Supporting the transition from grid-scale to emerging market wave energy converter design and assessment

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Abstract—**In the past decade there has been increasing interest in emerging markets for wave energy, both as a stepping stone for development and as a way to create new opportunities for offshore markets such as ocean observation or desalination. Developers who were once focused exclusively on grid-scale development have begun to engage with more unique markets. This has led researchers to begin examining means of assessing emerging-market devices. In this paper, we analyze the Technology Performance Level (TPL) Assessment for its potential use in the assessment of emerging market wave energy converters (EM-WECs). We use Quality Function Deployment (QFD) and a question-by-question analysis of the TPL assessment to determine the changes necessary for such an assessment to be applicable in emerging markets. We discuss how the primary differences between the markets could impact the viable development pathways for developers hoping to succeed in multiple markets. We determine that the different stakeholders and stakeholder requirements of some emerging markets compared to grid-scale applications should be met with changes to cost-to-performance metrics, prototype testing processes, recovery planning, materials selection, optimization objectives, and public engagement.**

Index Terms—**Blue Economy, development pathways, emerging markets, Technology Performance Level assessment.**

I. Introduction

EMERGING *markets*, sometimes referred to as *blue economy applications* are non-grid applications for marine renewable energy devices such as desalination, aquaculture, ocean observation, and autonomous underwater vehicle (AUV) recharging. For wave energy, these potential applications have grown in popularity because they are seen as both a way to improve technology development learning rates and as a way to create new opportunities for ocean-based sectors [1]. With burgeoning interest in emerging markets, researchers and developers are compelled to consider how to meet the requirements of sometimes vastly different end uses with the same base technology. To begin designing wave energy converters for emerging markets (hereafter referred to as EM-WECs), designers should first understand what the requirements are for those markets, and how those requirements relate to design parameters of the device.

The interest in emerging market applications has led to the anticipatory need for a tool for evaluating the performance capabilities of EM-WECs. The Technology Performance Level (TPL) assessment, a tool created to holistically evaluate the performance capabilities of grid-scale WEC concepts, may be able to be altered to guide a similar assessment of EM-WECs [2]. In this paper, we use knowledge gained from stakeholder analysis of three emerging markets and a question-by-question examination of the TPL assessment to identify the major differences that designers and assessors should consider when moving between grid-scale and emerging markets. We discuss how those differences influence pathways for both design and assessment of EM-WECs.

II. Stakeholder Analysis

Quality Function Deployment (QFD) is a stakeholder-focused product definition process meant to help designers understand and organize a design problem [3]. To perform stakeholder analyses, we follow the first several steps of QFD by determining:

1) Who the stakeholders are
2) What the stakeholders' requirements are for the system
3) Which requirements are most important to which stakeholders
4) How important each stakeholder's preferences are

We do this for three emerging wave energy markets identified in the U.S. Department of Energy's *Powering the Blue Economy* report; Ocean Observation and Navigation (OO&N), Underwater Vehicle Charging (AUV), and Desalination (DL) [1]. Stakeholders include purchasers, federal and local policymakers, manufacturers, installers, developers, investors, and others involved in any lifecycle stage of a device. This process of stakeholder analysis is similar to what was conducted to create the grid-scale TPL assessment [4].

We create a list of customer requirements then gather feedback from key stakeholders to score the impor-

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TABLE I
STAKEHOLDER WEIGHTS FOR EACH EMERGING MARKET

Requirement	DL	OO&N	AUV
Project Developer	0.25	0	0
Water utilities/purchasers	0.20	0	0
Military	0	0.20	0.20
NOAA/NWS/environmental agencies	0	0.20	0.10
Commercial users	0	0.15	0.20
State and Federal Regulators	0.15	0.05	0.05
Equity Investors	0.10	0.10	0.10
Academic Researchers	0	0.05	0.05
WEC developers	0.10	0.10	0.10
AUV designers	0	0	0.10
System operators	0.05	0	0
Marine Contractors	0.05	0.05	0.05
WEC manufacturers	0.05	0.05	0.05
Water end users	0.05	0	0
Ship navigators	0	0.05	0

tance of each customer requirement to each stakeholder on a scale of zero to six—zero meaning that the customer does not need to consider the particular customer requirement, and six meaning that the requirement is very important to them. We first consulted the stakeholders to make the initial list of requirements, and then we followed up with a form which allowed the stakeholders to rate how important each score was to them. In total, we spoke with five stakeholders, most of whom had expertise in multiple emerging markets including two with experience in desalination, two who work with AUVs, and two ocean scientists. When assigning scores, we considered how each customer interacts with the system, what advantages an EM-WEC could bring to those customers, and what potential risks the customer faces. After assigning an importance score to each requirement for each stakeholder, we assign a weight to each stakeholder. The sum of all customer weights in an emerging market is equal to one. The stakeholders and their assigned weights can be seen in Table I.

For our analysis, the individual stakeholder weights ranged from 0.05 to 0.25. We weigh most heavily the stakeholders who have the power to choose other forms of electricity generation technologies for their end use. The stakeholders who take the greatest financial risk when choosing a wave energy system are also weighted heavily. The mid-weighted stakeholders are those who assume some financial risk and/or have some power to prevent an installation. The low-weighted stakeholders include people who interact with EM-WECs but are not necessarily decision makers with respect to purchasing or policy. For the final importance score of each customer requirement, we multiply the importance score according to each customer by that customer's weight and sum the scores over all the customers. The overall importance scores range from 1.85 to 4.9 on the 0.0 to 6.0 scale. The customer requirements for each market ordered by importance score is shown in Tables II to IV. Next, we introduce the three emerging markets which we discuss in this paper.

TABLE II
STAKEHOLDER REQUIREMENTS: LARGE-SCALE DESALINATION

Requirement	Importance Score
Survivable	4.9
Reliable energy production	4.2
Safe	3.8
Serves population in need of water	3.8
Low capital cost	3.8
Low operational costs	3.3
Produces power in the tens of MW	3.1
No environmental degradation	3.0
Provides a good investment	3.0
Acceptable to other ocean users	2.9
Low maintenance	2.9
Easy to manufacture	2.7
Easy to install	2.5
Scalable	2.2

TABLE III
STAKEHOLDER REQUIREMENTS: OCEAN OBSERVATION AND NAVIGATION

Requirement	Importance Score
Reliable energy production	4.4
Survivable	4.3
Easy to install and recover	4.1
Safe	4.0
Low operational costs	3.5
Low capital cost	3.5
No environmental degradation	3.3
Produces power at 0-20W	3.3
Flexible in a variety of wave conditions	3.3
Low maintenance	3.3
Maneuverable	2.9
Adaptable to many instruments	2.5
Easy to manufacture	2.7
Able to supply power to various depths	2.4
Able to integrate with other renewables	2.3
Acceptable to other ocean users	2.0

TABLE IV
STAKEHOLDER REQUIREMENTS: AUV RECHARGE

Requirement	Importance Score
Survivable	4.3
Reliable energy production	4.2
Easy to Dock	4.2
Safe	4.1
Low capital cost	4.1
Operates over a wide range of depths	4.1
Can dock AUV in harsh conditions	4.0
Can store 66kWh-2.2kWh	3.9
Low maintenance	3.7
Easy to manufacture	3.6
Produces power between 200 and 1000 watts	3.4
Compatible with data storage	3.4
Low operational cost	3.3
Easy to install and recover	3.2
Maneuverable	2.5
No environmental degradation	2.2
Maintains vehicle stealth	2.0
Can store compressed air	1.8

A. Large-scale desalination

Desalination is the process by seawater (or wastewater) is converted into freshwater through thermal or pressure-driven methods. Desalination technologies are used in areas where there is a shortage of freshwater sources, but the processes are expensive, energy intensive, and potentially harmful to the environment. Wave power may be an attractive option for powering large-scale desalination operations because the energy resource is close to large coastal populations, many of which may face greater water insecurity in the future due to climate change [5]. Wave energy powered desalination could reduce the environmental impact of the high energy consumption of desalination [6].

The U.S. Department of Energy has identified two distinct markets for wave energy powered desalination, utility-scale and distributed systems [1, chapter 7]. We focus on utility-scale systems in this section. Of the emerging markets we examine, large-scale desalination is the emerging market with requirements closest to those of grid-scale devices.

The project developers are the stakeholders who assume the largest financial risk in a large-scale desalination project, therefore we weighted their preferences 0.25, the highest possible value for stakeholder importance. The project developers work closely with the water purchaser (often a utility) whose preferences are mostly related to cost and water quality. The water purchasers are also major decision makers, so their preferences were ranked equal to those of the project developer. The marine contractors and system operators are parties and individuals who will physically work with the EM-WEC. They care that the system is easy to interact with so they can perform their job functions properly, and their preferences are weighted the least (0.05) along with the water end-users and manufacturers. Regulators hold a unique role in that they must consider the safety and preferences of all parties, and ensure that project developers are held accountable. They are also responsible for understanding the potential risks of development to the natural environment. The WEC developers and equity investors also assume a financial risk, and therefore have been assigned a mid-range weight (0.1).

The potential of wave-powered large-scale desalination plants depends significantly on the cost of the plant, which is extremely site-dependent [5]. An ideal location is one where the cost of water is high and/or the need for water is not currently being met. We capture this fact in the requirement that the system serves a population in need of water, with an importance score of 3.8. A wave-powered large-scale desalination plant would need to be an option comparable in price to other options for freshwater supply. This is captured in the requirements for low capital and operational costs, which have importance scores of 3.8 and 3.3 respectively. Reliable energy production and survivablility are important to the financiers of the project, the end users, and the people who work with the system on a day-to-day basis. Six of the eight customers for large-scale desalination fit into one of those three categories, which makes reliable energy production (4.2 importance score) and survivablility (4.9 importance score) the most important requirements for the large scale desalination EM-WEC. This is true across emerging markets and grid-scale developments.

B. Ocean observation and navigation

Scientists, sailors, and military groups are consistently increasing the number of sensors, cameras, and navigational aids in the ocean for a wide range of purposes, from collecting data on the PH value of the water, to monitoring for foreign vessels. Researchers have begun to explore the potential of wave energy to power ocean observation and navigation [7]. It is a market which demands significantly less power than large-scale desalination or grid-scale operations. The sensors and platforms used for ocean observation and navigation demand power under 100 W [7]. With more than 80% of the world's oceans remaining unexplored, increased interest in the economic and climate-related functions of the ocean, and steady use of at-sea weather observation equipment, there will continue to be a demand for power at sea [1, chapter 2]. There is a demand for increased power availability at all depths and distances from shore including surface, subsurface, landward and seaward of the continental shelf [7].

The important stakeholders for EM-WECs for ocean observation and navigation include a variety of end users such as academic researchers, the oil and gas industry, the military, weather service providers, and ship navigators. We also must consider federal and state regulators, marine equipment operators, and WEC developers and manufacturers. The end users, being as varied as they are, have a greater role in dictating the system requirements, as they are the ones driving the need for wave energy devices. As such, the military and the National Oceanic and Atmospheric Association (NOAA)/National Weather Service (NWS)/environmental agency customers are weighted most heavily at 0.2. Commercial users were weighted 0.15 and academic researchers 0.05. The difference in end-user weights is reflective of the difference in predicted size of the future market [7].

If the end users are going to chose a WEC to power their operations, that WEC must provide a better option than what is currently available, which is typically a battery-powered or solar system. For that reason, reliable power production is the highest scoring customer requirement with an overall importance score of 4.4. A WEC system needs to allow for longer deployments, greater access to power, and improved spatial and temporal data resolution [7]. The system should produce power at 0-20W (3.3 overall importance score) depending on the application. Compared to desalination or grid-scale systems which are large and deployed for the long term, these smaller systems are subject to simpler permitting processes, making the regulators a less significant stakeholder (with a weight of 0.05) than they are for desalination. The marine contractors and WEC manufacturers are responsible for the continued operation and performance of the systems. Their preferences are weighted at 0.05 and 0.10 respectively.

The variety of end users leads to a few customer requirements related to the ability to the device to adapt to varied wave conditions (3.3), to many instruments (2.7), and to many places in the water column (2.3).

C. AUV recharge

AUVs (sometimes also referred to as unmanned underwater vehicles) typically have on-board computers, sensors, and power sources (batteries or compressed air) which are used to carry out underwater missions such as acoustic monitoring or seafloor mapping. They can provide cheaper and safer alternatives to human missions. Current AUV technology is limited by device endurance, ranging from hours to weeks, and the subsequent recovery and recharging of these devices costs hundreds of thousands of dollars [1, chapter 3]. Often, a vessel will retrieve the AUV and use a diesel engine to charge the battery system [1, chapter 3]. In sensitive missions, retrieval or resurfacing can compromise stealth [1, chapter 3]. Wave energy powered AUV recharge may reduce the need for retrieval, decrease carbon emissions, and reduce the risk of an oil spill. AUV recharge stations using EM-WECs could extend the length and range of AUV deployments. AUV recharge has similar stakeholders to ocean observation and navigation, but the power demand is higher, ranging from 175 to 1250 W [7]. AUVs tend to be more mobile than ocean observation and navigation equipment.

The commercial and military sectors are the primary end users, so each is assigned a weight of 0.20. Scientific end users are mainly comprised of federal organizations such as NOAA/NWS (0.1) and academic researchers (0.05). Each have different use cases for AUVs. WEC developers and equity investors bear a large financial risk, earning them a weight of 0.10. Manufacturers and marine contractors (both 0.05) interact with the system and care that it is both safe and easy to use. AUV designers have a mid-weighting of 0.10.

Underwater, wave-powered AUV charging stations have the potential to save hundreds of thousands of dollars [1, chapter 3]. However, the viability of these charging stations depends on location. Ideal locations will have a large wave resource but will also allow easy docking [1]. The end user's ability to utilize charging stations, regardless of location, meaning the EM-WEC must operate over a wide range of depths (importance score of 4.1), be easy to dock (importance score 4.2), and be able to dock in harsh conditions (4.0). There is a significant energy storage requirement for AUV recharge EM-WECs (importance score 3.9) as well as a data storage requirement (importance score 3.4). Like with ocean observation EM-WECs, AUV recharge EM-WECs should be easy to install and recover (3.2), but this requirement is not as significant compared to other requirements for AUV recharge because the most important end users (military and commercial) tend to have great financial and ocean-going means than the ocean observation end users.

D. Key differences and associated design specifications

We categorize the key differences between emerging and grid-scale markets into four categories: those related to cost, those related to the length and number of deployments, those related to the end-use power demand, and those related to the role of the public. These factors drive the differences in both what the important stakeholder requirements are and how a device's ability to meet those requirements is defined.

The capital cost for a WEC farm has been estimated to be in the millions of dollars per MW of installed capacity [8]. For reference, grid-scale fossil fuel power plants typically have 400-500 MW capacities. Additionally, Astariz et al. use several industry cost estimates, pointing out that pre-operating, license and permitting, mooring, and cable costs add up to several million dollars more per project. An EM-WEC designed to power a large desalination plant is would have a capital cost close to $4 million for the WEC and an additional few million for the desalination system [6], while the capital cost for most ocean observation or AUV recharge EM-WECs would be much less given the reduced power requirements [1, chapter 2]. As the scale of the costs and investment required for a device changes, so too do the most important customers and requirements. In a grid-scale project, the project developers are the most important customers. They are the ones who make major decisions and ultimately profit from a grid connected WEC farm. For an EM-WEC designed to power a weather buoy (for example), an analogous customer to the project developer does not exist. In this case the WEC is sold as an individual product to whomever wants to power a weather buoy or, more likely, sold under contract to a government organization [1]. The same may be true for an AUV docking station. Conversely, large-scale desalination projects are similar to grid-scale WEC arrays in that the most important customer is likely the project developer.

The differences in primary stakeholders due to scales of costs have some impact on the relative importance of high-level requirements, but overall, we see that many of the requirements are repeated in all three of the emerging market applications; devices should be survivable, reliable, and safe and costs should be minimized. That said, the defining specifications and target values for survivablily, reliability, and costs are not consistent between markets.

III. ASSESSMENT PATHWAYS

We can make suggestions for methods of assessing EM-WECs based on the stakeholder analysis and significant differences between grid-scale and emerging market requirements. In this section, we focus on changes that could be made to the current TPL assessment within the high-level capabilities, the individual questions, and the information requested in order to perform the assessment.

The TPL assessment contains 87 questions within the seven capabilities. We categorized each question based on its relevance for emerging markets as either being transferable, scalable, or irrelevant. Transferable questions are questions that should be included in the assessment of EM-WECs as written in the current TPL assessment. Scalable questions are those questions that are transferable in nature, but the potential responses to each question need to be scaled to correspond to the emerging market. Irrelevant questions are questions that do not need to be part of a performance assessment for emerging markets, as they relate to grid integration and other concerns exclusively of grid-scale WECs. Of the 87 questions in the TPL assessment, 56 are transferable questions, 26 are scalable questions, and 10 are irrelevant for emerging markets. Each question and its categorization can be found in the Appendix. In Table V we include a list of design specifications that are not accounted for in the grid-scale TPL assessment that should be given a related question in an assessment of an EM-WEC.

Overall, we observe that one of the primary difficulties of assessing emerging market devices as opposed to grid-scale devices is the difficulty of benchmarking a device against alternatives. For grid-scale energy conversion, there are clear cost benchmarks that need to be met, and the alternatives in terms of performance and benefits to society are well understood. For emerging markets, this is not always the case, which means that new benchmarks must be integrated into the assessment, and the end use must become an object of assessment to appropriately assess benefits.

A. Costs

The TPL assessment is divided into seven high-level capabilities; *cost of energy*, *investment opportunity*, *grid operations*, *benefit to society*, *permitting and certification*, *safety and function*, and *global deployability*. For emerging markets, the cost of energy capability would more accurately be called *cost of concept* to include any important cost factors distinct from cost of energy. For large-scale desalination, researchers have used levelized cost of water (analogous to levelized cost of energy) as the primary cost metric [6], [9]. Cost of energy is effectively a ratio of capital and operational costs to energy production. The TPL assessment includes questions about important factors which impact costs and performance.

From the costs side, installability could be considered an operational cost (rather than a capital cost) for devices that are intended to be deployed multiple times. In this case, recoverability also becomes important to the operational cost. Both can be estimated, as installability is in the TPL assessment, based on the time and equipment required. For AUV recharge and ocean observation, cost of power transport will not be a concern. On the performance side of *cost of energy*, the TPL assessment assumes that energy will be the product sold and that it is best to maximize both the amount of energy converted and the time in which a device is operational (availability). For an emerging market such as large-scale desalination, analogous measures can be applied to cost of water, but for an EM-WEC sold as a contained product, or through some other marketing structure, analogous measures might not exist. In such a case, the TPL Assessment would need to reflect the cost at which one might sell or lease a device.

The sub-capabilities of *performance* and *availability* need to account for how (and how often) a device is expected to perform. For ocean observation, metrics could include annual availability of sensors or costs per sensor/navigational aid powered. For AUV recharge, metrics such as cost/length of AUV deployment, maximum allowable AUV deployment, and annual AUV availability (measuring the time spent by an AUV over the course of a year on charging-related actions rather than mission-related actions) would capture performance requirements. Additionally, a measure of performance may also require a question about data storage capabilities. A high level metric comparable to LCOE could be ”return on mission” from EM-WECs.

B. Length and number of deployments

The length and number of deployments impact the requirements for lifespan of the device and components, recoverability, and maintenance. When it comes to lifespan and maintenance, questions should be reframed with reference to the emerging market, such as whether the lifespan of the device and components are expected to be longer than its intended deployment and if the maintenance plan aligns with the maintenance plan of any pre-existing offshore components. Metrics such as the time necessary between recovery and redeployment (minimum turnover time) and the total expected operational hours become relevant as the length and number of deployments change.

For an EM-WEC, *global deployability* can be understood to mean both geographically global and global among end users. In order to capture whether a device is globally deployable in terms of different end users, the assessment should include a question about its adaptability to different lengths of deployment and whether a device can be deployed multiple times.

C. End use power demand and type

The final output of the EM-WEC changes how we measure its ability to meet every stakeholder requirement. EM-WECs could output electricity directly to another ocean technology, pressurized water, compressed air, or potentially another innovative form of energy. The high-level capability *grid integration* would more aptly be called *use integration* for emerging markets. Use integration requirements are market-specific. For example, in AUV recharge, the stability of the point of docking is likely the most important factor in use integration. An assessment for such a device would consider the range of sea states where docking is possible, and the expected loads at the dock point.

The TPL assessment of grid-scale WECs reflects this need for power maximization and consistency through questions in the *grid integration* and *cost of energy* capability sections. In order to capture energy production requirements for more diverse markets, questions need to be added which measure the EM-WEC’s energy production with respect to the energy demand of the system with which it is integrated. Each question which explicitly references a MW range will need to be adjusted. *Global deployability*, as described in the previous section, should encompass the range of energy demands which a device could be scaled to meet and the number of design parameters which would require scaling.

D. Role of the public

The role of the public in some EM-WEC deployments will require changed to the *benefit to society* and *permitting and certification* sections of the assessment. We

TABLE V
ADDITIONAL REQUIREMENTS AND DESIGN SPECIFICATIONS FOR EM-WECS

Desalination	OO&N	AUV
Cost/L water	Cost/device	Cost/device
Water need at project site	Time for recovery	Time for recovery
Cost of brine disposal	Equipment for recovery	Equipment for recovery
Scalability	Number of compatible instruments	Stability of docking point
Ramp-up time	Data storage capacity	Data storage capacity
Water availability	Sensor availability	AUV availability
	Available energy/day*	Available energy/day*
		Surface penetration
		Compressed air storage capacity

*account for seasonal differences

noted that for a desalination project, one of the most important requirements was that it served a community in need of water. To capture that requirement, the TPL assessment could include improvement potential of U.N Sustainable Development Goals' metrics for water scarcity — water use efficiency and level of water stress — for the project site [10]. For emerging market applications, the system under examination in the *benefit to society* capability will need to include both the EM-WEC and the end use which the EM-WEC enables, as exemplified by the previous example. The *benefit to society* and *permitting and certification* sections of the current TPL assessment capture job creation, recyclability, spacial requirements, environmental impacts, and energy debt. Job creation, environmental impacts, and energy debt of the EM-WEC are not easily delineated from those of the end use and are heavily site dependent.

The TPL assessment currently uses a metric of FTE/GW, full-time employment equivalent per GW of installed capacity, to measure job creation. For EM-WECs, FTE is more appropriately measured per project. Furthermore, the assumption that a better devices is one which creates more jobs tends to be more applicable to projects which are imposed upon a community and are for profit. Such a metric does not make sense for a cooperative/community-owned project or a small device which is designed and manufactured outside of the place where it is deployed.

When it comes to environmental impacts, it is easy to imagine the difficulty in delineating between EM-WEC and end use. For instance, if an EM-WEC is used to power a high-polluting desalination plant, the isolated environmental impacts of the EM-WEC might be minimal, while those of the project as a whole would be high. That said, if the plant is to be sited and built regardless of the use of wave energy technology, then one rightfully questions whether the environmental impacts of the end use should be considered. Nonetheless, because the public (and government) would play a role in the siting and permitting of a desalination plant as they would for a grid-scale deployment, it follows that the impacts of the whole project should be considered, for, if the desalination project is not permitted, then the EM-WEC would not be necessary. For ocean observation specifically, the devices need to not only not cause environmental harm, but they must minimize all impacts they may have on the environment to allow for undisturbed ocean observation.

The TPL assessment uses the "time to pay back energy debt," which is the time it takes to create the same amount of energy which was used to produce, deploy, operate, and decommission the device, as a measure of greenhouse gas emission reduction. If an EM-WEC is supplying energy to an end use that may not otherwise require energy (maybe because it would not exist), the "time to repay energy debt" is not particularly relevant in terms of benefits to society. In these cases it is (again) difficult to capture the benefit of the EM-WEC without capturing the benefit of its end use. For an ocean observation EM-WEC, we might measure the benefit of the enabled data collection. Selecting metrics to quantify societal benefits is subject to one's understanding of a "good" society. For EM-WECs, it would therefore be best to base questions on engagement with impacted publics.

IV. DESIGN PATHWAYS

A. Costs

When beginning an EM-WEC project, even if the designers have a concept which they are trying to adapt to a new market rather than starting from scratch, they should identify which are the most important stakeholders, and what the requirements are of those stakeholders. The difference in the costs and size of investment necessary for different EM-WECs and the corresponding differences in important stakeholders and design requirements have implications for design practice at multiple stages of the design process.

Although there is debate over the appropriateness of the Levelized Cost of Energy (LCOE) metric for wave energy, the metric is still widely used. One reason for its continued use is that LCOE allows designers to benchmark their devices against other available energy sources. For emerging markets, the work of benchmarking alternatives will fall on the EM-WEC designer when a ubiquitous metric such as LCOE does not exist. Determining stakeholders and stakeholder requirements then benchmarking alternatives is standard systems engineering and product design practice that has been previously discussed in the marine energy field (i.e. [11] [12] [4]).

Further along in the design process, the differences in capital costs for devices should result in different approaches to computational modeling and prototype testing. As has been discussed in the literature, the testing of grid-scale WECs is both essential and high-risk [13] [14]. For that reason, researchers have attempted to standardize the computational and physical modeling steps for grid-scale WEC design [15]. The standard, grid-scale approach is not ideal for lower-cost devices due to its focus on computational modeling and simulation in the early stages and its multi-step physical modeling pathway in which the scale of the device is increased several times. The costs of physical modeling and prototype testing scale with the size of the device, therefore, for a smaller device, designers may be able to spend more time on physical models and prototypes and less time on computational modeling. They may also be able to create a full-scale prototype much earlier in the process, meaning physical validation of computational models can be done with less uncertainty and components used in prototype test may be reused in a full-scale device. Furthermore, for cheaper devices, designers may be more comfortable applying a Set-Based Design approach in which they embody multiple concepts simultaneously until one is determined to be clearly superior. Further discussion of current WEC physical modeling and prototype testing practices can be found in a review by Trueworthy and DuPont [11].

When a designer begins an EM-WEC project with a concept previously modeled or tested for grid-scale energy conversion, the appropriate pathways for prototype testing become even more variable. The hydrodynamics of wave-body interactions do not scale linearly with the size of the body and the wave resource at the intended location for a small EM-WEC is likely to be very different than that at the intended location for a grid-scale WEC. For these reasons, someone moving from grid-scale to EM-WEC design will not likely be able to simply scale their devices or use all information deduced from previous, scaled, test campaigns. For example, for a 1:50 grid-scale prototype, designers would test with equivalently scaled wave resource, and (potentially) a differently-scaled PTO subsystem, meaning that even though the size of the scaled WEC might be the same as the EM-WEC, the test conditions are not realistic for the EM-WEC and the PTO subsystem is not suitable.

In moving between grid-scale and emerging markets or working strictly on EM-WEC design for low-power applications, we suggest using an information deficit-driven approach to risk reduction through physical modeling. This involves identifying areas of significant uncertainty and establishing tests by which one can ascertain the most information (with the least amount of uncertainty) about the concept at the lowest cost. In some cases for small devices or devices which are altered from a previously-tested grid-scale concept, an information deficit-driven physical modeling approach might lead to early full-scale prototyping, or rapid partial prototyping of a novel component or subsystem followed by full-scale integration. The important thing to note is that a standardized approach to physical modeling (especially the approach suggested for grid-scale WECs) is unlikely to work for EM-WECs, especially for designers who are moving between grid-scale and EM-WEC design. Differences in computational and physical modelling approaches are driven by end use as well as costs. Those differences will be discussed in the forthcoming subsection C.

B. Length and number of deployments

Differences in the length and number of deployments between emerging market applications and grid-scale applications will require designers to reimagine installation and recovery planning and determine which parties will be responsible, select materials and components based on new lifespan requirements, work with end users to determine maintenance plans, and conduct new failure and availability analyses.

For grid-scale WECs, installation and recovery would be performed by major marine contractors once over the lifetime of the device. On the complete opposite end of the spectrum, an EM-WEC for ocean observation might be deployed off of the back of a research vessel numerous times by marine scientists. The requirements for these two types of installation are clearly very different. Designers should determine which parties are responsible for installation and recovery early on in the process, how much experience those parties have, and what tools they have available. Once they have determined this, they may begin to plan installation and recovery processes.

It is best practice to do this planning simultaneously with the physical design of the EM-WEC to avoid the chance of costly changes late in the process due to the failure to meet installation and recover requirements [16]. The size, volume, points of connection, modularity, and mooring methods all impact what installation and recovery methods are possible. For larger EM-WECs and grid-scale devices, installation and recovery simulations may be necessary, where as, for smaller devices, meeting with stakeholders and storyboarding the process may be sufficient. For devices which are easier to transport it may also be cost effective to do practice runs of both installation and recovery. In a case where end users will be deploying the device themselves, involving a third party in the planning process could prevent designers from overlooking important factors.

Devices with shorter lifespans or devices that are recovered and redeployed multiple times will have eased requirements for material durability. If moving from a grid-scale concept to a EM-WEC concept, designers can use their capital cost analysis to identify components or materials which could be replaced with cheaper components or materials. In maintenance planning, EM-WEC designers should work with end users to determine what their expectations are in terms of maintenance and whether co-maintenance with the end use technology could be cost effective for both parties.

Maintenance plans are typically inputs to failure and availability analyses. In failure analysis of devices which will undergo multiple deployments, designers need to consider potential failure between times of operation. In availability analysis they may need to account for the turn-around time between recovery and redeployment. Designers should consider what routine maintenance upon recovery is acceptable to the end user and how much that maintenance could prevent operational failures.

C. End use power demand and type

Computational modeling of the integration of wave energy devices with the grid is common in academic research (i.e. [17]). EM-WECs use integration will require new types of computational and physical modeling. This includes simulations of desalination systems such as that presented by Yu and Jenne [18], modeling of AUV docking procedures and the associated forces, or modeling of the power available in a multi-sensors, battery, and EM-WEC system. When it comes to physical modeling of use integration, it is much simpler for EM-WEC (especially for small EM-WECs) designers to test a physcial model or prototype with the actual end use system, such as ocean sensors or an AUV. Even a desalination system could be scaled and brought to a testing facility. This level of integrated testing is not possible for grid-scale devices except at testing centers such as the European Marine Energy Center or the in-progress PacWave facility.

For EM-WEC systems which are not required to be constantly generating output, the definition of both failure and availability change. Consider, for example, an EM-WEC for AUV recharge. This device needs to reliably convert wave energy such that a charge is available to the AUV when needed. This means that, depending on the size of the device, its energy storage capacity, and the amount of time the AUV can run between charges, the EM-WEC may not need to be converting energy at all times. The availability, then, would not be how often the device is converting energy (i.e. [19]) or the electricity generated over the possible electricity generated with no failures or maintenance (i.e. [20]), but rather how often the device has the appropriate amount of energy stored when the AUV docks to recharge. This is a more discrete way of defining availability, which will impact the statistical methods available for estimating availability. For instance, Abdulla et al. model availability using a 3-hour time-step and estimating power conversion, but for an AUV recharge EM-WEC, one might nest a model such as that into a model with month-long time steps (or whatever length of time between AUV charges). In this case, it may not always be considered a failure when the device stops producing energy.

A designer might find it to be more effective to slightly oversize a device and include failure recover mechanisms as opposed to designing to prevent minor failures such as pauses in energy conversion. Alternatively, a designer might choose to create a device that is extremely well suited for only a small range of sea states, potentially simplifying PTO/control, geometry, and mooring design (each of which may serve to increase power production at a wider range of sea states i.e. [21], [22]). The new definition of availability influences the risk attitude of the designer. When these sorts of choices become complex, designers may turn to techno-economic or multi-objective optimization as a method of decision-making.

The use of techno-economic optimization is common in marine energy research, i.e. [23] [24] and these methods have been picked up by some designers [11]. Cost, availability, and performance are three objectives common in optimization problems. For a smaller EM-WEC, the cost of a device might be used as a constraint rather than an objective. For instance, a stakeholder who intends to use an EM-WEC to power a seafloor-mapping AUV might have a fixed budget, and within that budget it might be more important that the device is easy to use and reliable. Whether the end use requires the EM-WEC to maximize energy conversion or to hit a target will impact how designers approach performance and availability optimization. As discussed above, the models of availability used in optimization might change as well. These changes mean that conclusions drawn from the optimization of a grid-scale device may not be applicable for a similar EM-WEC.

The way that the designer approaches cost, availability, and performance depends on the preferences of the stakeholders. In the examples provided above, we can see that preferences are not only market-specific, but they can be project-specific as well. The stakeholder analysis that we present in this paper is only a high-level look at stakeholder preferences. Designers can use QFD, just as we do, to complete a more detailed analyses. The project-specificity of requirements means that designers must make choices about when they will try to design for a wide range of project applications versus a specific project. Such concerns bring about attempts at modularity and adaptability that might be best addressed through multi-stage optimization approaches.

D. Role of the public

Across grid-scale applications, the role of the public and permitting procedures are becoming standardized [25]. The public impacts of electricity projects are relatively well understood and concern permitting, environmental impacts, conflict with ocean users, and local job creation. Such impacts are not as straightforward for emerging market applications. Device size and location will be major factors in determining the kind of permitting required.

Recently, there has been interest in community-driven design of marine energy technology, such as with the U.S. National Renewable Energy Laboratory's Energy Transitions Initiative Partnership Project Community Technical Assistance program. Such work requires designers to work with communities to address concerns related to (among others) resilience in the face of a changing climate, emergency response, and water security.

V. CONCLUSION

In this work, we categorize the most important differences between grid-scale and emerging wave energy markets and discuss how those differences impact design requirements. By understanding important differences in design requirements, we suggest ways of altering grid-scale WEC assessment and design practice to be more suitable for emerging markets.

Changes to the design and assessment process when moving between markets are driven by differences in costs, the length and number of deployments, the end use power demand and types, and the role of the public. An EM-WEC assessment must account for:

- Metrics for cost associated with selling or leasing
- Repeated installation and recovery
- New performance expectations
- Expected lifespan relative to end use
- Global use among different end uses
- Benefits of enabled end use

An EM-WEC design process must account for:

- New important stakeholders
- Lower costs of physical modeling and prototyping
- Installation and recovery planning
- New definitions of availability and reliability
- Maintenance planning relative to end use
- Integration modeling
- Site/project-specific needs

APPENDIX
TPL QUESTIONS RELEVANT TO EM-WECS

More recent changes to the questions and a digital assessment platform can be found online. The questions on the next page are taken from a scoring tool Excel file provided by the National Renewable Energy Lab and Sandia National Lab. The most recent publication containing individual TPL questions is from 2017 [2].

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Capability	Question
Cost of Energy	Are the components difficult to source, made of specialty material (very high cost, unknown properties for use/environment, specially made/order), or not suitable for mass manufacturing (difficult to work with and/or not suitable for conventional manufacturing methods)?
Cost of Energy	Will the device experience large structural loads due to breaking waves, large waves, or other environmental forces and will large structural components be needed to resist that force?
Cost of Energy	Are the components difficult to source, made of specialty material (very high cost, unknown properties for use/environment, specially made/order), or not suitable for mass manufacturing (difficult to work with and/or not suitable for conventional manufacturing methods)?
Cost of Energy	For an expected depth, is the station keeping system inexpensive and relatively simple
Cost of Energy	Does the cost and complexity of the station keeping design scale well with depth?
Cost of Energy	Considering the entire WEC, are there systems or components that are custom manufactured outside of expected or common practices? This could include custom generators, non-typical manufacturing processes, non-COTS components where COTS components are common.
Cost of Energy	What are the manufacturing facility requirements? Can manufacturing and assembly be done local to deployment sites or the WEC farm location (consider lifting, transport, launching, power, enclosures/environmental conditioning, etc.)?
Cost of Energy	What expertise is needed from the workforce (dependent upon: material type, level of tolerances that must be achieved, specialized safety, customized molds, etc.)?
Cost of Energy	Are any of the major structural or shell components complex to form?
Cost of Energy	Are there any components that are not readily manufacturable locally, are large and that will have to be transported overland with specialized vehicles or logistics?
Cost of Energy	Can the WEC device be assembled fully on shore or at the side of a pier in the harbor and towed easily and safety to the installation site or easily assembled offshore in a wide range of weather conditions?
Cost of Energy	How fast can the WEC be transported from the dock to the installation site and how weather/sea-state dependent is the tow?
Cost of Energy	What are the weather window requirements for installation? Are the WEC subsystems designed for the expected extreme loads, for the operating loads for the lifetime of the system and for the operational environment?
Cost of Energy	What are the known failure modes and frequency of failure for WEC subsystems and their components? What is the level of confidence for failure modes and frequency? What are the consequences of failure?
Cost of Energy and Investment Opportunity and Safety & Function	What are the limiting sea states that allow maintenance access? How is relative motion between WEC and work platform minimized? Or motion between WEC and PTO mooring?
Cost of Energy	Is the energy absorption by the wave power collecting systems sensitive to tidal height, tidal current, or wind?
Cost of Energy	What is the influence of the station keeping system on energy absorption?
Cost of Energy	How many conversion steps are there between the absorbing element and the component that produces the transportable power - how many times is the form of the energy significantly changed?
Cost of Energy	Within the WEC, what is the target ratio of instantaneous peak to mean power for the energy conversion drive train?
Cost of Energy and Investment Opportunity	Are the WEC subsystems designed for the expected extreme loads and motion, for the lifetime operating loads, and for the operational environment? Are all components mature technology with a history of use in the marine environment?
Investment Opportunity	Of the material types used in the WEC, are any rare or located only in particular parts of the world; i.e. what material types are vulnerable to price fluctuations?
Investment Opportunity	Are new manufacturing capabilities and/or new workforce expertise needed to construct the WEC?
Investment Opportunity	What are the known failure modes and frequency of failure for WEC subsystems and their components What is the level of confidence for failure modes and frequency? In terms of OpEx uncertainty, how well have the failure modes and frequency of failures been characterized and costed? What are the consequences of failure?
Beneficial to Society	Is the WEC and its components recyclable?
Safety and Function	Has a safety philosophy been incorporated into the design process?
Safety and Function	Is there a threat to human health and safety during any of the life cycle stages?
Safety and Function	Is any lifting by crane done at sea?
Safety and Function	Identify how susceptible the WEC device and station keeping system are to increasingly energetic conditions by identifying how they react (in terms of motions and loads) to highly energetic environments (i.e. large return period environments)
Safety and Function	What is the design probability of WEC loss?
Safety and Function	Can the WEC be easily detected by other users of the area?
Safety and Function	In the event of a collision, is the WEC able to mitigate damage?
Safety and Function	For all expected orientations and configurations other than during operation and survival, is the WEC as safe and survivable?
Safety and Function	Is the WEC and its subsystems designed for the expected extreme loads, for the operating loads for the lifetime of the system and for the operational environment?
Permitting and Certification	Can the technology form a farm that could co-exist with other potential users of the area?
Global Deployability	What is the water depth requirement to deploy the WEC farm?
Global Deployability	What geophysical conditions are required to deploy this concept?
Global Deployability	What is the sensitivity tidal range?
Global Deployability	What is the sensitivity to current?
Global Deployability	Are there any characteristics of the system and its impact on the environment that restrict its application in environmentally sensitive locations? (e.g. endangered and threatened species, migratory routes, large shifts in sediments, noise emissions, other emissions etc.)?