. suggest that integrating wave power into the grid could negatively affect the power quality [39]. 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 [38]. Blavette et al. conducted another case study about the grid affects of a medium sized

WEC array at different sites [39]. 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 [40]. 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 [40].

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 [42]. 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 rid-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 [41].

In Oregon, OWET recognizes the need to determine the requirements for grid integration [43]. 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 [42]. Since then, OWET has released another report that discusses the issues associated with integration [44]. 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 [43].

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.

VIII. Current Models

Currently, several cost models exist in the form of interactive spreadsheets. Carbon Trust released the first WEC cost model in 2006 [45]. 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 [13], [21], [45].

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 [10]. 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 it's usability regarding array optimization [11], [12].

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 [9]. 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 [10].

The most recent cost model was developed in the spring of 2014 at Aalborg University in Denmark [46]. 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 [46], [47].

Table 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

IX. 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.

Currently, WEC array deployment is a daunting prospect due to the volatility of the ocean and the uncertainty of the costs that may be accrued. 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.

X. Conclusion

The costs associated with wave energy converters are vast and difficult to 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.

REFERENCES

[1] M. Previsic, J. Epler, M. Hand, D. Heimiller, W. Short, and K. Eurek, "The Future Potential of Wave Energy in the United States," in *4th International Conference on Ocean Energy*, 2012, no. 1.

[2] Energy Technologies Institute and UK Energy Research Center, "Marine Energy Technology Roadmap Technology 2014," 2014.

[3] Marine Energy Group (MEG), "Harnessing Scotland's Marine Energy Potential," 2004.

[4] Forum for Renewable Energy Development in Scotland (FREDS) Marine Energy Group (MEG), "Marine Energy Road Map for Scotland," 2009.

[5] BBC News, "Scotland's first marine energy park launched," 30-Jul-2012.

[6] Marine Energy Group, "Marine Energy Action Plan," 2012.

[7] Dept. of Energy - Energy Efficiency & Renewable Energy, "2014 WATER POWER PROGRAM PEER REVIEW: Marine and Hydrokinetic Technologies," 2014.

[8] M. C. Reed, "Overview of Marine and Hydrokinetic (MHK) Energy Technologies."

[9] K. Ruehl and D. Bull, "Wave Energy Development Roadmap: Design to commercialization," *2012 Ocean.*, pp. 1–10, Oct. 2012.

[10] Sandia National Laboratories, "Cost Breakdown Structure for WEC Rated at 286 kW." 2012.

[11] NREL, "JEDI Marine and Hydrokinetic Model - User Reference Model." National Renewable Energy Laboratory, 2010.

[12] M. Goldberg and M. Previsic, "JEDI Marine and Hydrokinetic Model: User Reference Guide JEDI Marine and Hydrokinetic Model: User Reference Guide," 2011.

[13] Carbon Trust and Entec UK Ltd, "Cost estimation methodology," 2006.

[14] SI Ocean, "Ocean Energy : State of the Art."

[15] M. Leijon, H. Bernhoff, M. Berg, and O. Ågren, "Economical considerations of renewable electric energy production-especially development of wave energy," *Renew. Energy*, vol. 28, no. 8, pp. 1201–1209, 2003.

[16] R. Bedard, "Ocean Wave Power and Economics Assessment." Electric Power Research Institute, 2009.

[17] T. J. Stallard, G. P. Harrison, P. Ricci, and J. L. Villate, "Economic Assessment of Marine Energy Schemes," in *8th European Wave and Tidal Energy*, 2009, pp. 1118–1127.

[18] ECONorthwest, "Economic Impact Analysis of Wave Energy : Phase One," 2009.

[19] Carbon Trust, "Future Marine Energy - Results of the Marine Energy Challenge: Cost Competitiveness and Growth of Wave and Tidal Stream Energy," 2006.

[20] Carbon Trust, "Accelerating Marine Energy: The Potential for Cost Reduction - Insights from the Carbon Trust Marine Energy Accelerator," 2011.

[21] A. Copping and S. Geerlofs, "The Contribution of Environmental Siting and Permitting Requirements to the Cost of Energy for Marine and Hydrokinetic Devices," 2011.

[22] M. O'Connor, T. Lewis, and G. Dalton, "Operational expenditure costs for wave energy projects and impacts on financial returns," *Renew. Energy*, vol. 50, pp. 1119–1131, 2013.

[23] SI Ocean, "Ocean Energy : Cost of Energy and Cost Reduction Opportunities," 2013.

[24] D. L. Laird, E. L. Johnson, M. E. Ochs, and B. Boren, "Technological Cost-Reduction Pathways for Axial-Flow Turbines in the Marine Hydrokinetic Environment," Albuquerque, 2013.

[25] Ocean Renewable Energy Catapult, "Financing solutions for wave and tidal energy," 2014.

[26] J. Hayward, S. Behrens, S. McGarry, and P. Osman, "Economic modelling of the potential of wave energy," *Renew. Energy*, vol. 48, pp. 238–250, 2012.

[27] V. S. Neary, M. Lawson, M. Previsic, K. C. Hallett, A. Copping, J. Rieks, A. Labonte, and D. K. Murray, "METHODOLOGY FOR DESIGN AND ECONOMIC ANALYSIS OF MARINE ENERGY CONVERSION (MEC) TECHNOLOGIES," in *2nd Marine Energy Technology Symposium*, 2014, pp. 1–6.

[28] M. Previsic, "Economic Methodology for the Evaluation of Emerging Renewable Technologies," 2011.

[29] M. Previsic, O. Siddiqui, and R. Bedard, "EPRI Global E2I Guideline Economic Assessment Methodology for Offshore Wave Power Plants," 2004.

[30] C. Beels, P. Troch, J. P. Kofoed, P. Frigaard, J. Vindahl Kringelum, P. Carsten Kromann, M. Heyman Donovan, J. De Rouck, and G. De Backer, "A methodology for production and cost assessment of a farm of wave energy converters," *Renew. Energy*, vol. 36, no. 12, pp. 3402–3416, 2011.

[31] B. Teillant, R. Costello, J. Weber, and J. Ringwood, "Productivity and economic assessment of wave energy projects through operational simulations," *Renew. Energy*, vol. 48, pp. 220–230, 2012.

[32] R. Bedard, "Overview : EPRI Ocean Energy Program The Possibilities in California," 2006.

[33] M. Previsic, R. Bedard, G. Hagerman, and O. Siddiqui, "System Level Design , Performance and Costs for San Francisco California Pelamis Offshore Wave Power Plant," 2004.

[34] M. Previsic, R. Bedard, G. Hagerman, and O. Siddiqui, "System Level Design , Performance and Costs – Massachusetts State Offshore Wave Power Plant," 2004.

[35] R. Bedard, G. Hagerman, and O. Siddiqui, "System Level Design , Performance and Costs – Oregon State Offshore Wave Power Plant," pp. 1–63, 2004.

[36] R. Bedard, G. Hagerman, and O. Siddiqui, "System Level Design , Performance and Costs – Hawaii State Offshore Wave Power Plant," *Power*, 2005.

[37] G. Angevine, C. A. Murillo, and N. Pencheva, "ENERGY POLICY A Sensible Strategy for Renewable Electrical Energy in North America," no. April, 2012.

[38] A. Blavette, D. O'Sullivan, M. Egan, R. Alcorn, and T. Lewis, "Wave Energy Grid Integration in Ireland – A Case Study," in *3rd International Conference on Ocean Energy*, 2011, pp. 1–6.

[39] A. Blavette, D. L. O'Sullivan, M. G. Egan, and A. W. Lewis, "Grid Impact Assessment of a Medium Size Wave Farm Connected to Different Test Sites," in *4th International Conference on Ocean Energy*, 2012, pp. 1–6.

[40] T. Ahmed, "Electrical Technologies for Grid Integration of Ocean Wave Power into the UK National Grid," *J. Power Electron.*, vol. 10, no. 3, pp. 320–327, May 2010.

[41] D. O. Sullivan and G. Dalton, "Challenges in the Grid Connection of Wave Energy Devices," in *8th European Wave and Tidal Energy*, 2009, pp. 12–20.

[42] P. E. Ventures, "Oregon Wave Energy Trust Utility Market Initiative Integrating Oregon Wave Energy into the Northwest Power Grid," no. December, 2009.

[43] J. Klure, K. Dragoon, J. King, and G. Reikard, "Wave Energy Utility Integration - Advanced Resource Characterization and Integration Costs and Issues," 2013.

[44] Carbon Trust, "Cost estimation methodology," *Carbon N. Y.*, no. May, 2006.

[45] Aalbor University, "COE Calculation Tool for Wave Energy Converters." Aalborg University, 2014.