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Title: Wave Energy From Idea, to Concept, to Converter: Structuring Methods for Design and Evaluation of Wave Energy Devices

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Bryony L. DuPont

The amount of energy we use and the ways that we get that energy sit on the edge of dramatic change as the carbon budget which can keep the planet under 1.5C of global average temperature increase gets smaller [1]. In response, we continue to research and develop renewable energy technologies. Among these technologies are a diverse set of devices intended to convert the mechanical energy of wind-driven ocean waves to usable energy, typically in the form of electricity. Currently, researchers and developers work on wave energy devices for grid-scale energy applications as well as other emerging markets, such as ocean observation or desalination. Despite the large scope of potential uses for the technology, it is not currently being used as an energy source for any market. For many applications, the price remains too high and the technology too new.

The unique challenges for wave energy converter design—integrating complex

and uncertain technological, economic, and ecological systems, overcoming the structural challenges of ocean deployment, and dealing with complex system dynamics—have led to a disjointed progression of research and development. There is no common design practice across the wave energy industry and there is no published synthesis of the practices that are used by developers. This lack of established process likely contributes to the slow forward motion of the wave energy industry.

In this body of work, I have integrated knowledge of engineering design processes with research in current wave energy converter (WEC) design challenges and pathways, in order to better understand and improve WEC design practice. The results from these studies reveal the dominance of point-based design approaches in the field of WEC design, the areas of WEC design in which methodological improvements are most necessary, and the need for significantly better ways of distinguishing between the performance potential of WEC concepts. Despite the significant attention given to late-stage design optimization by academic researchers, developers are in need of improved tools for earlier in the process. Point-based design, even with late-stage optimization is not sufficient or entirely appropriate for the field of wave energy. Set-Based Design, multi-attribute utility analysis, the improvement of holistic performance assessments, and the conversion of those assessments for use in the conceptual design stage are the four methods which I examine in this work to improve early-stage WEC design.

Wave Energy From Idea, to Concept, to Converter: Structuring Methods for Design and Evaluation of Wave Energy Devices

by

Ali May Trueworthy

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APPROVED:

Major Professor, representing Mechanical Engineering

Head of the School of Mechanical, Industrial, and Manufacturing Engineering

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Dean of the Graduate School

Ali May Trueworthy, Author

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Chapter 1: Introduction

1.1 Objective and Overview

The purpose of this body of work is to determine ways to improve wave energy converter (WEC) design using engineering design methodologies, which are not currently being broadly employed in WEC design. Currently, researchers and developers work on wave energy devices for grid-scale energy applications as well as other emerging markets. The U.S. Department of Energy is currently hosting the Waves to Water Competition, in which participants design wave energy powered desalination systems, as well as the Ocean Observation Prize in which competitors use ocean energy technologies to power ocean observation/monitoring. Despite the large scope of potential uses for the technology, it is not currently being used as an energy source for any market. For many applications, the price remains too high and the technology too new. The unique design challenges for wave energy converter design—integrating complex and uncertain technological, economic, and ecological systems, overcoming the structural challenges of ocean deployment, and dealing with complex system dynamics—have lead to a disjointed progression of research and development. There is no common design practice across the wave energy industry and there is no published synthesis of the practices that are used by developers. The lack of established process likely contributes to the slow improvement of the wave energy industry. In this work, I examine how we can establish common processes, which processes they should be, and what research is necessary to adjust established design methodologies for application in wave energy.

In the forthcoming sections of this chapter, I provide an introduction to the field of wave energy through the lens of WEC design and I provide an overview of the relevant engineering design background. Chapter 2 contains work published in November of 2020 in the Journal of Marine Science and Engineering. It is a review of design practices for WEC design which includes project and product definition work done by researchers for the industry as a whole, the dominant practice in four stages of WEC design (project and product definition, conceptual design, embodiment design, detail design), and the design and evaluation methods available for designing toward 11 distinct requirements for wave energy converters. Chapter 2 also includes results from a survey of WEC designers, the results of which allow us to draw conclusions about WEC design practice not only from academic research, but from industry developers as well. Chapter 3 contains work published in the 2019 European Wave and Tidal Energy Conference proceedings; the testing of a Set-Based conceptual design process for WECs.

Chapter 4 and 5 include research submitted to the U.S. Department of Energy as deliverables for Task 8 of the LCP (Lab Collaboration Project) program, focused on advancing the mission of the WaveSPARC project. The work is a collaboration between our team within the Pacific Marine Energy Center (PMEC) and WaveSPARC researchers at the National Renewable Energy Laboratory and Sandia National Laboratory. The WaveSPARC project goals of enabling industrial partners to converge faster on high-performance concepts, and encouraging wider industry convergence on optimal WEC archetypes are being forwarded through the stakeholder and requirements project [2], the technology performance lever (TPL) assessment development [3], the employment of TRIZ (the theory of inventive problem solving) [4], and the eventual goal of patenting a few high-performance WEC concepts and making them available for industry use. This problem statement emerged from the observation of a problem with the way that WEC designers go about their work (focusing on readiness rather than performance) [5]. The problem identified by WaveSPARC is a problem of technology and of practice. Innovating and developing a WEC technology along an ideal TPL-TRL curve, where designers increase the performance capabilities of the concept prior to pushing it through expensive testing regimes,is a theoretical solution to the identified problem. That ideal design trajectory has been acknowledged by the industry, but there is still a significant need for effective ways of following that trajectory. Following the ideal TPL-TRL design trajectory requires a designers to be able to assess the TPL of their device. Chapter 4 includes an overview of the current state of that TPL assessment and our recommendations for its improvement. Chapter 5 shows how the TPL assessment could be adapted to emerging market WECs, specifically, WEC designed for use in large-scale desalination, ocean observation and navigation, and autonomous underwater vehicle (AUV) recharge.

I conclude this thesis by summarizing what these four studies mean for the field of wave energy and what future work remains.

1.2 Wave Energy

The switch from fossil-fuel energy systems to renewable energy systems is one of the major avenues for addressing climate change [6]. As a near-zero emissions energy technology, wave energy has the potential to be a part of that change. The primary function of wave energy technology is to convert the mechanical energy of wind-driven ocean waves to usable energy, typically in the form of electricity. Wave energy could provide electricity to the grid with more predictability than solar or wind energy [7], power off-grid off-shore operations such as aquaculture or ocean research [8], become an energy generator that is not bidding for large swaths of land, provide reactive power control with synchronous generators [9], and capture the large, dense energy source nearest to coasts where about 50 percent of the world's population resides. In some regions, the seasonality of the wave energy resource corresponds to the seasonality of electricity demand [10]. Environmental impacts research thus far, though limited due to the lack of sea testing, indicates that local environmental degradation due to wave energy could be minimized through early incorporation of environmental studies and continued research [11]. These potential advantages of wave energy are what continue to motivate academic research and industry development of wave energy devices.

Currently, there are 4–8 WEC design archetypes (depending on categorization) and dozens of device designs within each category of archetype. Devices differ in the method of energy absorption, for example, oscillating body devices use the relative wave-induced motion of two device bodies whereas oscillating water column devices use the motion of air (induced by the motion of the water column) through a chamber. Devices also differ in the type of wave motion that they convert, be it heave, surge, or gravitational potential. Some devices are designed to be fixed to the seabed or a breakwater while others float and have moorings [12]. Devices intended for grid-scale energy production will likely become members of arrays of devices, which some researchers argue will require distinct developmental pathways [13]. The major areas for wave energy research and development include hydrodynamics, materials, controls, moorings, ocean installation and deployment, and electricity conversion and transport. Each of these research and development areas, combined with the relative nascence of WEC deployment, makes the design space (the set of potential, complete design solutions) extremely large. With the recent surge of interest in off-grid WEC applications, i.e., [8], we can expect the design space to get even larger. Such a large design space demands organized design strategies to address the many challenges of WEC design.

There are four major programs in the area of marine renewable energy dedicated to organizing design and development strategies, two in the European Union and two in the United States. The DTOcean (first generation) and DTOceanPlus (second generation) projects, funded through the European Union's Horizon 2020 program and partnering with academic, private, and government researchers internationally, aim to create open-access suites of design tools for the "selection, development, and deployment of ocean energy systems" [14]. The software tools are available on GitHub, and descriptions of the alpha versions of the tools can be found in the publications section of the program's website. The tools range from tools for structured conceptual innovation to tools for logistics planning and were released in May of 2020, too recently for me to discuss their adoption in this thesis [14]. Nonetheless, we include details about some of the DTOcean-Plus tools throughout this review. MaRINET (Marine Renewables Infrastructure Network, first generation) and MaRINET2 (second generation) are also projects funded by the European Horizon 2020 program. They focus on the standardization of physical modeling and device testing procedures. They help to facilitate access to testing facilities and the training and dissemination of information necessary for productive, successful testing [15]. The WaveSPARC (Systematic Process and Analysis for Reaching Commercialization) project includes researchers from the United States Department of Energy National Renewable Energy Laboratory and Sandia National Laboratories working toward delivering "the necessary methods and tools to enable new, groundbreaking wave energy technology" [16]. Their work includes systems engineering analysis, concept development, and performance assessment [16]. The TEAMER (U.S. Testing Expertise and Access for Marine Energy Research) Program focuses, like MaRINET, on facilitation of testing. The program takes requests for technical support from developers and selects projects to fund for testing within the numerous affiliated facilities [17]. These four federal-level programs are indicative of the need for increased structure in the design and development of wave energy systems. The work contained in this thesis aligns with the WaveSPARC project. We worked with the researchers involved in that project, especially for the studies presented in Chapters 4 and 5.

1.3 Engineering Design

Much of the research contained in this thesis relies on the application of knowledge of engineering design to WEC design and assessment. It was because of my studies in engineering design that I could make the recommendations and conclusions present in each chapter of this thesis. Therefore, it is appropriate for me to give an overview herein of the relevant aspects of of engineering design.

Within engineering research, a significant portion of published work involves incorporating aspects of design science. This work makes up the field of engineering design. Research in engineering design is concerned with how we design high performance products and systems, how we can reduce costs throughout the design process, and how we can effectively embed knowledge into design. There are several text books that thoroughly outline engineering design processes. In *The Mechanical Design Process* [18], David Ullman outlines the mechanical design process in four main steps: project definition, product definition, conceptual design, and product development. Throughout the chapters of the book, Ullman further breaks down the process to project definition, product definition, concept generation, concept evaluation and selection, product generation, and product evaluation for performance and the effects of variation. Most engineering research falls into one of these categories. This overarching approach is similar to the approach presented by Dieter and Schmidt in Engineering Design [19]: define the problem, gather information, generate concepts, evaluate and select concept, product architecture, configuration design, parametric design, and detail design. Dieter and

Schmidt refer to the first four steps as “conceptual design” and the following three as “embodiment design”. There are still other models of the engineering design process such as those presented by Otto and Wood in *Product Design* [20], Pahl et.al in *Engineering Design: A Systematic Approach* [21], and others.

Within this high-level process there are different design approaches or design philosophies. To use a metaphor to distinguish between the overarching design processes and the individual design approaches, one might think of the overarching design process as the description of the most basic steps in human life- you are born, you breathe, you eat, you drink, you die. If that were the case, than a design approach could be seen as an individual’s worldview; impacting everything we do, how we live our lives, and how we interpret ourselves and our surroundings. These approaches can vary more by individual than the overarching process will. Design approaches are usually accompanied by a set of rules or principles. For instance, Axiomatic Design theory, which is focused on systems design, is based on two design ”axioms” or self-evident truths [22]. A design approach can influence how designers determine the system boundary. For instance, in ecological engineering, the ”system” is considered to be the ecosystem in which the engineers are working. An ecosystem is open, with constant flows of material and energy[23]. Sustainable design approaches were organized by Blizzard and Koltz into a set of three ”essential elements of the process” which they related to three ”design principles” and several ”design methods,” which are ways of enacting ”design principles” [24]. In this work, I refer to design processes, approaches, principles, methods, tools, and pathways. Principles are usually abstract and they influence what is considered acceptable design work throughout the entire design process. Methods are ways of carrying out processes (in line with principles), and tools are the physical or digital mechanisms that designer use to carry out the design process. Each of these aspects of design is related to how designers move from recognizing a societal need to realizing a final solution.

A system, as defined by design theorist Nam P. Suh, is ”an assemblege of sub-systems, hardware and software components, and people designed to perform a set of tasks to satisfy specified functional requirements and constraints” [22]. Issues related to systems design include how the system is designed (by which theory or philosophy), how the relationships between components are coordinated and managed, how stability and controllability are guaranteed, and how humans interact with the system. From this definition, we can see that issues related to the physical design, both form and function, of individual components or subsystems is not the main concern of systems design. Individual component or subsystem design fit better under the label of electromechancial design or product design [18], although the distinction is neither always clear nor always necessary. A WEC design project includes both the integration of already established technologies and the design of custom components. Therefore, it is important to recognize that there are distinct challenges to each design task, and that custom components inherently bring both risk and opportunity. I use the term ”product” when contextualizing wave energy devices into the frameworks of product design. Otherwise, I refer to wave energy systems, as both an individual WEC device and a WEC farm meet the definition of a system.

It is important to understand the distinction between a concept and a product. A concept is "an idea that is sufficiently developed to evaluate the physical principles that govern its behaviour" [18]. Concepts are what designers come up with in the early stages of the design process, prior to modeling or the definition of components. A product, on the other hand, is fully defined. It is ready to by built, used, or implemented, although it may not be the final outcome of the design process. In product design, the people who interact with the product are considered the *customers* [18]. Customers are not exclusively the end users. In systems design as well as political and social theory, people use the term *stakeholders*. In this work, I use the terms *customer* and *stakeholder* interchangeably. Customer/stakeholder requirements are the qualitative or quantitative qualities that the customers desire the designed system to have. Functional requirements are what the system must do. Design/engineering specifications are the quantitative metrics which determine an entities ability to meet the requirements (such as weight or volume) [18].

Some of the high-level stakeholder requirements for a WEC are common to many designed systems, like the requirement of low costs or the easiest manufacturing process possible. For these common requirements, there is research on design tools for meeting those requirements that can be applied across industries. Those tools are sometimes called DFX– design for X. Different "X"s include, manufacturing, environment, assembly, production, system quality, and life cycle costs [25]. In Chapter 2, I discuss the use of these DFX methods and tools for WEC design. I also detail some specific design approaches, including Systems Engineering, Set-Based Design, Axiomatic Design, and Ecological Engineering. I briefly touch on user-centered and participatory design processes.

Chapter 2: Design Practice for WECs

In this Chapter, I bring together academic literature, reports from these federal programs, and survey responses from WEC designers and developers to comprehensively review the practices of WEC design. My intention is to provide a review not of the field generally as previous reviewers have done, i.e., [9, 26, 27] but of the methodologies for design and development being researched and used in WEC design. I aim to expose to researchers specific areas of need for structured design tools. Although there are many academic publications which describe WEC design methodologies employed in research, there is no work which synthesizes the design methods and tools used by WEC developers throughout the design of a single device. In Section 2.1 of this chapter, I review the WEC design problem by discussing the societal need for wave energy development, the specific challenges the industry faces, the requirements of a WEC, and the metrics for success. In Section 2.2, I review the process of WEC design throughout project definition, conceptual design, embodiment design, and detail design. In Section 2.3, I outline the design and evaluation methods employed in WEC design (and more broadly) to achieve 11 specific design requirements. In Section 2.4, I discuss the development and results of a survey distributed to WEC designers and developers regarding the methods they use in WEC design. The survey results allow us to connect and compare the WEC design methods present in the literature with those being put to use in industry, providing insight that would otherwise be lacking in a literature review due to the fact that developers do not commonly publish their methodologies. To conclude, I (1) identify the design approaches and tools that are most widely used in practical WEC design, (2) identify areas where promising tools or methodologies already exist but are not widely applied, (3) identify the areas where designers are most in need of new tools and methodologies, and (4) identify areas where designers need a better understanding of the effect of design decisions on WEC performance.

2.1 Generalized Definition of a WEC Design Problem

The first steps in a design project are to identify the needs to be addressed, clarify the problem, define the requirements of the system and the necessary functions, and decide on metrics for measuring successful performance [18]. These steps have been taken on at the scale of the entire industry by various wave energy researchers, through research such as stakeholder analyses, wave resource assessment, and other projects which we will discuss in this section. Industry-wide, generalized project definition can be helpful to designers when defining their individual project, but should not entirely replace the project definition stage of the individual project.

2.1.1 Identifying Needs and Clarifying the Problem

For grid-scale WEC design, wave energy researchers have identified the societal need for near-zero-emissions energy sources given the present and future consequences of climate change caused by greenhouse gas emissions [28]. To better understand how wave energy might be able to satisfy this need, researchers have made estimates of total potential electricity production and done wave resource assessment which can help developers and governments choose the best locations for WEC farms. The potential electricity which could be generated by ocean renewable energy technology (wave, tidal, current, and salinity gradient combined) was estimated by Sims et al. to be 500 GW capacity globally [29] and the global energy potential as 20 EJ/yr by Krewitt et al. [30]. These estimates consider energy resource and technical potential, but not social, political, or economic factors. Wave energy-specific resource assessments dealing with quantifying total resource and have been done globally (estimating a global gross resource of 3.7TW [31], 2.11TW [32]), as well as for many specific regions such as the Pacific Northwest of the United States [7], the continent of Australia [33], the Mediterranean [34], the Atlantic coast of Europe [35], and many more. These regional assessments can further inform designers by quantifying the dominant wave frequencies, seasonality, water depth, distance from shore, and directionality of the wave resource. From these resource assessments, the functional design challenges of converting wave resource into usable energy emerge.

To further help clarify the design problem, economic studies have identified some of the most pressing areas for improvement of WEC design in order to drive down the cost of energy. Studies suggest that researchers and developers must increase the amount of energy that a WEC systems can produce annually [36] and prove the long-term reliability of that energy production [37]. They also recommend that WEC designers must improve the mooring systems, control strategies, and power take-off (PTO) efficiency of WECs. Collectively, economic studies show that designers must learn to prototype with low-cost materials and improve modeling verification. They acknowledge that lack of deployment and testing experience has led to the need to improve installation practices, make more accurate cost estimates, gain public acceptance, and better understand environmental effects [36, 37, 38, 39].

Identifying other societal needs besides that for low-emission electricity has led researchers to suggest the application of wave energy in emerging markets such as desalination or sustained ocean observation [8, 40]. Research and development of WECs designed for off-grid markets has the potential to allow for the smaller deployments that give developers the experience necessary to address the aforementioned installation, cost, and uncertainty-related challenges [8, 40]. If developers can break into smaller markets, they may be able to secure some of their own income and learn lessons which will drive future innovation. The hope is that off-grid deployments can help to break what some call the “wave energy paradox” in which lack of investment and support, lack of deployed devices, and lack of commercial returns combine to paralyze innovation [41]. Researchers have further diversified the potential applications of wave energy through studies on remote communities where the cost of energy is already high i.e., [42] and through co-location studies which explore the potential of combined energy generation with offshore wind to reduce structural, installation, and maintenance costs, i.e., [43]. The diversity of need and potential application of wave energy explored in research serves as a baseline for WEC designers as they clarify the specific design problem which they will address.

2.1.2 Define Requirements and Functions

The customers for a WEC project include the electricity end-users, utilities, local, state, and federal governments and permitting organizations, potential projects developers, system operators, manufacturers, and local communities near the wave energy site. Figure 2.1, created by Babarit et al. shows the many stakeholders involved in a WEC design project, their relative importance, and the part of the process in which they are involved [2]. Having identified the stakeholders for a wave energy project, Babarit et al. go on to outline the explicit needs of those groups using a systems engineering approach [2]. They identify seven first-tier stakeholder requirements: *have a market competitive cost*, *provide a secure investment opportunity*, *be reliable for grid operations*, *benefit society*, *be acceptable for permitting and certification*, *be safe*, and *be globally deployable.* They then translate those needs into a taxonomy of functional requirements for wave energy converters, the highest level of which includes *generate and deliver electricity from wave power*, *control farm and subsystems*, *maintain structural and operational integrity of farm* *and subsystems*, *provide suitable access and transportation*, and *provide synergistic benefits* [44]. From the first functional requirement's sub-requirements, we can identify the common subsystems of a WEC—subsystem that collects wave power (the WEC), that convert wave power (the PTO), that transports power, that controls the physical position (mooring/foundation), and that controls the internal dynamics (controls) [44]. Research done by Ruiz-minguela et al. determines a similar set of stakeholders and stakeholder requirements, categorizing stakeholders into either financiers, condition setters, developers, and energy users. For grid-scale WEC development, they note that the project developers are the most important stakeholders, followed by the financiers and conditions setters, and energy users as the least important. They use a matrix-based approach adapted from axiomatic design (discussed in the following section) to translate stakeholder requirements onto functions, subsystems, and components [45].

2.1.3 Metrics of Success

One of the primary performance measures for energy generating technologies is the Levelized Cost of Energy (LCOE). LCOE is the total annual cost of a technology, including all capital and operational costs, normalized by the annual energy production of a device, measured in $/kWh. In the case of wave energy, both the costs and annual energy production are estimates with levels of uncertainty corresponding to the maturity of the technology [38]; in the case of WECs, the uncertainty is quite high. Researchers and developers have created models to estimate the

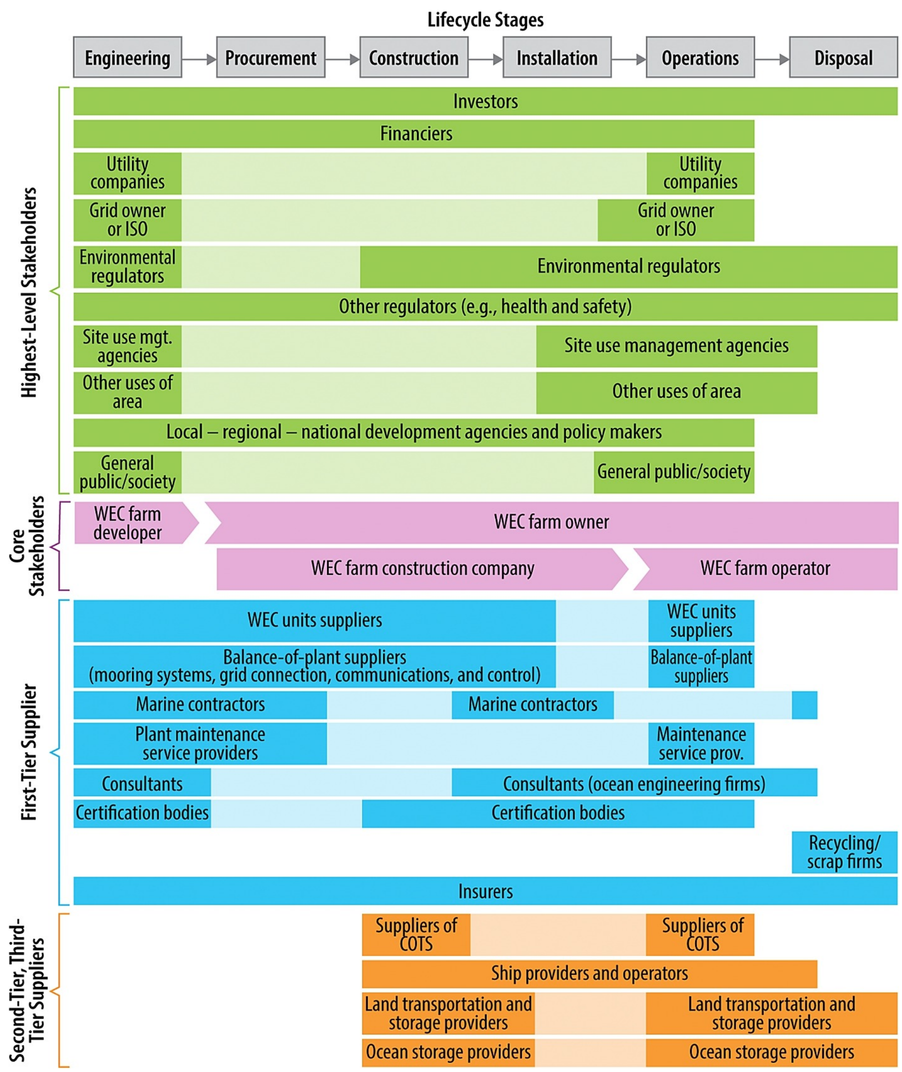

Figure 2.1: WEC Farm Stakeholders

The stakeholders throughout the lifecycle of a wave energy farm project determined by Babarit et al. [2]. Image created by Alfred Hicks of the National Renewable Energy Laboratory for publication in *Stakeholder requirements for commercially successful wave energy converters* by Babarit et al. in Elsevier's Journal Renewable Energy. The image was reproduced with permission from the publisher.

LCOE of different wave energy devices, e.g., [36, 38, 46, 47, 48]. For wave energy and other devices with high uncertainty due to lack of maturity, LCOE is not the best indicator of economic performance or commercial readiness [37, 49]. Researchers and organizations have come up with a few other metrics to use to quantify performance and benchmark WECs between one another. Babarit et al. use absorbed energy per characteristic mass [kWh/kg], absorbed energy per characteristic surface area [MWh/m^2], and absorbed energy per root mean square of PTO force [kWh/N] [50]. Each of these quantities relates energy production from numerical models to a cost-related metric that can be quantified with significantly less uncertainty than, for example, lifetime operational costs. Another study by Babarit compares WECs of different archetypes based on their capture width ratio (CWR) which is the ratio of the capture width, defined as the absorbed power over the wave power per meter wave crest, to the characteristic length of the device [12]. This metric accounts for hydrodynamic performance, but no cost drivers, as does the commonly-used mean annual energy production (MAEP) metric. Estimating MAEP requires power matrices from time domain simulations and site-specific wave data. Hiles et al. estimate that between the uncertainties in the simulations and those in the wave data, estimates of MAEP have an uncertainty of 2–20% [51]. Economically-focused metrics include the net present value (NPV), internal rate of returns (IRR) and payback period (PBP). Guanche et al. show a method for statistically estimating these metrics and understanding their variability due to changing wave conditions [52]. A paper by Caio et al. summarizes the use of these and similar metrics by various organizations, emphasizing the lack of convergence on a standard performance measure [41].

In the U.S. Department of Energy's Wave Energy Prize, the judges used some of the metrics discussed above, along with a metric of capture width per characteristic capital expenditure (ACE) and a metric of hydrodynamic performance quality (HPQ). HPQ used the ACE metric along with multipliers based on mooring loads, station keeping, peak to average absorbed power, PTO behavior, absorbed power in realistic seas, and control effort expended [49]. The multipliers accounted for other important performance requirements beyond cost and energy production, such as reliability and grid compatibility. In a further effort to account for important factors in WEC design and create an industry-standard assessment of performance, especially for devices of low Technology Readiness Level (TRL) and thereby high uncertainty, researchers at the National Renewable Energy Lab and Sandia National Labs have created a techno-economic performance assessment called the Technology Performance Level (TPL) Assessment [44]. The TPL assessment quantifies performance through a question-by-question assessment performed by experts in the field with information provided by designers. Rather than a single metric which can be calculated to varying levels of uncertainty depending on the modeling and testing which has been done for a device, TPL includes qualitative and quantitative performance measures under which device properties are estimated within high-medium-low ranges. Though TPL could become a comprehensive measure of performance, it cannot be used in device design optimization, while other metrics can.

2.2 Stages of a WEC Design Process

Throughout the literature, there are many methods presented for specific aspects of WEC design, especially numerical modeling and optimization. Yet, as Henriques et al. point out, "in general, it has been observed that information and knowledge have been presented dispersed and without integration [...] but no global overviews have been reported in a systematic and comprehensive way" [53]. Portillo et al. present the overview of the life cycle of a wave energy project, shown in Figure 2.2.

The overview provided by Portillo et al. is not intended as a detailed process for designers to follow, yet examining the gaps in the process they outline can help us begin to understand where we can improve and adjust WEC design practices. The process shown in Figure 2.2 begins with the definition of the WEC and the PTO concept during preliminary design, after which designers create and validate a numerical model and gather data about a selected site. For a general design project, 50–80% of the cost is committed during conceptual design [54, 55], the part of the design process leading up to concept definition; yet the process shown in Figure 2.2 does not show any steps leading up to concept definition. This reflects the tendency of WEC designers to under-utilize or even forgo the conceptual design process (shown in Sections 2.2.2 and 2.4.2) which could be due to lack of experience with conceptual design processes, or to shortcomings of those processes for application in WEC design. The first performance assessment shown in Figure 2.2 does not occur until after model validation, indicating that designers might not evaluate concept variants before spending the time and money necessary to create and validate models. Conceptual design steps in the WEC design process need to include early evaluation of concepts prior to spending significant amounts of time and money defining a single concept because failed concept selection will lead to higher development costs and longer development times later in the design process [21]. In Figure 2.2, following the preliminary performance assessment based on numerical models, designers may have to circle back to concept definition (iteration is not shown for image clarity). As we will see in the following sections, modeling and simulation processes have been well detailed in literature, but the steps that designers should take to make the next iteration better than the last once they have simulation results are missing from Figure 2.2 as well as from the literature more generally.

Following Figure 2.2, once preliminary design is complete, designers work through detail design which includes hydrodynamic optimization, PTO sizing and selection, mooring systems selection, and another performance assessment followed by structural design. Designers may return to concept selection should the results of the second performance assessment be unfavorable. Following detailed design, designers move on to physical model design and testing, where they incur significant costs, then implementation, for which there are few examples for WECs, i.e., [57]. Weber et al. have discussed the importance of not entering the testing stages too early, or with a WEC that cannot meet the design requirements [5]. Avoiding such pitfalls requires design techniques which will help designers ideate better WEC concepts from the start. These techniques will likely need to extend beyond the

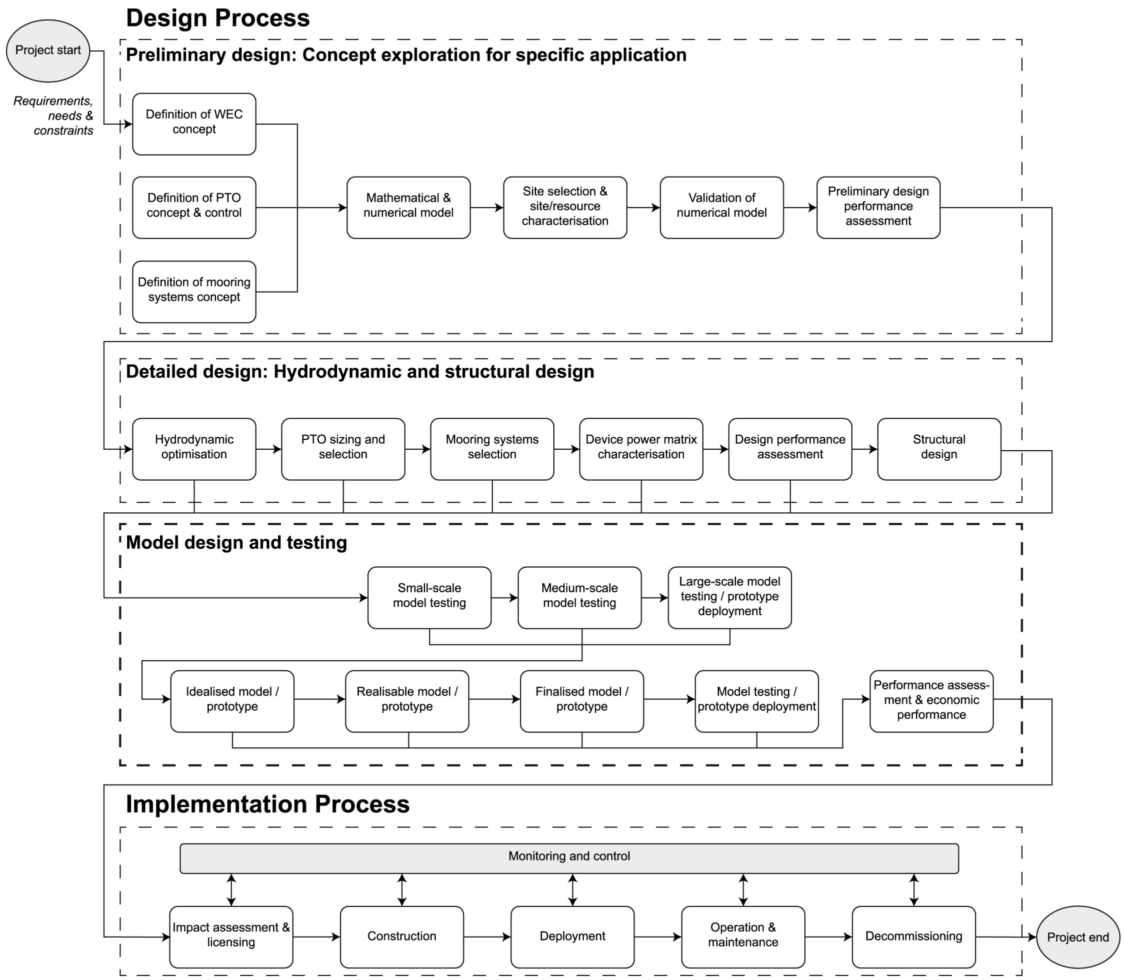

Figure 2.2: A WEC design process

The WEC design process as presented by Portillo et al. [56] with iterative arrows removed for clarity. Image was adapted by Portillo et al. from their previous publication [53] and republished in Wave energy converter physical model design and testing: The case of floating oscillating water columns in Elsevier's Journal Applied Energy. The image was reproduced with permission from the publisher.

modeling and optimization techniques which are currently central to WEC design. Design theorist Nam p. Suh points out that design techniques based on modeling and optimization “do not provide tools for coming up with a rational system design beginning from the definition of the design goals” [22]. The need for WEC design methodologies and tools which emphasize the early stages of the design process has been identified by several design researchers [5, 58, 59]. In the following sections, we discuss methods at four stages (project definition and management, conceptual design, embodiment design, and detail design) which may help to fill some of the gaps in the WEC design processes illustrated by Figure 2.2, systematically address the challenges discussed in the previous section, and improve the overall trajectory of WEC design.

2.2.1 Project and Product Definition

The project and product definition stages of the WEC design process should include identifying need, clarifying the problem, defining requirements and functions, and determining metrics for success [18], as mentioned in Section 2.1. Designers or supervisors might also determine a design philosophy which they intend to use to guide the rest of the project. The need for near-zero-emissions energy technology has been largely accepted by the wave energy industry and research fields, and for that reason, techniques for need finding have not become an essential piece of the WEC design process, even as interest in alternative markets grows. Nevertheless, need finding remains important for enabling individual projects to achieve their intended end use and to be accepted by users and the community. This fact is exemplified by the ever-growing body of research in the areas of user-centered design, human-centered design, participatory design, codesign, and design justice in which community and user needs are centralized in the design process [60]. Typical techniques for need finding include interviewing, surveying, or observing customers [18], while more cross-cutting techniques focus on involving potential customers throughout the design process [61]. Early stakeholder meetings with manufacturers, utilities, or even potential end users are forms of need finding used in the wave energy industry. Successful need finding will enable designers to identify explicit needs of the customers, implicit needs, and niche needs. The requirements outlined by Barbarit et al. [2] and discussed in Section 2.1.2 can be considered explicit needs. Implicit needs, needs which customers may not be able to recognize or articulate, and niche needs, those which are specific to a discrete customer population but present a unique market potential, are often project-specific. Greater participation in need finding could lead to new pathways for wave energy. Designers may use templates such as those provided by David Ullman in *Modern Product Design* to make need finding more productive and to derive an adequate problem statement from the work [18].

Quality Function Deployment (QFD) and functional modeling are methods for dealing with customer and functional requirements. QFD includes defining and weighting customer requirements, relating those requirements to measurable engineering specifications, benchmarking competitors against those customer requirements, and determining the relationship between engineering specifications [18].

QFD can help designers determine what the most important specifications of the WEC are and what potential trade-offs exist between and among engineering specifications and customer requirements. The visualization for QFD is called a House of Quality (HoQ). We have included an example of the central section of the HoQ in Figure 2.3. In this section of the HoQ, the designer identifies how each design specification relates to each customer requirement (1 representing a weak relationship, 3 moderate, and 9 strong). Given the designer-input weights of the customer requirements and the relationships between requirements and specifications, the HoQ calculates the relative weight of each design specification (fourth row from top). The weights can be used to focus design efforts throughout the process. A complete HoQ requires designers to input target values for design specifications, something that designers might not otherwise do this early in the design process. It also requires designers to define relationships between design specifications (the "roof), which I do not show here. The weights and relationships input into the HoQ may be changed as the designer learns about the system. The Structured Innovation design tool from DTOceanPlus includes QFD for use in ocean energy applications [59], and the method was employed by Ruiz-Minguela et al. in their 2019 publication [45].

Functional modeling, or functional decomposition, helps designers answer the question, *what must the product do?* Designers begin the model with the primary function, then decompose that function into sub-functions (boxes) and operating flows (arrows) [62]. When creating a functional model, the designer does not specify components, instead, specifies abstract functions. A functional model can be

Relationship Between Requirements:
9 - Strong 3 - Moderate 1 - Weak

Row Number	Max Relationship Value in Row	Relative Weight	Demanded Quality (a.k.a. "Customer Requirements" or "Whats") / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	Mass	Surface Area	Number of active parts	Working depth range	Archetype	Orientation/ directionality	Number of mature technologies	Number of structural components	Number of consumable components	Number of Installation steps	Number of manufacturing steps	Control strategy/ control force	Mooring type	Hydrodynamic geometry	Component lifetime	Number of jobs created
			Column Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
			Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
			Requirement Weight	447.67	419.77	430.23	105.81	304.65	125.58	387.21	150	276.74	247.67	233.72	322.09	512.79	313.95	463.95	73.256
			Relative Weight	8.33	7.81	8.01	1.97	5.67	2.34	7.21	2.79	5.15	4.61	4.35	5.99	9.54	5.84	8.63	1.36
			Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)																
			Minimize (▼), Maximize (▲), or Target (x)																
			Target or Limit Value																
1	9	11.63	Power Production	9	9		3	3	3						9	9	9		
2	9	11.63	Low capital cost	9	9	9				9	9		9	9	9	9	9	9	
3	9	9.30	Low operational cost	3		9				9		9			1			9	
4	9	9.30	High availability			3		3	3	9		3	3		1	3		9	
5	9	11.63	Reliable and survivable	3	3	9	1	9		3	1					9		3	
6	9	8.14	Easy to manufacture	9	9	9		1		3	3	1		9			9		
7	9	9.30	Easy to install and maintain	9	9	3	3			3	1	9	9			9		9	
8	9	10.47	Integrates with electric grid					9	3						9	3	3		
9	9	8.14	Safe and low environmental impacts	1	1	1		3		3		9		3		3		9	
10	9	6.98	Acceptable to the public	1	1														9
11	9	3.49	Globally deployable	1	1		9	3	9	1			9	9		9			3

Figure 2.3: House of Quality (HoQ) for a WEC

An example of the central part of a House of Quality (HoQ) filled out for a grid-scale WEC.

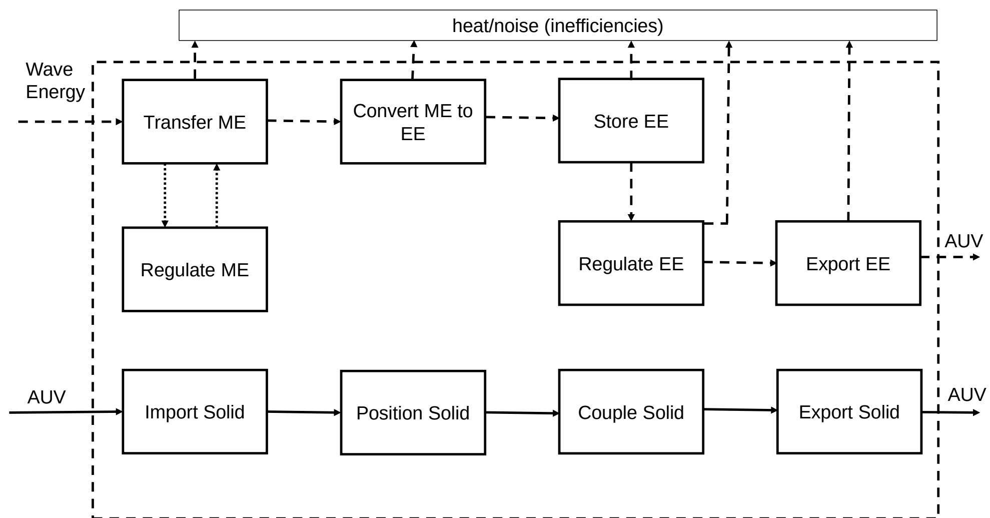

Figure 2.4: Functional Model for AUV recharge WEC

An example of the a simple functional decomposition for a WEC designed for autonomous underwater vehicle (AUV) recharge.

used for the stages of a WEC's lifetime in which there are human–WEC interactions (suhc, helping designers identify where human interaction is necessary and potential human-caused errors [63]. An example of a high-level functional model for a WEC intended for autonomous underwater vehicle (AUV) recharge is shown in Figure 2.4.

Design philosophies are overarching approaches to design. Those which have good potential to guide WEC design include Systems Engineering, Set-Based Design, Axiomatic Design, and principles of Ecological Engineering. It is also likely that user-centered and participatory design approaches will prove valuable for emerging market WEC devices for which the end user has more direct contact with the device, such as devices designed for AUV recharge.

- **Systems Engineering** is a more traditional engineering practice than those mentioned above. Systems Engineering and standard product design methods guide designers through similar initial design steps of determining a mission, identifying stakeholders and stakeholder needs, identifying the functional requirements to satisfy those needs, and using the relationship between the stakeholder needs and the functional requirements to set targets for the functional requirements. Bull et al. applied the Systems Engineering approach to a wave energy farm to propose taxonomies for WEC capabilities (sometimes called stakeholder needs or customer requirements) and WEC functional requirements [44]. Systems Engineering encourages designers to consider the whole life cycle of the WEC and to decompose the WEC into rational subsystems.

- **Set-Based Design** is a design methodology which encourages designers to develop multiple concepts concurrently. Instead of choosing the best concept variant with the limited knowledge intrinsic of the conceptual design stages, Set-Based Design focuses on eliminating inferior concepts while iteratively defining and developing the other concepts in order to avoid choosing a concept based on imprecise data [64]. The methodology encourages designers to update their problem statement as they learn more about the problem. Set-Based Design has been acknowledged as particularly useful for design problems with high degrees of uncertainty [65], such as WEC design [58]. Delaying commitment to a single concept has shown to decrease the time and money spent throughout the design process [66]. Set-Based Design could help WEC designers follow the TPL-TRL curve suggested by Weber as a pathway toward successful commercialization [5] by integrating performance assessment prior to concept selection and refocusing WEC design toward performance rather than exclusively readiness.

- **Axiomatic Design** is a design theory for general systems, including non-physical systems, which uses a rigorous decision-making framework to guide designers toward rational designs of reduced complexity. Axiomatic Design theory is based on the theorem that the best design is the one in which all functional requirements are independent (Axiom I) and the information content is minimized (Axiom II). System architecture is defined using matrices and flow diagrams [22]. Proponents of Axiomatic Design claim that it reduces technical and business risk compared to heuristic design methods.

Axiomatic Design was integrated into an early design stage of marine energy design by Ruiz-Minguela et al. and determined to help determine risk factors, focus designers on key properties of the system, and compare concept alternative [45]. The theoretical definition of a successful system in Axiomatic Design could help WEC designers assess their WECs with less uncertainty and its rigorous process for decision making could guide WEC designers toward better designs before they conduct detailed hydrodynamic modeling and testing campaigns. Non-physical requirements of WECs, such as community and government acceptability, may be more challenging, but by no means impossible to integrate into Axiomatic Design.

- **Principles of Ecological Engineering** provide guidance for the design of systems which are integrated into the natural environment. Typically, Ecological Engineering processes are applied to projects at the junction of ecology and engineering such as wetland restoration or or sustainable timber harvest [67], but Bergen et al. assert that the principles of Ecological Engineering can be applied to any engineered system which extracts natural resources [23]. This would include WECs harvesting energy from ocean waves. The principles of Ecological Engineering include the two design axioms from Axiomatic Design as well as "design consistent with ecological principles", "design for site-specific context", and "acknowledge the values and purposes that motivate design" [23]. The principles of Ecological Engineering could help WEC designers improve the resilience of WEC systems, better account for upstream and downstream effects, utilize natural ecological functions, and integrate their primary purpose throughout the design process. Ecological engineering practice may also lead to unique WEC concepts through its emphasis on functional diversity, site-specific solutions, and human values.

2.2.2 Conceptual Design

Once designers have defined the goals of the project and the requirements of the WEC, they are ready to ideate WEC concepts. A concept is "an idea that is sufficiently developed to evaluate the physical principles that govern its behavior" [18]. The conceptual design process can be broken up into concept generation and concept evaluation. Overall, the employment of structured conceptual design methods has been limited in WEC development as well as WEC research [59]. There are few publications that detail the conceptual design of a WEC. Those that do display a similar approach to one another: identify the most pressing challenges in WEC design, then select an existing WEC archetype and present 1–3 design ideas to address those challenges. Some examples of such an approach are shown in a publication detailing the design of the SEAREV WEC [68], another describing a WEC designed for hydrogen production [69], and another on the Inertial Sea Wave Energy Converter (ISWEC)) [70]. For the SEAREV WEC, the designers considered survivability, maintenance, and performance as the most pressing challenges and chose to address those challenges with a fully-enclosed rotating-mass WEC with latching control. They avoided end stops and emerging superstructures [71]. Boscaino et al. focus the design of their WEC for hydrogen production on reliability [69]. Bracco et al. choose the ISWEC to address the challenge of reliability and survivability by enclosing all components of the WEC into one seawater-tight floating body as well [70]. The piece-wise innovation exhibited by these design decisions which focus on a single primary challenge does not cover the breadth of challenges that WEC designers must overcome. This type of design is commonly known as spiral design or point design. Point design typically requires many iterations and leads to feasible, but not necessarily optimal concepts [64]. Structured concept generation and evaluation methods may be able to help designers ideate high performing concepts which address the full scope of challenges in WEC design.

2.2.2.1 Concept Generation

Methods of concept generation are typically categorized as creative methods or rational methods. Creative methods include brainstorming, sketching, and mind mapping. Some general rules of creative processes are that all judgment/evaluation should be avoided until the end of the process and all ideas should be recorded. Concepts may be generated verbally or on paper, by individuals or by groups. Varying group size and time limits and preventing fixation on a single idea are important aspects of the creative concept generation process [18]. Rational concept generation methods include the theory of inventive problem solving (TRIZ), biomimicry, and morphological matrices. The application of TRIZ in WEC design has been discussed in detail by Costello et al. [4] and has been integrated into the Structured Innovation design tool by DTOceanPlus [59]. On the website triz40.com, designers can use an online matrix to work through TRIZ [72]. Methods of biomimetic design have been applied to wave energy as well, i.e., [73, 74]. There have not been publications on morphological techniques applied to WECs, but So et al. show an example of a morphological matrix for the mechanical to electrical power train in their publication on PTO-Sim, a library for WEC-Sim which models different PTO elements [75]. In a morphological matrix, each row is a subfunction, and each cell in that row is a different concept for carrying out the subfunction. Designers create concept variants by combining a single concept from each row. Morphological techniques have received attention as the basis for computational conceptual design [76]. It has been shown that design teams that generate many concepts early in the design process are more efficient in terms of cost and time, overall [77].

Conceptual design is not limited to the definition of high-level WEC characteristics. The strategies can be used to design subsystems and components as well. Storyboarding is a conceptual design method common in the film and animation industry, but has been researched and used in engineering fields as well [78]. In engineering design, storyboarding is an effective way to "demonstrate system interfaces and contexts of use" by creating graphical narratives [78]. Throughout Section 2.4 of this paper, we mention potential uses of storyboarding for developing WEC survival strategies, manufacturing plans, and installation and maintenance outlines. Manufacturing, installation, and maintenance are all aspects of WEC design that exemplify the human-WEC interface while creating survival strategies are preparing the WEC system for changing contexts of use. Truong et al., provide details on how to perform storyboarding.

The methods of hierarchical decomposition can guide designers in the continual use of conceptual design methodologies. Hierarchical decomposition is a process in which designers decompose the system from the highest level systems into subsystems, sub-subsystems, and so forth, down to individual components [79]. Ruiz-Minguela et al., present a system hierarchy for a grid-scale WEC [45]. Designers may begin by defining the highest-level concepts, then work down, using decisions from the higher-level as constraints on conceptual design of lower-level systems. Hierarchical system's design beginning at the highest-level is "usually acceptable when the system design and architecture are mature and the new design is not fundamentally different from experience. However, for cases where it is permissible and, in fact, desirable to explore completely new architectures, it can often be unclear how the hierarchy of the design parameters should be set" [79]. Guindon's research on software systems reached a similar conclusion that "a top-down decomposition appears to be a special case for well structured problems when the designer already knows the correct decomposition" [80]. We argue that WEC design is an area where completely new architectures are desirable due to the fact that none of the current concepts has proven to be ideal.

The alternative to the top-down approach would be a co-design approach in which multiple subsystems are designed concurrently beginning in the conceptual design stages. Multi-subsystem co-design [81] has received attention in the wave energy control design and optimization fields, i.e., [82, 83]. Co-design could be an effective approach for WEC design given the strong impacts of design decisions made for one subsystem on another subsystem (and vice versa), such as the impacts of device geometry on optimal control strategy [84, 85] or of array layout on control strategy [86]. Implementing co-design practices from the conceptual design stages, or even simply restructuring the typical hierarchy could allow designers to take advantage of the interactions between subsystems to come up with novel WEC concepts. The Design Structure Matrix (DSM) is a tool that can be used to distinguish the relationships between subsystems/components during the early design stages and can help designers determine a hierarchy for design. Like for TRIZ, there is an online tool for DSM as well [87].

2.2.2.2 Concept Evaluation

Methods of concept evaluation include decision matrices, concept screening, utility analysis, Pugh methods, and strengths, weaknesses, opportunities, threats (SWOT) analysis. The overarching design approach implemented by a design team will impact how concept evaluation methods are used, for example, a design team using Set-Based Design might choose to input ranges of values into decision matrices when there is uncertainty and only eliminate a concept from consideration when it is dominated by another concept (its highest score is lower than another concept's lowest) as described by Malak et al. [88]. Alternatively, a team following axiomatic design may evaluate concepts in reference to how well they satisfy the two design axioms. Design teams often allot a specific amount of time to the conceptual design stages, and choose a concept at the end of that time regardless of the uncertainty that remains [64]. Some industries have industry-specific conceptual design techniques. For example, chemical engineering process design researchers have presented a hierarchical conceptual design process [89], and sustainable product designer researchers have presented a tool called the "GREEn Quiz" to improve the understanding of design trade-offs during the early design phases [90].

WEC designers might benefit from WEC-specific conceptual design techniques. Our research group is currently testing a tool similar to the GREEn Quiz for use in emerging market WEC conceptual design. Bubbar et al. offer a WEC-specific concept evaluation method based on Falnes' method of turning the linear power optimization problem into an analytical problem which can be solved using mechanical circuit representations. Designers may solve the analytical problem by matching the impedance of the WEC to that of the PTO to determine a maximum power capture [91]. This theory could allow researchers to compare the maximum theoretical power of a WEC architecture (which they define as "the set of *configurations*, which share the same device topology" [91]) to that of other WEC architectures. The method offers an alternative to detailed modeling and simulation for evaluation of power production in the conceptual design stages. Designers can compare their device's power output to that theoretical maximum [91].

2.2.3 Embodiment Design

Embodiment design is the stage where designers identify critical specifications, generate overall layouts, detail subsystems, and build models and prototypes. It is the stage of the design process focused on iteration and feedback [18]. The work of conceptual and embodiment design often overlaps, especially if designers are working on multiple concepts. Many of the design methods and tools which we discuss in Section 2.4 are a part of the embodiment design stages, but in this section, we will focus on numerical modeling and prototyping, as these are two of the central aspects of WEC embodiment design.

2.2.3.1 Numerical Modeling

Tools for numerical modeling of wave energy devices include hydrodynamic solvers, dynamic analysis software, and simulation tools. These tools help designers determine localized WEC effects, work toward control design, and calculate annual energy production, among other quantities [92]. The hydrodynamic solvers simulate a WEC's response to wave action. Many WEC researchers and developers use boundary element method (BEM) solvers [92], which use linear potential flow theory to estimate wave–body interactions. Though linear potential flow theory has limitations in terms of the fidelity of results, it is common in early stages of WEC development because of its quick computational speed compared to nonlinear simulation methods such as computational fluid dynamics (CFD) or smoothed-particle hydrodynamics (SPH) [93]. A study comparing linear, weakly nonlinear, and fully nonlinear modeling techniques determined that for small to medium wave conditions, linear models give results close to those of nonlinear models and should be used in those scenarios due to their computational efficiency [94].

Common BEM software tools used in wave energy include Ansys Aqwa, WAMIT, and NEMOH. Of the three, NEMOH is the only open source software. When Penalba et al. compare NEMOH to WAMIT, they identify a lack of manual and test cases as "a significant weakness of NEMOH" [93], but this issue has recently been addressed by Ancellin et al. in their introduction of Capytaine, a Python-based linear potential flow solver which is meant to be easier to maintain and develop [95].

Each of these BEM solvers simulates in the frequency domain, meaning that if a designer wants to simulate the WEC in the time domain (which is necessary to model nonlinearities such as turbine dynamics [96]), they must input the outputs of the BEM solvers (hydrodynamic coefficients) into a simulation platform such as Matlab Simulink or Python. There are numerous documentations of this process, e.g., [97, 98, 99]. Nonlinear and weakly nonlinear methods have been reviewed, i.e., [92, 100, 101], compared against linear methods, i.e., [94], and improved upon, i.e., [102] throughout the literature. Dynamic analysis software that may be used in numerical modeling includes ProteusDS, Orcaflex, and Flexcom Wave, while specialized simulation tools include WEC-Sim [98] and InWave [101]. For modeling moorings, designers can use OrcaFlex, MoorDyn, or a custom approach like that presented by Paduano et al. [103]. WEC designers are heavily reliant upon numerical modeling and simulation, making the body of literature which describes the strengths and weaknesses of different approaches very valuable to designers.

Researchers have created Reference Models of WEC archetypes [36, 104, 105] that can be used as a starting point for numerical modeling. Generic numerical models of PTO subsystem components have also been created [75] as well as techniques for generic representations of control forces [83]. Designers may also use mathematical representations of moorings to approximate a mooring force on the device prior to integrating mooring models [106]. A designer's prioritization of subsystems will determine which, if any, of these surrogates they use. Since academic research tends to focus on one area of WEC design at a time, there remains a need for research on how the use of surrogate representations of subsystems in numerical modeling impacts WEC performance and what the best approaches are for using them. A better understanding of these implications would help designers determine subsystem hierarchy or choose to implement co-design approaches.

Models provide an opportunity for designers to evaluate WEC performance prior to prototyping and testing campaigns. In addition to dynamic modeling and simulation, techno-economic evaluation, which includes results from simulations as well as economic metrics, is also a major part of embodiment design. O'Connor and Dalton provide a detailed methodology for assessing techno-economic performance for devices of various rated powers at various locations [107]. They estimate the cost of electricity, net present value, and annual energy output by accounting for feed-in tariffs, availability, transmission costs, discount factors, cost reduction for multiple devices, and scaling of available power data. For the devices they examine, the Pelamis P1 and the Wavestar, they determine that smaller rated devices produce higher relative energy outputs, but larger devices lead to better economic returns. They also show that techno-economic performance is site-dependent [107]. Topper et al. also present a method for techno-economic modeling, which they apply to tidal energy converters [108]. Techno-economic models are necessary for techno-economic optimization in the detail design stages, which we will discuss in Section 2.3.4.

2.2.3.2 Prototyping and Testing

Prototyping and physical model testing occurs in both the embodiment and the detail design stages and ranges from 1:100 scale prototypes of single components to 1:1 prototypes to test survivability, installation, or market testing. If we consider the phases laid out by the MaRINET2 project in their report on instrumentation best practices—Phase 1 for concept validation, Phase 2 for performance estimates, Phase 3 for real seas performance, and Phase 4 for fully operational testing—we can see that even in such an idealized development pathway, the distinction between embodiment and detail design phases is not always certain, especially when it comes to physical modeling [109].

The MaRINET2 development pathway includes objectives, scales, and test wave types for each phase of testing. The pathway implicitly indicates an order of subsystem design which goes WEC body/energy absorption subsystem, PTO, then control, moorings, and power transport in Phase 3 [109]. Contradictions thus emerge between conceptual design, numerical modeling, and optimization (discussed in the next section) on the one hand, and development pathways on the other regarding when and how different design parameters should be investigated and chosen. Weber explores these contradictions and proposes a reimagined development pathway which is not driven by achievements in physical testing (often called technology readiness levels), but rather a combination of conceptual performance evaluation and technology readiness which could improve information gained from test campaigns and reduce overall costs [5].

Although a scaled WEC tested in a wave tank can give extremely valuable data to designers, the designers must understand the geometric, hydrodynamic, thermodynamic, and aerodynamic similarities between the model-scale and full-scale WECs in order to deduce reliable conclusions about their WEC [110]. The ability to do this requires that scaling laws are accounted for and proper instrumentation is used during testing, for which guidance can be found in the MARINET2 report on best practices for instrumentation [109]. In depth discussions regarding device scaling for specific projects can be found in academic publications. Falcão and Henriques derived a scaling rule for an oscillating water column (OWC) device using dimensional analysis [110]. Sheng et al. also work with the OWC to show that Froude scaling is appropriate so long as the scaled device is working at a high Reynolds number [111]. Schmitt and Elsäßer show that Froude scaling is appropriate for wave surge converters as long as the geometry and side shapes are within constraints [112]. Whereas device geometry can be scaled using Froude laws, PTO scaling is based on the device forces and velocities (as opposed to the device characteristic length and stream velocity for Froude similitude), indicating that the two subsystems do not scale in the same way [96]. The MaRINET2 report details analytical and physical modeling guidelines for different PTO mechanisms and acknowledges the need for standardization of instrumentation for PTO testing. Overall, they recommend a "stepped, structured approach of increasing scale and model size that should reduce, or highlight, any scaling errors as size increases" [109].

Portillo et al. provide a summary of the standards and guidelines for WEC model testing. Though they recognize, "There is no clear consensus on what should be the different scales for testing. These depend, certainly, on the specific technology, costs, availability of test facilities/infrastructure, and other resources required to accomplish the purpose of the tests" [56], they outline the essential steps for testing WECs, including planning and data processing, building CAD models, searching for available components and material, and verifying material properties [56]. It is important to consider prototype cost and material scaling when choosing materials and components for a prototype [113]. The MaRINET2 Deliverable 2.28 on model construction methods gives directions for how designers should choose the scale of the prototype and the test setting depending on test objectives. They identify common elements to use to represent scaled PTO subsystems, and to select appropriate materials. The authors detail common materials for the WEC structure, buoyancy, ballast, mooring lines, and anchor, noting that early in the process designers should use light materials with a low level of detail and at later stages cheap and robust materials. Leakage, still water level, center of gravity, moment of inertia, natural periods of oscillation, instrumentation and control system, PTO characteristics, and mooring characteristics are all aspects of physical model design that need to be considered relative to the test objectives [113].

2.2.4 Detail Design

Detail design is the part of the design process where designers create visualizations, determine final design specifications that will be important for the implementation stage, and create product portfolios that are useful for preparing for the final build of the product and for communicating the functionality and market opportunity of the product [18]. Manufacturing and assembly processes are sometimes determined during the detail design stage, but methodologies like concurrent engineering and design for manufacturing encourage designers to consider manufacturing and assembly processes in the conceptual design stages [25]. Detail design is the stage of the WEC design process in which optimization methods are used. Optimization algorithms use analytical or numerical system models, user-defined objective functions, and product constraints to determine the optimum value for a design parameter(s) [114].

Researchers employ optimization methods with the objective to minimize cost, e.g., [115], maximize (or sometimes minimize variability of) power production (energy absorbed and/or converted), e.g., [116, 117, 118], or maximize reliability, e.g., [119]. There is also research on multi-objective optimization, such as the maximization of mean absorbed power with the minimization of construction cost, e.g., [120, 121]. These different objectives are applied to device geometry, e.g., [116, 117, 122, 71], control systems, e.g., [68, 116], PTO systems, e.g., [53], moorings, e.g., [115], foundations, e.g., [119], and array placement, e.g., [123, 124]. Pichard et al. present a method of optimizing the scale of a device for techno-economic performance [125]. Some more advanced work includes control system impacts on geometry optimization, e.g., [84]. With co-dependent subsystems and the many requirements that are to be fulfilled by WECs, optimization algorithms are growing in terms of the number of design variables, number and complexity of optimization loops, and the size of the objective function. Sirigu et al. use genetic algorithms to deal with the multi-variate problem of optimizing WEC techno-economic performance [99]. Optimization is computationally expensive and requires that many design decisions have already been made, making it useful in detail design, but not a tool for concept generation. That said, conclusions drawn from optimization research can be generalized and used to influence design decisions in the conceptual stages. For example, Gomes et al. use hydrodynamic optimization on floating oscillating water columns to define length, diameter, and thickness quantities for a specific asymmetric device. They determine that the distance between the floater bottom and the length of the “large thickness tube” have significant influence on the radiative capabilities of the device and tend toward the upper bound value [122]. This conclusion can be used by oscillating water column device designers early in the design process.

2.3 Design for WEC Requirements

There are many other design approaches that may be used in the conceptual, embodiment, and detail design stages of WEC design in order to meet the design requirements for WECs. In this section, we discuss requirement-specific methods and tools that are common in the industry as well as some that have not been widely applied to WEC design, but could be used to improve the practice. Section 2.3 is organized to follow the design process sequentially; we discuss design methods as they relate to the stage in the design process. In this section, we discuss methods as they relate to specific design requirements. We define 11 separate design requirements, identify the measures used to evaluate each requirement, and discuss the design methods and tools available to fulfill each requirement.

2.3.1 Power Production

The design requirement for power production captures the WEC's ability to convert energy from the ocean waves to usable energy. For grid-scale WECs, this usable energy is electricity, although for some emerging markets it might take another form. Power production is commonly measured through MAEP [51, 3], CWR [12], and transformed and delivered efficiency [126]. Researchers with DTOceanPlus recommend that CWR is used to measure performance of low-TRL devices and power matrices for higher-TRL devices [126]. Power matrices show the mean power (absorbed or converted) over a range of significant wave heights and average wave periods [50]. The DTOceanPlus project has created an assessment tool for "system performance and energy yield" which enables designers to assess device efficiency, alternative metrics of energy performance, energy production, and power quality.The documentation of that tool includes a number of other metrics that are used for power productions [127].

Design strategies to improve power production (as well as evaluation strategies) often depend upon the numerical models and simulations discussed in Section 2.2.3. Designers often create numerical models early in the design process and use them iteratively—modeling a system, simulating its performance, changing parameters to improve performance, and so on—as exemplified by Ruellan et al. in the design of the SEAREV WEC [68]. Once enough parameters have been defined, optimization methods can be used to improve power production. Parameters of the main subsystems of a WEC may be optimized to increase power production, including the WEC, PTO, controls, and moorings, but their interdependence can make the optimization processes more difficult as discussed in Section 2.2.4. The PTO, moorings, and control strategies all influence the motion of the WEC, indicating that improving power production may require those subsystems to be designed concurrently. Appropriate control design has the potential to double the energy output of a WEC [128]. The DTOceanPlus project has developed and released (May 2020) tools for energy capture, energy transformation, and energy delivery, each of which may be useful to improve device power production [109]. The wave energy field has not yet identified device-agnostic principles for improving power production, though Babarit et al. show that the device archetype does not automatically make a significant difference [12]. Identifying principles for improving power production could lead to early-stage design tools which can decrease the time and effort spent on numerical modeling, model validation, and simulation.

2.3.2 Capital Cost

The capital cost (CAPEX) of a WEC project includes all the expenses prior to operation, including design, procurement, manufacturing, installation, and permitting expenses [104]. Measured in national currency, CAPEX estimates are integrated into the LCOE calculation. Reducing the capital cost of WECs will be an important part of making wave energy a feasible renewable energy source. Chang et al. determined the need to reduce CAPEX and operational cost (OPEX) costs by about 45% to meet the cost-competitiveness goal of offshore wind energy of $0.30/kWh USD [38]. It can be difficult to evaluate the capital cost of WECs due to the limited experience across the industry building and deploying full-scale systems. As shown by Farrell et al., uncertainty is high, and costs are dependent on government policy [129]. Costello et al. identify important capital cost drivers as device surface area, device displacement, number of PTO units, maximum PTO effort, maximum PTO excursions, and maximum device power [130]. Factors outside the designer's control, such as changes in policies and permitting practices also impact capital costs.

In order to design toward these CAPEX goals, designers must evaluate their own devices, increasing the fidelity of the evaluation as they move along through the design process. Estimates of CAPEX will increase in certainty as they increase in fidelity, and designers must remain aware of the level of uncertainty throughout the process. To evaluate CAPEX, designers can use baseline estimates from the offshore wind industry or the oil and gas industry to estimate the capital cost of a WEC. They can also begin with estimates from the marine energy Reference Models 3 [36], 5 [104], or 6 [105] (introduced in section 2.2.3). Chang et al. begin with baseline values and use a mass ratio to estimate the CAPEX and OPEX of different devices [38]. Designers may choose to perform in-house cost estimates or to hire subcontractors for the job. Early cost estimates may be based on only the costs of the most expensive components of a device in order to simplify design and evaluation. A common design method is to simply use estimates of capital cost to identify the most expensive components or services (such as transportation of materials) and redesign those aspects of the system, i.e., [71]. This iterative method can be time consuming and is best coupled with methods which help designers make better decisions from the conceptual stages. To reduce capital cost, designers can employ design for manufacturing or design for assembly methods (discussed further in the Manufacturing and Material Selection section 2.3.6) [25]. Eliminating components which are subject to major price fluctuations as well as decreasing the number, mass, and volume of components will also help reduce capital cost [131]. Later in the design process, capital cost can be included in optimization algorithms as discussed in the Section 2.2.4.

2.3.3 Operational Cost

OPEX can be defined as "all annual costs required to maintain optimum mechanical performance," including scheduled and unscheduled maintenance and insurance [132]. O'Connor and Dalton divide OPEX into insurance costs, replacement costs, overhaul costs, and annual operations and maintenance. They show that common metrics for operation and maintenance costs are currency/MWh, percent of initial cost, percent of total OPEX, and percent of cost of electricity [132]. It is important to note that the most common metric, currency/MWh, is site-specific and should be qualified as such [38, 132]. The metric of % of initial cost is a non-site-specific metric that is sometimes used for operations and maintenance costs (which make up a large portion of OPEX) [132]. Though the annual OPEX of a WEC is estimated to be 1–10% of the capital cost [133], it is more difficult to estimate given the lack of experience in WEC operation.

OPEX can be estimated by designers using many of the same methods as capital cost, and similar iterative design methods or optimization can also be employed. DTOceanPlus offers a System Lifetime Costs assessment tool [127]. The cost drivers for OPEX include accessibility and technology maturity, but have not been researched as extensively as the drivers of CAPEX [132]. For that reason, iterative design methods of reducing OPEX are less dependable. Designers can reduce OPEX by selecting components according to a lifetime maintenance schedule, synchronizing maintenance and reducing visits to the deployment site [3]. Designing components to be modular, durable, and adaptable will reduce operational cost affiliated with device failures, while automating routine maintenance and monitoring of the WEC system will reduce operational cost affiliated with personnel. Choosing components which are non-hazardous and recyclable helps to reduce decommissioning costs associated with environmental regulations, as noted in studies of oil rig decommissioning [134]. DTOceanPlus offers a logistics and marine operations tool to help designers plan operations [126]. Design for remanufacturing is the process of designing products such that the components or materials may be recovered and reused. Remanufacturing can be both economically and environmentally beneficial [135], and may be especially applicable for WEC designers building scaled prototypes. Harnessing the benefits of remanufacturing may also allow for opportunities to reduce capital cost and increase technology learning rates by making short-term deployments more economically feasible. OPEX research by O'Connor and Dalton suggests that "designers will need to choose whether to opt for longer lasting more expensive devices which require lower annual maintenance costs, or cheaper devices with short device lifetimes requiring overhaul mechanisms that enable easy and cheap retrieval from ocean site to maintenance dock" [132]. Rapid technology development based on fast learning rates and short diffusion timescales has been identified by Wilson et al., as an important factor for technologies intended to help with decarbonization [136], implying that in the early stages of WEC development, the latter option may be preferable. A final design strategy for reducing OPEX is to reach out to potential insurers early on in the design process in order to get estimates of insurance costs and begin working to decrease them.

2.3.4 Availability

Availability is traditionally defined as the amount of time a system is functional over the amount of time it is needed. Abdulla et al. argue that this traditional definition is not suitable for WECs because it "requires specifying the definition of a functional system" [137]. Instead, they define availability as the electrical energy generated over the electrical energy that would have been generated over the same period of time if there was no downtime. DTOceanPlus simply uses the percentage of time in which the WEC is producing energy [127]. The availability of a WEC has a significant impact on its annual energy production and OPEX, and therefore its LCOE [132].

In early stages of design, one may estimate the range of sea states for which the device is functional and use wave resource data to estimate availability along with a generic frequency of failure [138]. In order to estimate availability in such a way that it helps in design decision-making, designers may choose to create statistical models of availability as Abdulla et al. did for the Oyster-2 [137]. Abdulla et al. use power matrices, historical wave, tidal, and weather data, mean time between failure (MTBF) data for components, and maintenance timelines to estimate failure rates. They use OREDA, a commercial component industry database of MTBFs, to determine MTBFs and operational experience and they use operational reviews to determine maintenance timelines [137]. Designers can use models like this one to estimate the impact of system layout, preventative maintenance, system aging, wave height, and tidal restrictions on availability. DTOceanPlus offers a system reliability, availability, maintainability, and survivability assessment tool [126]. Improving availability requires designers to select and configure components such that they can handle failures [139]. WEC designers need to factor in the location at which repair will take place and the weather window necessary for repair if it is offshore [3]. This requires knowledge of offshore operations and meetings with stakeholders. Designing in redundancy for critical WEC functions and standardizing the fasteners, components, and tools needed for maintenance will also improve availability.

2.3.5 Reliability and Survivability

Reliability and survivability are closely related to availability. In fact, reliability, as measured through failure rates, is typically an input to an availability model [127]. We discuss it separately here because unlike environmental conditions and maintenance strategies, reliability can be extremely difficult to estimate (and thereby design for) for WECs given the lack of deployment experience. Clark and DuPont review the ways that wave and tidal energy researchers and developers have attempted to measure reliability, including factor approaches in which a base failure rate is multiplied by independent factors, accelerated lifetime testing approaches, and failure modes and effects analysis (FMEA) [140]. The International Organization for Standardization defines reliability as "the ability of a structure or structural member to fulfill the specified requirements, during the working life, for which it has been designed" [141]. Johannesson et al., members of the Swedish

RiaSor 2 project, present a method of determining device safety factors through a Variation Modes and Effects Analysis (VMEA), a method which increases in complexity throughout the design stages and is meant to make up for shortcomings in the FMEA [142]. Johannesson et al. use the VMEA to perform fatigue design assessment [142], and Atcheson et al. use VMEA to quantify load uncertainties [143]. General reliability standards have been published by the British Standards Institution [144], while both the European Marine Energy Centre (EMEC) [145] and the International Electrotechnical Commission (IEC) [146] have published wave energy specific standards. Survivability is measured by the range of sea states in which a WEC can operate or the probability of structural failure [126].

Designing for reliability and survivability is rooted in calculations of load and fatigue. Destructive testing or load testing on components or prototypes for which performance data may not be available helps designers understand the weak points of their concept and the operational sea state range. Margheritini et al. used a 1:60 prototype equipped with pressure cells to measure the wave loading on the Sea Slot-cone Generator. They used the results to redesign the WEC to reduce structural loading [147]. Clark et al. use fatigue analysis to account for reliability in the objective function of a WEC optimization algorithm [119]. In earlier design stages, designers might use literature to understand common failures, as done by Boscaino et al. They perform what they call a “reliability-oriented approach” in which they do a literature-based failure analysis and develop a modular WEC to increase reliability [69]. FMEAs are also common in the early stages to identify the most likely failures and then perform low-cost, isolated testing and analysis [127].

Researchers from NREL and Sandia National Labs have developed a toolbox called the WEC Design Response Toolbox which is openly available on the WEC-Sim github. The toolbox includes environmental characterization, short-term extreme response, long-term extreme response, fatigue, and design wave composition capabilities and is meant to improve the WEC survival design process [148]. Altering the configuration of the WEC during high sea states can serve as a way to increase survivability, such as Oscilla Power has done with the Triton device [149]. To come up with such a configuration, designers can perform survival strategy storyboarding (described in Section 2.2.2). To improve survivability, designers can implement life-extending controls such as those discussed by Stillinger et al. [150]. Accounting for environmental factors such as the site's water pressure, salinity (air and water), temperature variations, marine life, and extreme wave events when making structural and material decisions can improve reliability and survivability [151].

2.3.6 Manufacturing and Materials Selection

The manufacturing processes and materials selection for a WEC directly impact the CAPEX and the survivability. Manufacturability is typically measured in the time and cost of manufacturing [126]. The DTOceanPlus project has suggested a metric of manufacturing readiness level (MRL) which they borrow from the Department of Defense [126, 152]. For designers, meeting the requirement for manufacturability means understanding the available materials and manufacturing processes such that they may design a device which can be manufactured with ease, at a low cost, and with minimal risk. To evaluate manufacturability, designers can make in-house estimates of manufacturing processes, timelines, and costs which are improved by reaching out to potential manufacturers. Involving manufacturers early in the design process can prevent designers from overlooking important factors [25]. When making in-house estimates, it is helpful for designers to look to other offshore industries, as they have to deal with similar environmental challenges to materials selection. Hudson et al. document the material challenges for WECs and how they impact the commonly-used materials. They discuss corrosion, fatigue, corrosion fatigue, wear/fretting fatigue, marine fouling, and impact loading and fracture and the causes, effects, and mitigation strategies for each of these challenges [153]. A report by the US Department of the Interior Minerals Management service identified applicable standards and codes for materials which included ISO 2394: 1998 (for testing of structural materials), API RP 2SM (for testing of synthetic mooring ropes), and DNV-OS-C401 (for testing of electrical equipment and cables). They also identify manufacturing guidelines which include API RP 2A-WSD, DNV-OS-C410, and the EMEC standards for manufacturing [154].

Few publications discuss WEC design for manufacturability and materials selection. Malca et al. discuss the influence of material selection on the structural behavior of a bottom-mounted linear hydraulic PTO point absorber [155], and Le et al. in the design of a bucking diaphragm WEC [156]. Le et al. use the Cambridge Engineering Selection Software (now sold as GRANTA Selector) to choose a material for the diaphragm of the WEC according to the required yield strength and bulk modulus [156]. They also detail an experimental set-up for materials testing [156].

Herrmann et al. summarize design for manufacturability (DFM) techniques which can be used in each stage of the design process as well as in concurrent engineering. DFM encompasses the consideration of product shape, size, material, and number of components [25]. Concurrent engineering is the practice of simultaneously designing a product and determining the manufacturing processes which will be used to make it [25]. Das et al. introduce Pro-DFM, a way to model and evaluate manufacturability based on procurement, handling, assembly, and inventory. Pro-DFM combines cost and manufacturability assessments to provide designers suggestions for low-cost product realization [157]. Using a resource such as Matweb, an online source for materials information, could help WEC designers find the appropriate materials [158]. Other methods that WEC designers might use to improve manufacturability include manufacturing storyboarding, stakeholder meetings with manufacturers, and materials selection based on finite element analysis [155]. Designers may add modularity to the WEC, standardize parts, and reduce custom component complexity. It is important for WEC designers to understand the materials and manufacturing processes which are available for them in the prototyping, one-off testing, and mass manufacturing stages of design. It is, of course, best to use the lowest-cost materials possible in prototyping, but when doing so, designers must know how those choices impact experimental results [113].

2.3.7 Installation and Maintenance

Installation and maintenance of offshore technology is much more expensive than for onshore technology, and is, therefore, an important aspect of WEC design. Installation duration and costs are the common measures of installability [126]. Designers may evaluate these qualities via simulations, prototype testing, or feedback from subcontractors. A report by US Department of the Interior Minerals Management service outlines relevant codes and standards for installation [154], but as with manufacturing, approaches for design for installability and maintainability in the early design stages are different from approaches in the later design stages which are guided by these standards.

There is significant research on how installation and maintenance impact the economics of wave energy, i.e., [159], but less work on how WEC design decisions (including decisions about installation and maintenance strategies) influence installation and maintenance capabilities. Operational simulations which consider maintenance strategies have been introduced by Teillant et al. They consider unscheduled maintenance which occurs randomly based on an FMEA table [133]. The DTOceanPlus project includes Logistics and Marine Operations tools which aim to help designers with vessel selection, weather windows, and preventative and corrective maintenance planning [160]. Rémouit et al. discuss the applicability of divers and underwater vehicles in marine renewable energy installation and maintenance, identifying the situations in which one is more time and cost effective than the other [161]. Other design methods to improve installability and maintainability include storyboarding, the application of conceptual design methods to installation and maintenance strategies, and stakeholder meetings with installation and maintenance personnel. Designers may also consider combined installation with other offshore structures or integration into breakwaters [162]. Mooring design is highly influential on the installability and maintainability (as well as survivability) of a floating WEC farm [163]. Johanning et al., introduce a design methodology for identifying plausible station-keeping techniques [164]. Finally, designers might review publications and reports of other WEC installation processes such as [159] as Rinaldi et al. do for tidal deployments [165] and learn from other offshore industries [166].

2.3.8 Grid Integration

Integrating a WEC into an electric grid depends on the frequency of the output power, the consistency of the electricity production, the predictability of production [167], and how quickly production can be curtailed. Power electronics, energy storage, and control strategies directly impact grid integration [168] whereas array placement, distance from shore, and predictability of wave resource contribute to the consistency, predictability, and cost of transport of the produced power. The peak-to-average power ratio is a common measure of the quality of power produced by a WEC array [169]. Minimizing the peak-to-average power ratio has emerged as a research objective in array placement/optimization i.e., [170, 171, 172] as well as in control design, i.e., [53, 169]. The standards for marine energy grid integration can be found in IEC TC114 62600 and power quality standards for wind energy can be found in IEC 61400-21, both of which are discussed by Kracht et al. in the MaRINET report on grid integration and power quality testing [173]. Power quality measures relate to minimizing both voltage and frequency fluctuations and include include reactive power and flicker coefficients (among other measures) associated with grid codes [173]. The MaRINET report on demand side grid compatibility offers methods for designing control systems and array layouts to meet grid codes [174]. Flicker is a measure of voltage fluctuations which is impacted by the WEC farm size and architecture, device type, control, and sea state [175]. Although the impacts of flicker depend on the grid strength [176], Kovaltchouk et al. present a method of evaluating flicker independent of the grid [175]. Blavette et al. point out that because site-specific grid compatibility studies are time consuming and require a lot of detail, developers often put them off. To address this issue, they present a method using DIgSILENT power systems simulator to simulate the compatibility of a WEC farm with a generic grid representations which vary in strength [176].

Short term energy storage such as hydraulic accumulators (i.e., [177, 178]), flywheels, batteries, or super-capacitors have been subjects of research related to minimizing power fluctuations [50, 82] as have power electronics [170]. Combining wave energy with other renewables has also been explored as a way to make systems more compatible with the electric grid, i.e., [7, 179]. A numerical model which includes WEC control strategies, PTO, and power electronics is referred to as a wave-to-wire model. Wang et al. present a strategy for control design using wave-to-wire models [180], and Penabla and Ringwood present a method for developing high-fidelity wave-to-wire models. Iterative design using these models is a common design strategy, but since power system dynamics are on much shorter timescales than WEC dynamics, a complete wave-to-wire model can be computationally expensive [181]. Parkinson et al. and Reikard show methods for performing short-term forecasting and simulation of WEC-grid integration [167, 182]. Designing to reduce sensitivity to wave direction and sea state and to improve consistency of power production is most effective if began during the conceptual design phase. As discussed previously, WEC design often begins with the design of the subsystem that absorbs wave energy, leaving consideration of grid integration until later in the design process. Considering the end use earlier in the design process may help to improve the integration of the WEC with the grid, or whichever other end use for which the WEC is designed by forcing designers to understand the power quality requirements of the end use early. This will help developers avoid making high-cost deployments without the necessary knowledge on how the WEC will integrate with the grid [181]. Grid integration requirements are, of course, less applicable for WECs that are designed for non-grid applications, but the steps that designers take to consider the electric grid in WEC design may be used as a model for how designers can design for any end use.

2.3.9 Environmental Impacts and Safety

The environmental impacts affiliated with wave energy have been researched rather disparately in areas related to noise and light impacts, habitat change, sediment transport, wildlife behavior, pollution, and impacts of electric cabling. There is not a standard way of measuring all environmental impacts, but regulatory agencies require their assessment [183]. Apolonia et al. propose a method for Environmental Impacts Assessment and Socioeconomic Impact Assessment for nearshore wave energy devices [184]. Willsteed et al. argue the need for cumulative environmental assessments of marine energy devices which can bring together environmental impacts research and place it in the context of climate change and other ocean uses [185]. To get the necessary permits for testing or deployment, WECs are subject to environmental impacts assessment [186] and safety requirements. Folley et al. point out that Boussinesq, mild-slope, and spectral wave models are more suitable for determining environmental impacts than potential flow models or QFD [92].

Design for improving safety and reducing environmental impacts has been piecewise, including noise reduction, elimination of hazardous fluids and components, and minimizing human–device interaction. Additional methods for improving operational-stage environmental impacts include prototype testing with data collection, tools for which are being developed by researchers [187]. Designing to reduce environmental impacts requires communication and work between scientists and designers, which methods of Ecological Engineering help to facilitate [67].

WEC designers could benefit from employing sustainable design/design for the environment (DfE) practices as well. Life Cycle Analysis (LCA) is one of the most popular tools in DfE, but it requires a fully defined product [188]. Telenko et al. present a compilation of DfE principles and guidelines that designers can employ in the conceptual and embodiment stages to lower the environmental footprint of a product [188], most of which are focused on resource use, which receives less attention in marine energy development compared to operational-stage impacts. Nature-inspired design strategies [189], remanufacturing, and optimization methods which integrate environmental impacts (as an objective or constraint) and safety (as a constraint) are all methodologies related to DfE. Marine energy has been identified as one of the major potential ocean-based solutions to address climate change and the effects of climate change on ocean ecosystems [190]. As wave energy expands its intended end-use, designers may even choose to design systems which address the current threats to ocean ecosystems.

2.3.10 Acceptability

The acceptability of a WEC can be difficult to measure given the irrationality of human nature. Nonetheless, with this requirement, we attempt to gauge the likelihood that a WEC project will be embraced by the local governments and communities. Measures of acceptability have been proposed by governance and human dimensions researchers in wave energy. Acceptability may depend on environmental impacts and safety concerns, but, Henkel et al. point out that "Coastal stakeholders' support for offshore renewable energy technology may be based on perception rather than an understanding of technological specifics of a project" [186]. This means that we can make preliminary assessments of acceptability based on environmental impacts, safety, competition for ocean space, job creation, or even more detailed equity metrics such as the Gini coefficient [191], but ultimately, the acceptability of a wave energy project will be contingent upon the symbolic interpretations of both technology and of ocean place of the local community [192]. Testing is seen by the public as an important factor in the development of wave energy [193]. Researchers emphasize the need for good communication with the public and policy makers, participation in outreach or community partnerships by developers, and the creation of websites that are able to address the concerns of the public [193]. Though technical researchers often discuss the visibility of WECs from shore as an important factor to acceptability, social science researchers have shown that visibility is not a primary concern [194].

Acceptability may be achieved through design methodologies such as participatory design [195] and ethnographic need-finding [196], design for local manufacturing [3], and community engagement [193]. More non-traditional methodologies might include taking a site-specific approach which accounts for the community as part of the system via the principles of ecological engineering or even via engaging in customer co-design projects to build understanding of the WEC system and customize it to the needs of the specific community.

2.3.11 Global Deployability

The global deployability of a WEC encompasses its ability to operate in many locations which differ in terms of wave conditions, environment, geophysical conditions, socioeconomic status, energy demand, and manufacturing and deployment capabilities. The TPL assessment considers water depth requirements, geophysical requirements, minimum feasible wave resource, sensitivity to tidal range and current, impacts on environmentally sensitive areas, and necessity of specialized manufacturing, construction, assembly and installation tools [3]. Most evaluation of global deployability is via qualitative reasoning based on some fraction of these contributing factors. Researchers use Geographical Information Systems (GIS) datasets from projects such as that performed by Cradden et al. [197] to assess different sites around the world for their suitability for wave energy. Nobre et al. use a multi-criteria analysis method along with GIS to identify the best sites for a WEC deployment based on depth, sea bottom type, wave resource, other marine area uses, and several other factors [198]. Vasileiou et al. use a similar method for combined wind-wave systems [199]. Ghosh et al. use multi-criteria decision making techniques and artificial neural networks to index potential wave energy sites [200]. Each of these methods requires input criteria, some of which are based on the deployment requirements of the WEC. This, like many other methods in WEC design, leads designers into an iterative design process of defining the details of a concept, understanding the site requirements based on those design decisions, determining the deployability, and then redefining the details of the design based on the potential deployment sites. Where WEC design strategies fall short is in the interplay between the WEC parameters and the site requirements. There are no methodologies which help designers make decisions which improve/expand the deployability of the WEC other than the iterative process described above, and even then, we have limited data on how specific design decisions expand or constrain deployability.

2.4 WEC Designer and Developer Methods

In order to give a complete review of WEC design methods, it is important that we discuss the methods employed by WEC designers, not just those present in research. Given that industry designers and developers do not regularly publish in academic journals, we combine our literature review with an analysis of survey results from WEC designers to integrate that perspective and complete the picture. We surveyed 25 respondents, 20 of whom identified themselves as WEC developers (either designers or supervisors), four academic researchers, and one researcher from a national lab or similar entity in order to fill this gap in knowledge of the WEC design process. The qualification for participation in the survey was that the respondent must have participated in the design of a WEC which has been tested in the water. This could include scaled prototypes and testing in tanks, flumes, oceans, or other bodies of water. Although this qualification allows for a wide range of development stages, it guarantees that designers have at least made it through conceptual design and significant portions of the embodiment design stage, which is where most of the methods we asked about would be applied. We eliminated responses based on WEC design projects which were completed in order to create test platforms. Participants were self-selected and anonymous. We use this survey data along with the knowledge of the WEC design process detailed above to identify trends in WEC design methods, common tools and approaches, gaps in methodologies, and areas for improvement of the WEC design process.

2.4.1 Survey Overview

The WEC Design Methods Survey began with baseline questions about the role that the respondent has in WEC design and how the primary device archetype was selected for their design project. The second section of the survey asked which general design approaches/philosophies and conceptual design methodologies the respondents employed. We asked at which point in the design process a deployment site was selected. For most questions, respondents were allowed to select more than one answer. The remaining eleven sections of the survey asked the same set of questions for each of the eleven design requirements. Respondents were asked what design methodologies/tools they use to design for a particular requirement, what methodologies or tools they use to evaluate success under that requirement, at what point in the design process they began to consider a particular requirement, how often (scale of 1–10, Never to “Every time I make a design decision”) they consider the requirement, and how satisfied (scale of 1–10, “not satisfied” to ”I highly recommend them”) they are with the methodologies and tool available to them for designing for the requirement. In the power production section, we also asked the order in which the design team designed subsystems of the WEC and the power production metric which most influences their design decisions.

Respondents were asked to respond to the best of their knowledge regarding their project as a whole, not just their personal experiences. For example, if the design team uses CFD, the respondent should select CFD even if they do not personally work with CFD. Respondents were able to skip questions, but any response with entire sections left blank were deleted to ensure the quality of the data collected. We did not ask for any personally or professionally identifying information in the survey in order to protect the privacy of individuals and companies. This means that we are unable to connect the responses to particular devices and thereby make conclusions about how well particular methods work, but we believe that requiring that information may have deterred many respondents from participating. We are also unable to confirm the proper use of any of these methods, meaning that there is some uncertainty in the responses related to name recognition. For example, a respondent could be familiar with the term "systems engineering," which may lead them to select the approach even if they haven't properly adopted the approach. Nonetheless, we are able to get a good idea of what methods designers are using and how satisfied they are with those methods.

2.4.2 Survey Results

2.4.2.1 Design Philosophy and Conceptual Design

Respondents were asked which design approaches they used to shape their overall design process. The results are shown in Figure 2.5. The three most popular responses were the three most traditional approaches—spiral design, Systems Engineering, and product design methods. This is consistent with the literature we reviewed, where Systems Engineering approaches and product design methods such as QFD were emphasized by both federal-level research groups [14, 16] and independent researchers [45]. The spiral design process is embodied in the piece-wise innovation of the projects discussed in Section 2.2.2 [68, 69, 70], and is not considered a good methodology for reaching optimal solutions [64]. That said, spiral design is popular in software engineering and known for its emphasis on risk assessment [201]. The popularity of spiral design indicates a need for researchers and designers to continue to apply and publish the results of more structured methodologies. The three popular approaches were also the only approaches which were selected by the nine respondents who only selected one approach, indicating that designers do not consider any of the other approaches to be sufficient for stand-alone use (most of which are not intended for stand-alone use). In all five instances that a respondent selected Set-Based Design, they also selected spiral design and Systems Engineering. Set-Based Design and Systems Engineering are compatible approaches, but combining Set-Based Design and spiral design likely requires some alterations to each approach. Effective alterations might include using Set-Based Design for the conceptual design stages and Spiral Design for embodiment and detail design, or using the spiral design process on multiple concepts until they are all well-enough developed to select the best one. All respondents who selected Ecological Engineering Principles, Axiomatic Design, Hierarchical Decomposition, Ethnographic Design, QFD, whole system trades analysis (WSTAT), SWOT, or Decision-based design also selected three or more other approaches.

Figure 2.6 shows how the respondent and/or their design team chose the primary archetype for the device. Nearly half (12 out of 25) of the respondents answered that the team or the team leaders had an original idea which served as the primary archetype. This method of choosing a design project is common, though it is considered to be a weak strategy which relates to premature commitment to a concept as is exemplified by the vast body of conceptual design research. Schmidt and Calantone point out that managers who built projects on original ideas are less likely to acknowledge when a project is failing. They call this "escalation of commitment," and determine that it is a major problem in new product development [202]. Only two of the respondents went though a conceptual design process to select the primary archetype. Given the importance of conceptual design to the success of a product [203], this data shows the need to more broadly employ traditional conceptual design methodologies to WEC design, as well as the need to develop conceptual design methodologies better suited to the challenges of WEC design. The fact that many WEC designers do not perform structured conceptual design is reflective of the general lack of literature covering the topic for WEC design (as discussed in Section 2.2).

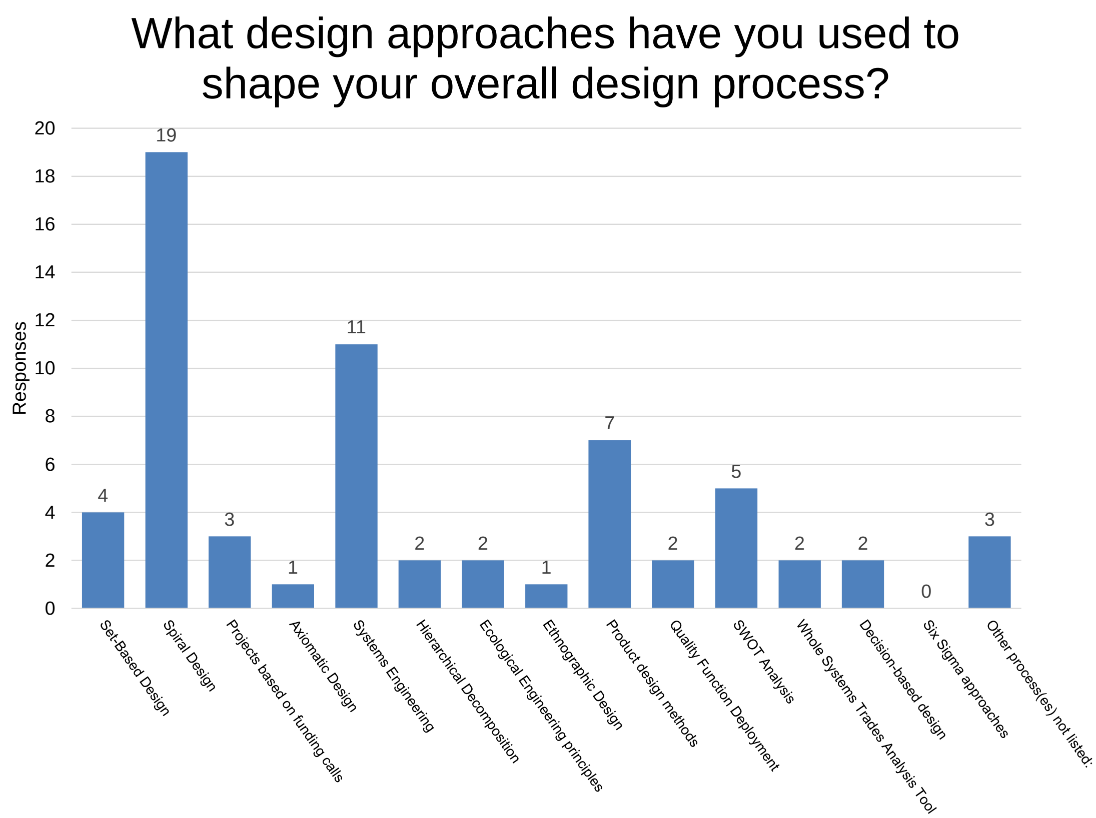

Figure 2.5: Designers Overall Approaches

The only approach which was used by more than half of the respondents was spiral design, which we described as iterative design through concept, model, optimization, prototype, back to concept. This approach is similar to that described by Henriques et al., [53].

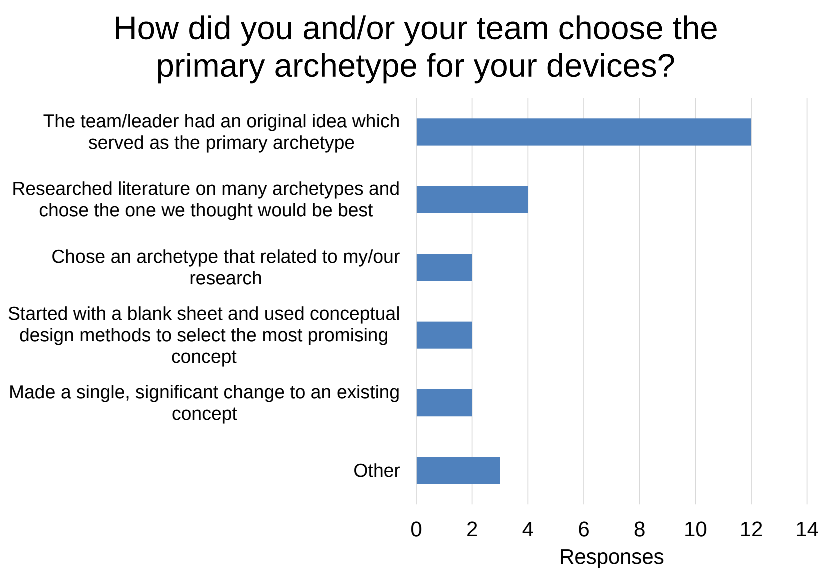

Figure 2.6: Designer's Concept Selection

The majority of respondents chose the primary archetype of their device from an original idea of the team of the leader. Only two of the 25 respondents used conceptual design methods.

Although conceptual design methods are not popular for choosing a primary archetype, 18 of the 25 respondents reported using conceptual design methods at other points in the design process. The most popular methods were mind mapping/brainstorming (11/25 respondents) and design structure matrices (6/25 respondents). Biomimicry and C-sketching were not used by any respondents, and brain writing (1), morphological matrices (1), TRIZ (2), computational concept generation (2), and Functional Decomposition (4) were each used sparingly. The popularity of "brainstorming" is unsurprising, given that the term is sometimes used as a blanket term for coming up with ideas. The use of some of these methods outside of the system-level conceptual design phase indicates that many researchers are decomposing the WEC into multiple subsystems. Designers may be more comfortable with applying these approaches to subsystems because other decisions that have already been made regarding the WEC design provide the constraints necessary to make the evaluation of subsystem/component concepts less uncertain. For example, it is easier to evaluate (with certainty) concepts for a hydraulic PTO subsystem given the constraints of the prime mover than it is to evaluate how well a specific WEC archetype will meeting the numerous design requirements. This indicates that within conceptual design, WEC designers may benefit from new methods of dealing with uncertainty such as that discusses by Malak et al. in Section 2.2.2 [88].

2.4.2.2 Common Design Methods

Table 2.1 shows all of the design methods and tools that are employed by 12 or more of the 25 respondents, our chosen benchmark for a "commonly used method" which indicates a level of convergence by the industry on that method. We recognize convergence as indicating one of two things; that the industry has reached a best available approach or that the industry has adopted an imperfect approach according to norms of another industry or engineering tradition. A lack of convergence indicates that there is no clear best option, and it can also indicate disorganized knowledge about methodological options or differing needs of specific projects. Using only survey responses, it can be difficult to determine the implications of convergence/non-convergence on design methods for the industry, but when we use knowledge from the literature reviewed in the rest of this paper, we can make an informed analysis.

From Table 2.1, we see that there are 22 methods (out of 100 different options across the 11 requirements) used by 12 or more of the 25 respondents throughout the 11 WEC requirements. Using wave resource assessments to design globally deployable WECs was the most commonly used method, followed by the iterative design of WEC and PTO subsystems by modeling, simulating, changing parameters, and returning to the modeling stage. The iterative method of improving power production is similar to the process described by Portillo et al. [56] and discussed in Section 2.2. An iterative method was also most common for reducing capital cost. As discussed, iterative methods can be slow, are unlikely to lead to an optimal design, and can lead to many costly late-stage design decisions [64], leading us to conclude that this convergence is more a reflection of engineering tradition than best practice. The selection of components based on lifetime maintenance scheduling, though an important method, only addresses one element which affects availability–planned maintenance [137]. Designers did not converge on a method for designing for availability related to failure reduction. For installability and maintenance, environmental impacts and safety, acceptability, and global deployability, designers converged on methodologies recommended by the DTOceanPlus and WaveSPARC projects. There were no common practices for designing to reduce operational costs or for grid integration, and only one for capital cost and availability, indicating the need for continued research toward best practices in designing for each of these requirements.

Despite the popularity of optimization in research, no optimization method was used by more than half of the designers, indicating that none of them have been adopted as best practice. The disparity may be due to the background knowledge needed to use optimization methods effectively, the number of ways that optimization can be applied, or the differences in the way designers prioritize the different design requirements. Given the minimum requirement of the survey that survey respondents must have tested their device in the water (tank testing acceptable), there is a chance that some of the respondents simply have not made it to an optimization stage in design. In Table 2.2, we show all of the optimization methods that we asked respondents about and the percentage of respondents who use each method. Controls optimization and hydrodynamic optimization to determine

WEC shape and/or size were the most popular methods. Given that hydrodynamic optimization appears in Figure 2 as the first step of detailed design, it is surprising that the use of the method is not more common among designers. It is worth noting that when designers optimize using capital cost, they more often try to estimate capital cost rather than use a representative measures such as mass or volume. Operational cost, availability, variability, and installability/maintainability, are more often used in optimization algorithms as objective functions rather than constraints, while environmental impacts and safety measures are used equally as objective function and constraint.

For each design requirement, at least half of the respondents used multiple methods for design and evaluation of the requirement, as shown in Table 2.3. In many cases, satisfying requirements demands the employment of multiple approaches. For instance, when considering survivability, designers need to consider the impacts of all possible wave conditions as done by Mundon [149] while also considering the challenges to survival due to marine life, sediment, and salinity [151]. Accounting for both of these challenges to WEC survival can, understandably, require multiple design methods. Evaluation methods can differ according to the stage in the design process. As designers move toward better defined concepts, reducing uncertainty, they might move toward more detailed evaluations. For instance, in early stages of design, a WEC developer might make cost estimates in-house based on stakeholder engagement and/or estimates from other offshore industries, while later they might choose to hire a subcontractor such as done by Cordinnier et al. [71] to make more project-specific estimates. We discuss com-

Table 2.1: Common Deisgn Methods

Design methods used by 12 or more of the 25 respondents and the associated design requirement.

Method	**Requirement**	**Percentage of Users**
Iterative design of WEC and PTO Subsystems (model, simulate, change parameters, model...) [56]	Power Production	68
Controls optimization [68, 116]	Power Production	48
Iterative design by approximating the cost of all components and redesigning the most expensive [36]	Capital Cost	56
Selection of components based on lifetime maintenance schedule [137]	Availability	64
Design for a 50-year wave [149]	Survivability and Reliability	56
Prototyping and prototype testing [113]	Survivability and Reliability	64
Stakeholder meetings with manufacturers [71]	Manufacturing and Materials Selection	48
Design for Manufacturing [25]	Manufacturing and Materials Selection	48
Installation and maintenance storyboarding [59]	Installability and Maintainability	52
Application of conceptual design methodologies to installation and maintenance planning [126]	Installability and Maintainability	52
Stakeholder meetings with installation and maintenance personnel [2]	Installability and Maintainability	52
Eliminating or minimizing entanglement hazards [151]	Environmental Impacts and Safety	56
Eliminating hazardous fluids [126, 204]	Environmental Impacts and Safety	60
Minimizing human–device interaction [204]	Environmental Impacts and Safety	60
Reducing visibility [126]	Acceptability	52
Reducing ecosystem impact [151, 204]	Acceptability	52
Design for local manufacturing [126]	Acceptability	52
Community engagement [193]	Acceptability	48
Design for flexibility of wave conditions [204]	Global Deployability	60
Wave resource assessment [32]	Global Deployability	72
Design for modularity [157]	Global Deployability	56
Standardization of manufacturing, construction, assembly, and installation needs [113, 157]	Global Deployability	48

Table 2.2: Percentage of respondents using each optimization method

Method	Requirement	Percentage of Users
Multi-objective optimization	Power Production	24
Controls optimization	Power Production	48
Optimization with power production as objective function	Power Production	32
Hydrodynamic optimization to determine PTO characteristics	Power Production	28
Hydrodynamic optimization to determine WEC shape/size	Power Production	40
Optimization with genetic algorithms	Power Production	20
Array optimization	Power Production	16
Optimization algorithms which represent cost as mass or weight	Capital Cost	20
Optimization algorithms which represent cost as volume	Capital Cost	8
Optimization algorithms which estimate and minimize capital cost	Capital Cost	24
Supply chain optimization	Capital Cost	32
Optimization using operational cost as an objective	Operational Cost	16
Optimization using operational cost as a constraint	Operational Cost	4
Optimization using availability as an objective	Availability	16
Optimization using availability as a constraint	Availability	8
Reliability-based optimization	Reliability	24
Optimization using installability or maintainability as an objective	Installability and Maintainability	4
Optimization using availability as a constraint	Installability and Maintainability	0
Optimization to minimize variability	Grid Integration	12
Optimization using grid characteristics of variability as constraints	Grid Integration	8
Optimization using environmental impacts of safety as an objective	Environmental Impacts and Safety	20
Optimization using environmental impacts of safety as a constraint	Environmental Impacts and Safety	20

monly used overall metrics and evaluation methods in the next subsection.

Table 2.3: Respondents Using Multiple Methods

Requirement	Percent (Design)	Percent (Evaluation)
Power Production	84	75
Capital Cost	84	75
Operational Cost	57	76
Availability	76	50
Survivability and Reliability	76	68
Manufacturing and Materials Selection	83	88
Installability and Maintainability	78	61
Grid Integration	60	67
Environmental Impacts and Safety	95	76
Acceptability	100	76
Global Deployability	89	78

2.4.2.3 Common Metrics and Evaluation Methods

We asked designers how often they considered each design requirement. Knowing what requirements a designer considers important can help us to understand why/how they select certain metrics and evaluation methods. Figure 2.7 shows the responses with minimums, maximums, means with standard deviation, and outliers. For each requirement, there is a wide range of answers, with the response of 10 indicating that the designers consider that requirement every time they make a design decision, 7–8 indicating most of the time, 5 about half the time, 2–3 sometimes, and 0 never. The wide range could indicate that designers, on the whole, have a hard time relating individual design decisions to design requirements. For example, it may be difficult to consider availability when making a decision about device geometry if the designer does not know how a specific change in device geometry influences the design parameters which determine availability.

At the same time, there may be design decisions by which a design requirement is not (or does not seem to be) affected, and therefore designers do not consider it. To continue with the same example, maybe the designer does not think that their choice of device geometry influences availability. QFD might help designers understand when a design requirement should be considered by requiring them to relate customer requirements to design specifications [18]. Researchers should take steps toward clearing up some of these relationships as well, especially for the requirements which have the largest standard deviation of answers-availability, grid integration, environmental impacts and safety, and acceptability. In Figure 2.7, power production, hydrodynamics, capital cost, and survivability, all have a mean above 8 with a standard deviation below 2. These requirements are the ones considered, on the whole, most often. Acceptability and grid integration had the lowest mean ranking, with the mean designer considering the requirement just over half of the time.

Figure 2.8 shows the methods/metrics that designers use to evaluate the overall success or preparedness for market of their devices. LCOE is clearly the most commonly used. It is also the most influential metric regarding power production, shown in Figure 2.9. This is reflective of a significant body of research on how to estimate LCOE for WECs discussed in Section 2.1.3, e.g., [36, 38, 46, 47, 48], but does not seem to reflect the level of uncertainty associated with the metric [37, 49]. Despite researchers' claims that LCOE is not the best metric for WEC performance, it is clear that designers do not see a viable alternative. We can see from Figure 2.8 that TPL assessment [44] has not yet been widely adopted as a

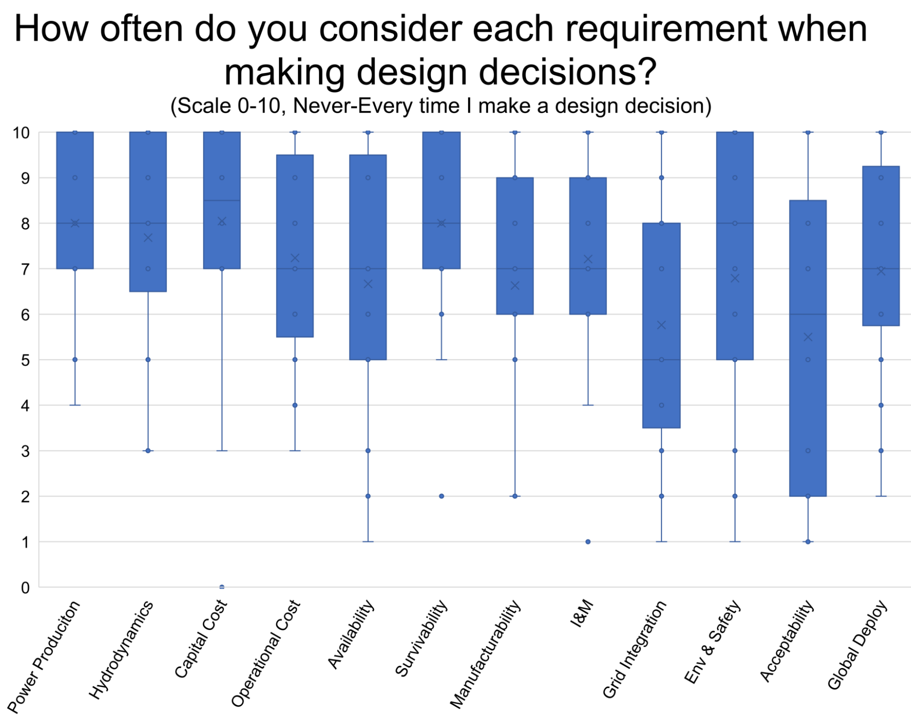

Figure 2.7: Consideration of Requirements

Respondents were asked how often they consider each design requirement when making design decisions.

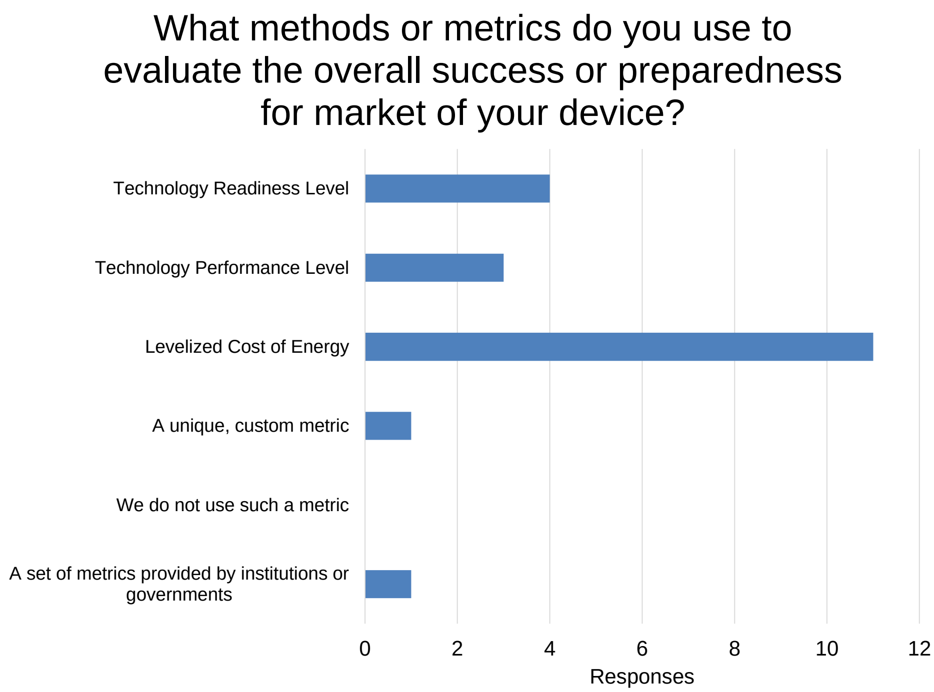

Figure 2.8: Designer Metrics of Success

Metrics for evaluating the overall success or market readiness of a WEC.

metric for success/preparedness. In Figure 2.9 we see 23 positive responses for metrics that account for both power and cost (two from the "other" category) and 22 positive responses for metrics which did not involve cost directly.

Aside from LCOE as a common metric for both overall performance and power production, there are several other requirement-specific evaluation methods used across WEC design. Table 2.4 shows the evaluation methods (for all categories aside from power production) which are used by 12 or more of the 25 respondents. There were no common methods of evaluation in the categories of grid integration,

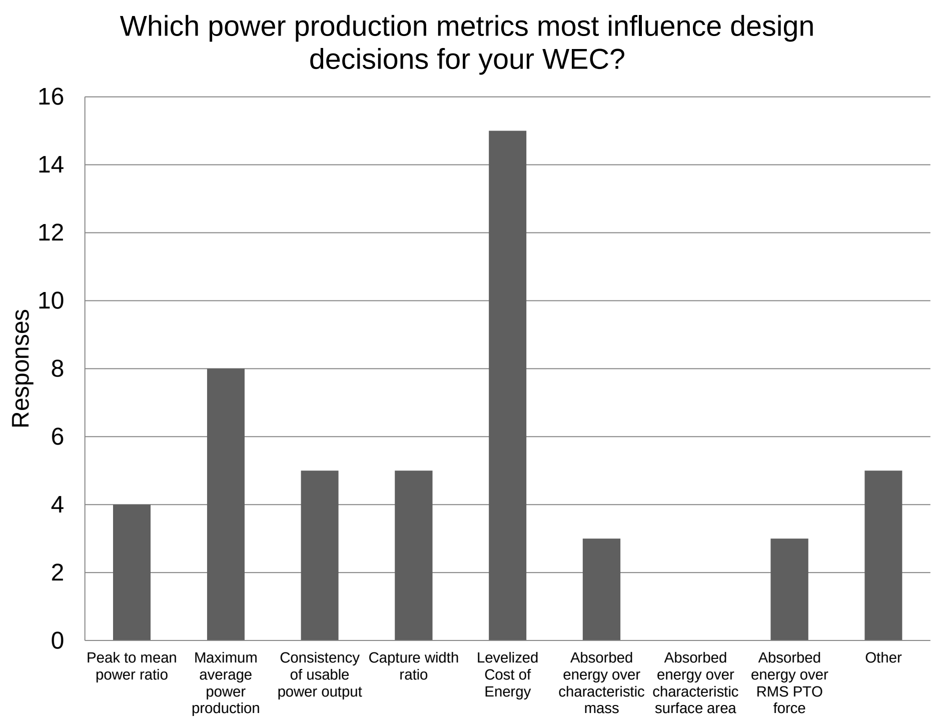

Figure 2.9: Designer's Power Production Metric

Power metrics used by WEC developers. The other response included capital cost (CAPEX) over annual productivity and absorbed energy over CAPEX of main components.

environmental impacts and safety, and acceptability. This could be because these are considered more as binary requirements by some (a concept is either able to be integrated or not, safe or not, etc.) or because there simply are not satisfactory methods of evaluating these requirements. LCOE appears twice more as a common method for evaluating capital and operational cost. The next most popular evaluation method is using numerical simulations of extreme seas to evaluate reliability and survivability, e.g., [149]. Dynamic modeling and simulation make up a large portion of WEC research leading to robust evaluative capabilities for understanding the system dynamics and power production (discussed in Section 2.4.2). Table 2.4 shows that designers lack similar capabilities to evaluate the WEC in terms of other system requirements.

2.4.2.4 Dynamic Modeling

We asked designers about specific software tools as well as methodologies for dynamic modeling of WEC devices. A total of 21 of the 25 respondents use time domain simulations with hydrodynamic modeling, which, as mentioned, is required in order for designers to account for device nonlinearities [111]. This is consistent with the considerable amount of research which takes advantage of time domain simulations. Of those 21, nine model the system hydrodynamics linearly, seven use weakly nonlinear approaches, and five model nonlinear hydrodynamics. This could relate to the type of device, stage of development, or experience of designers [94]. CFD methods are used by 11 of the respondents. Five respondents use WEC-

Table 2.4: Common Evaluation Methods

Evaluation methodologies or tools used by 12 or more of the 25 respondents as well as the design requirement for which they were used.

Method	Requirement	Percentage of Users
Cost Estimates by subcontractors [71]	Capital Cost	48
In-house capital cost estimates based on research and stakeholder engagement [46]	Capital Cost	52
LCOE	Capital Cost	60
In-house operational cost estimates based on research and stakeholder engagement [46]	Operational Cost	56
LCOE	Operational Cost	48
Failure Modes and Effects Analysis [59]	Availability	48
Extreme sea state numerical simulations [149]	Survivability and Reliability	60
Manufacturing cost estimates and timelines provided by subcontractors	Manufacturing and Materials Selection	52
Installation and Maintenance timelines and estimates provided by subcontractors [126]	Installability and Maintainability	48
Estimate of a minimum feasible wave resource for an attractive LCOE [3]	Global Deployability	56
Depth and geophysical requirements [3]	Global Deployability	52

Sim [98]. Nine respondents use frequency domain simulations. Of the boundary element solvers, WAMIT was the most popular (nine respondents) followed by Ansys Aqwa (7), then NEMOH (4). Other software used by one or two respondents included Rhino mesh simulator, Orcaflex dynamic analysis software, and Flexcom Wave WEC simulator. No respondents use ProteusDS dynamic analysis software. Knowing the common software used in industry may help researchers decide which to use for their own work.

2.4.2.5 Requirement Consideration and Subsystem Design

We asked respondents at what stage in the design process they began to consider each requirement. As a result that the process of designing a wave energy converter does not follow a prescribed pathway, we gave designers 11 options for responses and allowed them to select multiple options if appropriate. Figure 2.10 shows the collective responses, in the order that they were presented to respondents. It is a possible sequential order for WEC design aside from the placement of detail design. Although *While performing detail design* is the most commonly selected option, it is also one of the least informative data points given that different designers may have different definitions of *detail design*, just as we have defined *detail design* in this paper a bit differently than Portillo et al. did in Figure 2.2. Analyzing the other response options, we see that for each requirement, there were five or fewer respondents who considered the requirement before selecting a concept, which supports the conclusions of the literature reviewed in this paper which calls for

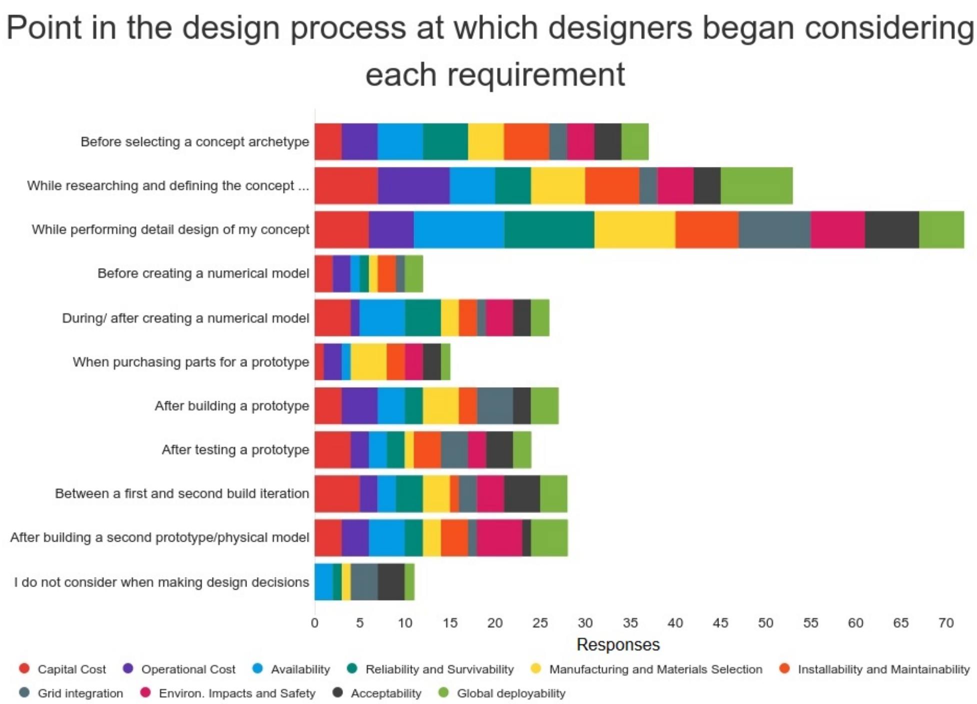

Figure 2.10: Point in the design process when designers consider each requirement

improved conceptual design strategies [5, 58, 59]. Grid integration had the fewest considerations (2) prior to concept selection as well as during research/concept definition. For each requirement, there were respondents (though few) who did not consider the requirement until after building a second prototype or not at all. From design research, we know that considering all design requirements early in the design process leads to higher-performing concepts [20], therefore Figure 2.10 shows us that we still have work to do when it comes to giving designers the tools they need to do that.

When we asked respondents the order in which they designed five subsystems of the WEC (WEC, PTO, control, moorings, power transport), 18 responded. Nine of the designers responded that they designed the WEC, PTO, control system, moorings, and power transportation subsystems concurrently. Figure 2.11 shows the order in which the remaining nine respondents designed the subsystems. Generally, we see that WEC designers design the WEC subsystem and PTO in the first half of the process and the power transportation subsystem in the second half. Mooring and control design lingered in the middle. This order resembles the order suggested in the MaRINET2 publication on instrumentation best practice [109], but the fact that half of the respondents said that they designed the subsystems concurrently indicates a shift in industry toward co-design following that suggested by some control designers [82]. There is a significant space for further research on how those concurrent subsystem design processes should be carried out in wave energy.

2.4.2.6 Deployment Site-Agnostic Design

Of the 25 respondents, 10 indicated that their WEC was designed to be deployment-site agnostic. A deployment-site agnostic device will likely have a slightly different set of requirements than those discussed in this paper. Global deployability would likely be of higher importance; there might be different methods used for modeling given the need to understand performance in many different conditions; and the ways of designing for and evaluating manufacturability, installability, grid integration, environmental impacts, and acceptability might be different due to the fact that the designers need to satisfy the requirement for many potential sites.

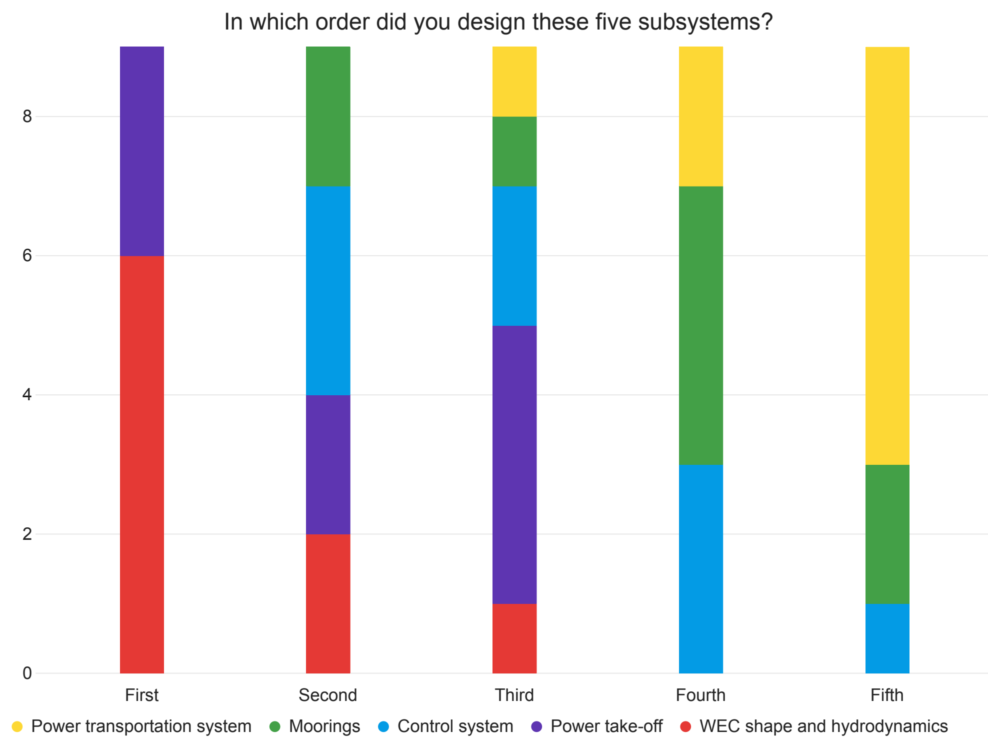

Figure 2.11: Order of Subsystem Design by Nine Respondents

We did not find any notable methodological differences between the designers who claimed their WEC was site-agnostic and those who did not, but the sample size was too small to say definitively that methodological differences do not exist. This challenges us to question whether site-agnostic or site-specific approaches are better for WEC development and what changes would need to be made to current design processes for either approach. Committing fully to site-specific or site-agnostic design would lead to slightly different stakeholder and functional requirements than those addressed in this paper. Furthermore, different design philosophies would be useful for site-agnostic vs. site-specific approaches. For example, the principles of Ecological Engineering would not be suitable for a site-agnostic project, given the second principle's emphasis on site-specific design. While site-agnostic design might seem financially appealing, site-specific design could help wave energy gain the support and thereby experience needed to continue development. Further research in design theory and direct comparison of site-agnostic and site-specific projects may shed light on the best pathway forward.

2.4.2.7 Designer Satisfaction

For each design requirement, we asked respondents how satisfied they are with the tools available to them for meeting that design requirement. They responded with a score between 0 and 10 ("not satisfied" to "I highly recommend them"). All requirements, except for capital cost, had a satisfaction range of nine or more, meaning every requirement area had both satisfied and unsatisfied designers. Capital cost had a range of eight. There were no requirements for which respondents were significantly more dissatisfied with the methods and tools available. The mean levels of satisfaction were between 4.9 (availability) and 6.66 (power production). Availability, operational cost, and grid integration were the requirements for which respondents were least satisfied, but when normalized by the individual respondent's average level of satisfaction, availability, installation and maintenance, and grid integration received the lowest scores. Eight respondents gave availability the lowest score, three for installability and maintainability, and two for grid integration. Given the variability in how much designers attend to each requirement shown in Figures 2.7 and 2.10, the variability in satisfaction is not surprising.

2.4.2.8 Under-Utilized Methods and Choosing a Method

Throughout this paper, we have identified and provided resources for numerous design methodologies which could be employed in WEC design. Choosing which to use may seem overwhelming (although design researchers such as Giambalvo et al. have published work intended to help designers choose [205]). As academic researchers we can further help designers choose methodologies by testing the methodologies and developing them to be more applicable to the unique challenges of WEC design. Some tools and methodologies which are worthwhile for continued research in WEC design include:

- Set-Based Design.

- Ecological Engineering.
- Axiomatic Design.
- Ethnographic Need-Finding.
- Participatory Design.
- Quality Function Deployment.
- Conceptual Design Methods.
- Installation Storyboarding.
- Redundancy of Critical Function.
- Subsystem Co-design.

2.5 Trends, Shortcomings, and Areas for Further Research

From a design theory standpoint, wave energy development includes some of the most difficult aspects of both product and systems design. Like product design, WEC design requires designers to create custom components by identifying customer needs, generating concepts, and detailing designs using models and prototypes. Like systems design, WEC design involves the integration of subsystems of off-the-shelf components and the need to satisfy multiple levels of stakeholders [2]. WECs, whether for grid applications or emerging markets, are systems which are embedded into other complex technical (the grid/emerging market technology), economic (the electricity market), social (coastal communities), and natural (the ocean) systems upon which the WEC designer has little control.

Despite the designer's inability to control the larger systems in which their designed artifacts operate, they must understand the impact on the larger systems (such as grid impacts, environmental impacts, and acceptability), and must be able to respond to changes in those systems (such as changing energy policies). Each of these larger systems is changing in response to the same societal need that drives the design of those systems—the need for low-emission energy [190, 206]. The ocean, furthermore, makes prototyping and testing difficult and poses major environmental design challenges [151]. The harsh yet endangered ocean ecosystems lead to the amplified need for highly reliable, low maintenance, easy-to-test systems with minimal negative environmental impacts. These changing contexts make prioritizing design requirements a challenging task. The need for low-emission energy will not be entirely fulfilled by wave energy, meaning wave energy development is both in competition with and reliant upon the development of other renewable energy technologies [7]. This can make it difficult to benchmark a technology against others on the market in a meaningful way. The unique challenges of WEC design, the fact that it does not fit neatly into any one design framework, and the fact that it requires the consideration of many systems considered to be outside of the boundaries of the designed system demand that we reflect upon and improve our current design strategies.

Through this review, we observe an emergent pattern in WEC design. Researchers have made and continue to make significant strides in evaluative techniques for WECs. This is understandable, given that in order to design toward specific requirements, we must first be able to evaluate performance in terms of those requirements. As these evaluative techniques emerge, academic researchers have focused on embedding these evaluations into optimization algorithms as a primary design methodology. As we see from the survey results, these optimization techniques are not being universally adopted by WEC designers. This could be for a number of reasons, including the time and computational demands of complex optimization problems. Furthermore, optimization algorithms cannot be entirely depended upon to integrate all of the requirements of a WEC. This leaves WEC designers using mostly iterative design methods in which they define the parameters of a WEC then evaluate performance under a single or a few requirements, often using qualitative methods for evaluating requirements which are not evaluated within numerical simulations. Once they have evaluated the performance, they redefine the parameters of the WEC according to its observed weaknesses, then return to evaluation. Although this iterative process is an essential element to engineering design, it leaves a lot to be desired in terms of guiding designers toward initial concepts with the potential for high performance. The iterative process also lacks guidance for using the output of WEC evaluations to make design decisions that improve performance as measured under the multiple WEC performance criteria.

When it comes to improving WEC design, iterative techniques are only as good as the evaluations upon which they are based and the understanding of the relationship between individual design decisions and the results of those evaluation. In this paper, we have presented some existing design techniques that might be able to address the shortcomings in the WEC design process and we have identified areas where new design techniques would be beneficial. The DTOcean and DTOceanPlus projects have created openly-available design tools, discussed throughout this paper, in order to satisfy some to the gaps in WEC design and begin standardizing the process [14]. Their tools will need to be accompanied by design techniques which are developed, tested, and improved by wave energy researchers. A few important areas of future research are listed below.

- **Relating design decisions to customer requirements** It will be the role of researchers to clarify how different design decisions impact a WEC's ability to meet each design requirement and to create the tools that can help designers understand, visualize, and quantify those impacts. An example of such a tool would be one that relates design parameters to deployment site criteria in order to characterize how individual design decisions impact the wave resource available globally to a WEC.

- **Early assessment of all design requirements** Although usable power production is the primary goal of WECs, and improving power production continues to be the main focus of much of the academic research, wave energy development is at a point where many of the methods of energy absorption and conversion are well understood. For that reason, designers will need to begin to consider requirements other than power production and hydrodynamics earlier and more often. This will require assessment techniques geared toward WEC concepts with high uncertainty.

- **Addressing grid integration and end use** Grid integration is a requirement that consistently stood out among others. There were no common design or evaluation methods for grid integration, it was the requirement considered least often when making design decisions, the fewest respondents considered it prior to concept selection, and it was one of the requirements for which designers were least satisfied with the tools they had available.The widespread use of LCOE as a performance metric may contribute to the challenges designers face in designing for grid integration. The metric does not value any ancillary benefits that WECs could provide to the grid, which could become more important as more renewable energy sources come online. WEC designers need better tools for considering grid integration which are less computationally expensive than wave-to-wire models and do not require a fully-defined WEC concept.

- **Conceptual design processes** As has been emphasized in previous WEC design research, engaging in structured conceptual design processes stands to save WEC designers time and money. With so many WEC concepts being proposed, conceptual design methods can help designers begin with a clean sheet. Concept evaluation methods can offer designers opportunities to evaluate concepts before creating detailed models.

- **Exploring new design philosophies** As we have seen throughout this paper, systems engineering approaches tend to dominate the WEC design process although other design philosophies such as Ecological Engineering, Set-Based Design, and User-Center/Participatory design for emerging market WECs have the potential to guide WEC design in new directions. Further research is needed to determine whether any of these other design philosophies will lead to improvements in WEC design.

- **The impacts of model surrogates** As discussed in Section 2.2.3, WEC designers may use surrogate representations of subsystems in early numerical models of WECs. How they do so depends on the prioritization of subsystems, which we analyzed for the survey respondents in Section 2.4.2. No research exists which explores the impacts of using these surrogates on the eventual performance of a WEC device. Such research could better inform design approaches (such as the extent to which co-design should be implemented), as well as the way that designers decompose WEC subsystems.

- **Materials selection at various design stages** Prototype testing and the deployment of scaled WECs will be essential to gaining the experience necessary to drive down costs, reduce risk, and gain acceptance in the public eye. Gaining a better understanding of what components can be tested and what investigations can be performed at various scales of prototyping and how results scale to the full-sized WEC can help researchers and developers determine ways to cut material and manufacturing costs of prototyping.

- **Need-finding and site-specific design** Given the opportunities for WECs which include grid-scale development and emerging market off-grid development as well as the driver of WEC development—climate change—there is more than one potential path for wave energy. Although we summarize stakeholder and functional WEC requirements in this paper, a particular project or site will have its own set of unique requirements. Developers should not forgo the need-finding design practices that allow them to determine those unique requirements. Just as the device requirements are site-specific, researchers have shown that the economic viability of a WEC is also site-specific. These facts challenge us to more closely evaluate the meaning and value of technology convergence and global deployability to determine the best pathway for WEC development. The pathway chosen will, as discussed, impact which design methodologies are most appropriate.

Chapter 3: Set-Based Design Approach for WECs

Whereas Chapter 2 included a broad review of design methods and tools in WEC design, this chapter includes our work with one specific method– Set-Based Design. I gave a brief overview of this method in Chapter 2, but I will go into more detail here, discuss its use with multi-attribute utility analysis, and describe the results of a workshop in which we tested Set-Based Design and multi-attribute utility analysis in the conceptual design stage of WEC design. The work I present in this chapter was also presented at the 13th European Wave and Tidal Energy Conference in 2019.

3.1 Set-Based Design

SBD is an approach to conceptual design which has received some attention in literature, but mostly as a theory, without details on how to organize, reduce, refine, and model concepts. Little has been published on the application of SBD. Though these steps may seem, to some, as similar to many other design processes (and in many ways, they are), it is the application, the time spent at each stage, and the methodological inclusion of stakeholders in the design process that provide key differences.

A technical paper from the American Society of Naval Engineers by David J

Singer discusses SBD and its potential application in ship design [64]. Hannapel et al. have also published on design optimization algorithms based on SBD [207]. Toyota Motor Company has been highlighted by Ward and Sobek et al. as an example of success of SBD, the specific application of which they call Set-based Concurrent Engineering [66], [77]. These reports provide support for the structure of SBD, but no guidance on the actual implementation of SBD in practice. One major shortcoming of SBD theory is that, for design problems where there are multiple requirements that must be satisfied, SBD does not give clear means for incorporating trade-offs and preferences [88]. Malak et al. outline a strategy which combines utility-based decision theory with SBD to give designers a means for incorporating trade-offs and preferences [88].

The SBD approach stands out from traditional, point-based design. It allows designers to develop multiple concepts concurrently, putting off commitment to a single concept while assembling more information about the problem. The approach was first presented as-named by Ward et al. in 1997 [65] as a method for solving design problems which have high levels of uncertainty. Using Set-Based Design, the designer focuses on eliminating inferior concepts and iteratively adding detail until they converge on a single, strongest concept. By developing many concepts and eliminating inferior concepts instead of selecting one single concept for further development and iteration, designers avoid choosing a concept based on imprecise data. Concepts are, by definition, imprecise. SBD's iterative path through conceptual design encourages designers to model at higher fidelity at each subsequent stage. As concepts become more precisely defined, designers are able to distinguish between concepts with high certainty. They can then continue to increase model fidelity with the concepts that are likely to meet the design requirements and eliminate concepts which, according to the current model fidelity will not be able to meet those requirements. SBD capitalizes on two significant paradigm shifts in engineering design by allowing designers to maintain and refine a large set of foundationally independent concepts. First, it has been shown that engineering design entities that do not focus on a single concept early in the design phase (and instead generate many concepts) design more efficiently in terms of time and cost [77]. In traditional point-design, feedback from downstream entities (such as manufacturers and end users) usually comes after upstream entities (design engineers) have committed to a concept, so changes can only be minor. Analysing and refining many concepts— while potentially adding time during the early design phase— leads to higher- performance solutions that are more quickly implementable, and effectively reduces the need for iteration in later stages of design [77]. Secondly, SBD is a conceptual-phase analogue to design optimization. Like design optimization, SBD uses a large set of potential solutions that thoroughly explore the solution space and use refinement methods to converge on a single, optimal design. When applying an SBD approach designers will:

1. Identify customer requirements and stakeholder needs.
2. Translate stakeholder needs into functional requirements and design specifications
3. Ideate a wide set of functionally varied concepts (Set A).

4. Iterate the Set A with various stakeholders from early on, removing or refining concepts that don't meet the stakeholder's requirements.

5. Form Set B from refined concepts, adding new concepts where appropriate. Add detail to the concepts in Set B and iterate again with stakeholders. Repeat these steps, adding fidelity to the design each time, until a final set has emerged.

6. Employ design convergence methods to analyse viability of each concept in the final set

7. Select most viable concept for further design refinement and development.

These steps are visualized in Figure 3.1.

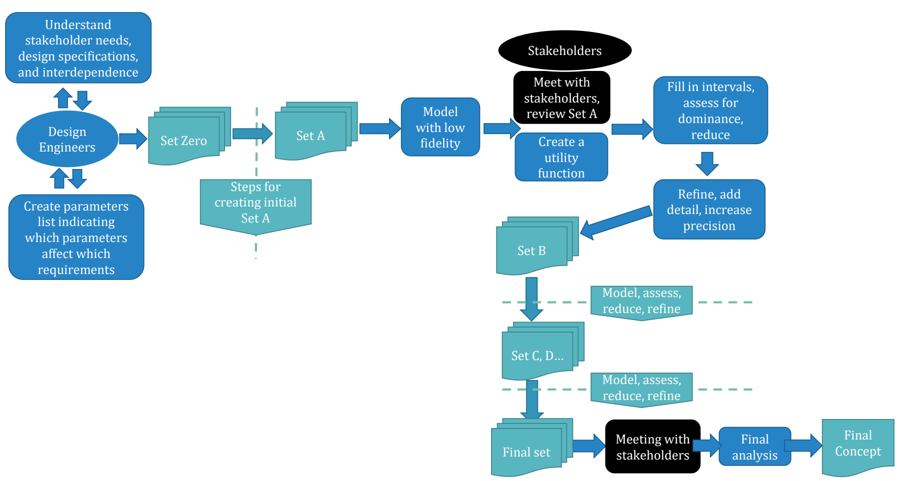

Figure 3.1: Set-Based Design Visualization

On the left of Figure 3.1, "understand stakeholder needs, design specifications, and interdependence" and "create parameters list indicating which parameters affect which attributes" are two tasks that should be done continuously throughout the design process. As designers model WECs, meet with stakeholders, and perform comparisons of different concepts, they will improve their understanding of stakeholder needs and the effects of individual parameters on system performance. Dieter and Schmidt point out that along with systematic processes for conceptual design, designers should take steps to encourage creative thinking [19]. Creative thinking techniques such as brainstorming, brainwriting, and concept sketching should be applied when creating Set Zero. Designers should first ideate freely, creating a broad set of imprecise concepts. Malak et al. define a concept as, "not a highly detailed product, but rather a general approach to implementing a function or system"[88]. The top half of Figure 3.2 shows the steps to develop Set A from Set Zero.

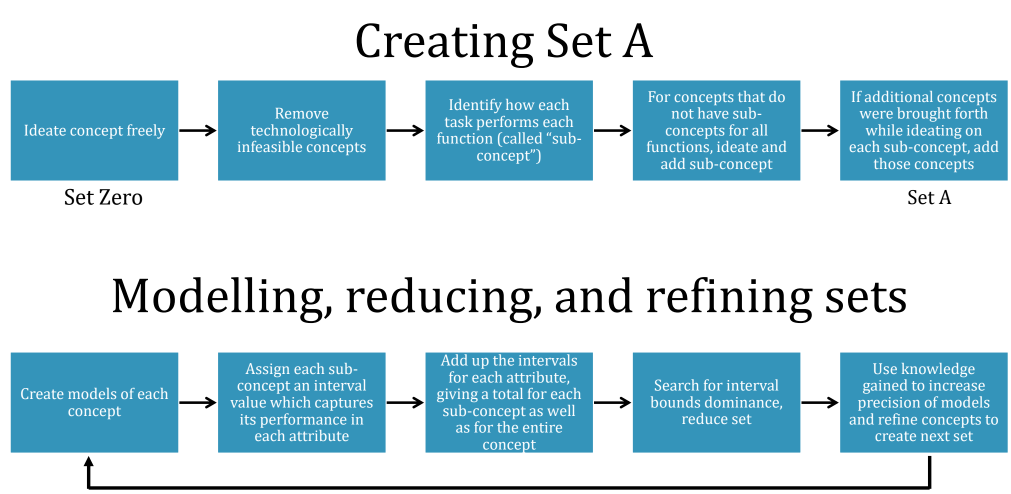

Figure 3.2: Set-Based Design Initial Set Creation and Iteration

Once designers ideate the initial set, they remove infeasible concepts. With the remaining concepts, designers should identify how the concept performs each function. This step is included to ensure that each concept can perform all required functions of the device. It also helps the design team to identify any areas in which they may need to dedicate more attention. For example, if half the concepts in Set Zero do not have an identifiable method of position control, the design team may consider looking again at the project requirements and parameters and searching for any gaps in their own understanding which may have led to the oversight. For the concepts that may not meet some functional requirements, detail should be added. The mechanism through which a concept performs a certain function is called a sub-concept. For example, if a linear generator is used for power conversion, the linear generator would be the sub-concept that satisfies the power conversion functional requirement. It may be necessary, when ensuring that each concept has a sub-concept that satisfies each functional requirement, to ideate a single sub-concept. If completely new concepts emerge from this ideation, they should be added to the set. This completes the creation of Set A. Once Set A has been defined, designers model, reduce, and refine the concepts iteratively, increasing precision with each iteration until they have converged on a final set. The methods for modelling, reducing, and refining sets are described in the bottom half of Figure 3.2. The concepts should be improved and modelled with increased fidelity as designers proceed through the design process— beginning with back-of-the-envelope calculations and moving toward computational models.

3.2 Utility Analysis in Set-Based Design

Combining methods of utility analysis with SBD gives designers a way to include trade-offs and preferences when evaluating concepts. It should be noted that methods of concept evaluation such as utility analysis are distinct from methods of product evaluation such as TPL Assessment, but, there is also a significant amount of overlap. Methods of concept evaluation should reflect the same qualities emphasized in product evaluation, just altered to fit the fidelity of the design. Both are necessary in a design process. Unlike standard utility analysis which focus on selecting the best concept through its measured or estimated utility in a variety of attributes, the method presented by Malak et al. focuses on eliminating inferior concepts by answering the questions "will I ever choose Alternative X?"

When applying utility-based decisions in SBD, the designers create a utility function, shown in the top right of Figure 3.1, which weights each attribute of the concept. Designers evaluate concepts based on the utility function. Malak et al. suggest that for Set-Based Design, inputs into the utility function should not be individual scores, but instead ranges of possible scores that reflect the imprecision of the concept [88]. Applying the utility function to each interval, designers can assess the utility of each sub-concept as well as the whole concept. The utility intervals of different concepts can be compared using interval dominance criteria to reduce the set. The interval dominance criteria say that a dominated concept is one for which the expected utility, no matter where it lands on the interval, will always be less than the lowest possible expected utility of another concept.

This dominance criteria can be applied to both concepts and sub-concepts. When a sub-concept is dominated, designer may change or improvement of the sub-concept rather than eliminate the entire concept to which it belongs. Malak et al. also present a method for accounting for shared uncertainty when assessing concepts for dominance. They write, “when uncertainty is shared among all possible actions, it means that a particular future condition or event is independent of the current decision.” An example of shared uncertainty in WEC design could be the rate paid to vessel personnel for maintenance activities. The uncertainty in the rate of pay would contribute to a widening of the interval value of operational costs, which may result in overlap of the operational costs of different concepts. To account for shared uncertainty, one could plot the utility as a function of personnel pay rate. If at every possible pay rate, concept A has a higher utility than concept B, than concept A dominates concept B and concept B should be eliminated. It may not always be possible to eliminate concepts based on the dominance criteria. In this case, Malak et al. recommend refining the problem, dividing the concept into sub-concepts, and adding detail to concepts to decrease imprecision. Beneficially, this iteration aligns with the iterative nature of SBD.

3.3 Set-Based Design and Utility Analysis for WEC Design

SBD has features which make it suitable for addressing the specific challenges of WEC design. Primarily, SBD allows for adjustment of the concept to changing requirements or infrastructure. This feature is suitable for the energy market given the many stakeholders and the volatility of customer requirements. Rising concerns regarding anthropogenic climate change and energy security leave the energy markets susceptible to changes in local to international government policy. Supporting technology being developed for the marine energy market, such as autonomous underwater vehicles, energy storage, and grid integration systems, could also have significant effects on the cost of WEC development. SBD allows designers to develop a set of concepts, so changes in the design requirements are easier to adjust to. Even if a design team has converged on a single concept, they have a whole set of other concepts that have been well fleshed out should there be a change in the supporting technology or energy market which leads to the chosen concept to no longer be the best. Another aspect of wave energy that could impact WEC design is the knowledge of environmental impacts and the permitting processes. Since this knowledge is being developed alongside WEC technology, flexibility in WEC design to adhere to new regulations or permitting processes is important. For example, knowledge of environmental impacts in certain regions could create significant costs increases for WECs that exceed threshold noise levels or permitting processes could restrict vehicle use for installation. Both scenarios could lead to changes in the ability of a concept to meet customer requirements.

SBD combined with utility analysis would allow for development of multiple concepts even when knowledge is imprecise or incomplete. Due to the harsh environment in which wave energy systems are deployed, the importance of system reliability is heightened, as maintenance in an offshore environment is expensive and often confined to a small weather window. Utility analysis lets designers explore the impacts of reliability while SBD allows them to continue developing multiple concepts as they collect knowledge of and assess the concept's reliability. There are many trade-offs for WEC systems, which could be better understood with the use of utility analysis in SBD. For example, while good PTO control can improve the efficiency of a WEC, it also increases the complexity, which can result in decreased reliability, increased maintenance costs, and increased structural fatigue [208]. Understanding which trade-offs to make is a lot like an optimization problem, to which SBD is conceptually analogous. SBD's conceptual optimization is also suitable for WEC design given the abundance of existing concepts, as it is a good method of comparing the many them without performing high fidelity modelling and costly testing.

3.4 WEC Design Workshop

To test this SBD approach, we held a workshop with 12 engineering students at Oregon State University. Herein, these students will be referred to as "designers." The purpose of the workshop was to assess whether the SBD approach has the potential to increase WEC device performance when applied in the early stages of conceptual design. The workshop also functioned as a trial for the application of SBD theory, which was important given the lack of published work on method of applying SBD. Assessing the applicability and effectiveness of the SBD approach in the early stages in a small-scale, controlled setting allowed us to understand how we need to continue to develop the approach for application in industry.

3.4.1 Methodology

We assembled three groups of four designers, all of which are engineering students at Oregon State University. The designers were tasked with developing grid-scale WEC concepts to meet the functional and customer requirements presented to them at the beginning of the workshop. The customer requirements are listed on the left-most column of the matrix shown in Figure 3.3 and the functional requirements along the top row. The requirements were derived from the Technology Performance Level assessment.

In an industry environment, the designers would establish these requirements, and design requirements could change based on the stage in the design process. Mapping customer requirements to functional requirements is another significant area of design study which is not explored here. The requirements were chosen to best suit the time and knowledge limitations of designers. The four functional requirements are: 1). Collect wave energy, 2). Control position, 3). Convert wave energy to electrical energy, and 4). Transport energy to shore. The customer requirements/attributes are 1). Capital Expense, 2). Operational Expense, 3). Electricity Generation, 4). Availability, 5). Uncertainty, and 6). Survivability. Each customer requirement was defined for the participants along with examples of the contributing parameters. For example, operational expense was defined as, "the costs incurred during operation and maintenance," and the parameters that participants were given to consider were technology class of components, ease of maintenance, depth and distance from shore, size and weight of parts that need to be moved, vessels and personnel required for maintenance, availability of spare parts, and durability. The requirements were presented to all participants before they were divided into teams. We presented a taxonomy of customer requirement to designers help convey the connection between requirements and to indicate the flexibility of each requirement. The taxonomy is presented in a manner similar to that in which the full TPL taxonomy is presented in the TPL assessment documentation [44].

Concept Aa m n	Collects Wave power	Controls position	Converts power	Delivers power	Interval sum in each attribute
Capital Expense	$[x_{11}(Aa)\ y_{11}(Aa)]$				$[x_{1T}(Aa)\ y_{1T}(Aa)]$
Operational Expense					
Electricity Generation					
Availability					
Uncertainty					
Survivability					
Expected Total Utility	$[x_{T1}(Aa)\ y_{T1}(Aa)]$				$[X(Aa)\ Y(Aa)]$

Expected utility of sub-concept

Total expected utility of concept

Figure 3.3: Decision Matrix for SBD Workshop

Once the designers were briefed on the problem, they were split into groups and given three different sets of design instructions. The first control group, C1, was instructed to produce a single WEC concept. C2, the second control group, was instructed to produce 3 WEC concepts. Both C1 and C2 were given a decision matrix to use if they wanted but were not directed to use the interval sum method described in Section 3.3. W1, the workshop group, was instructed to follow the SBD application described in Sections 3.1, 3.2 and 3.3 with the interval sum method. They were instructed to weight all customer requirements evening in the utility function. In the matrix cells, they placed an interval score corresponding to how well the subsystem met each requirement. The interval can be represented for Set A concept a as:

$$[x_{nm}(Aa)y_{nm}(Aa)] \tag{3.1}$$

The expected utility of a sub-concept, then, is

$$[x_{Tm}(Aa)y_{Tm}(Aa)] = [\sum_{i=1}^{i=n} U(x_{im}) \sum_{i=1}^{i=n} U(y_{im})] \tag{3.2}$$

And the expected utility of the concept

$$[x(Aa)y(Aa)] = [\sum_{j=1}^{j=m} \sum_{i=1}^{i=n} U(x_{ij}) \sum_{j=1}^{j=m} \sum_{i=1}^{i=n} U(y_{ij})] \tag{3.3}$$

Group W1 was asked to present 3 concepts which were included in their final set and indicate the single concept upon which they converged. We made it clear to W1 that all of their concepts were to be evaluated, not just the one they indicated to be the best.

The groups submitted their concepts via a Technical Submission Form which was altered from the original TPL Technical Submission Form developed by the U.S. Department of Energy Wave-SPARC project team [204]. The submission form given to designers only included questions and requests which the TPL submission

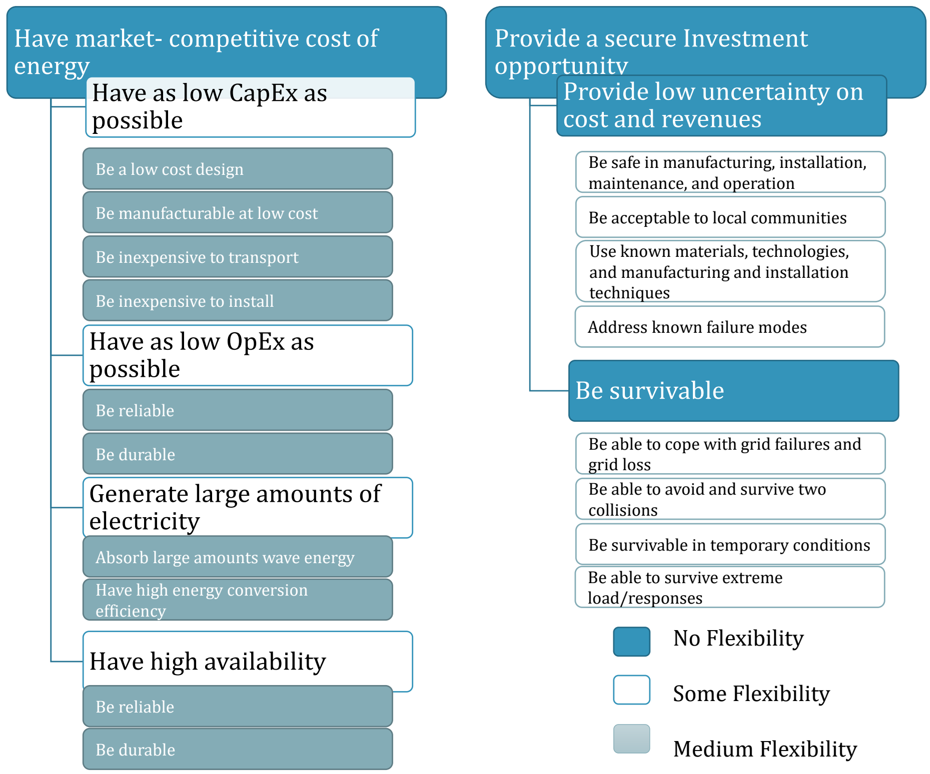

Figure 3.4: Taxonomy of Customer Requirements Presented to Designers

form indicated was appropriate for concept of Technology Readiness Level (TRL) 1-2. The form can be found in Appendix 6. It should be noted that the concepts the designers came up with were not well enough defined to be considered TRL 1-2. As we will discuss in the conclusion of this chapter, one of the primary findings of this workshop was that there is a need for methods of assessment that are suitable for WEC concepts, as the assessments available for low-TRL designs are not able to distinguish between concepts.

We included a description and some data about the theoretical site that the designers were working with at the beginning of the form. Given that power generation estimates are not simple to make for early WEC concepts, we also supplied designers with a plot of capture width ratios (CWRs) according to characteristic dimension for different types of WECs, which was based on data presented by Babarit [12]. Babarit organizes devices into five categories (each with a subcategory for "variants") which include fixed oscillating wave surge converters, oscillating water columns, heaving devices, floating oscillating wave surge converters, and overtopping devices. To avoid pre-populating designers with already-existing WEC concepts, we did not provide designers with these same categorizations, for that would have required us to give device examples. Instead, we abstracted the labels of the type of WEC to the type of wave motion they capture and their location in the water column, as shown in Figure 3.5. Once they estimated the CWR using the plot in Figure 3.5, designers used Equation 3.4 to calculate power generation in a 40kW/m sea.

$$P = J * CWR * B \tag{3.4}$$

Where:

- P = Absorbed Power of Concept
- J = Wave Resource (given as 40kW/m)
- CWR = Capture width ratio (looked up on plot)
- B = Characteristic Dimension

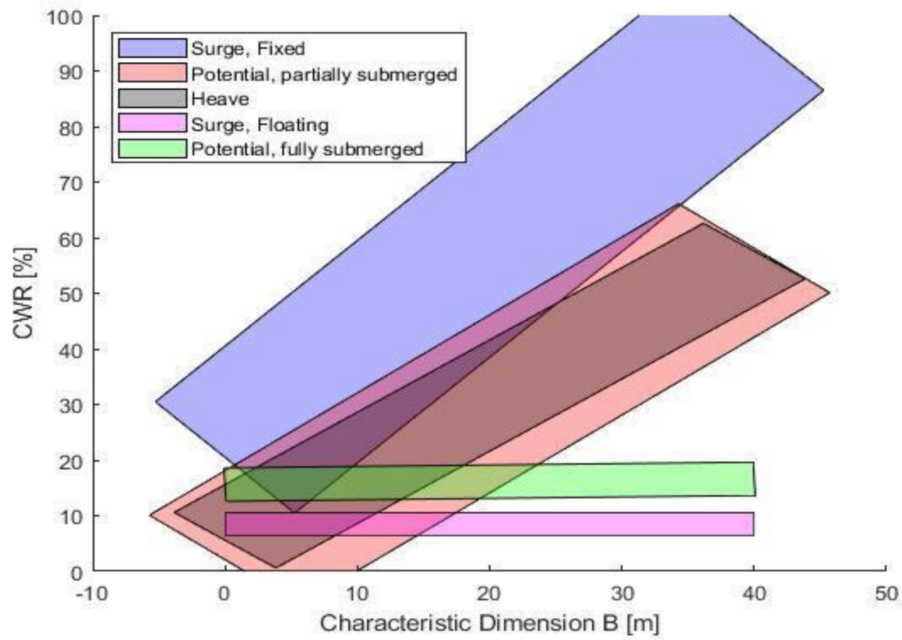

Figure 3.5: Capture Width Ratio Approximation

This method of "calculating" the potential absorbed power is crude, as it had to be given the constraints of the workshop which we will discuss further in Section 3.4.2. In all likelihood, this method would not provide WEC designers with accurate power estimates (even with wide intervals), and is has not been tested for that accuracy, but in this workshop, accuracy was not necessary. What was necessary was that the designers and the assessors estimated power production in the same way (which they did) and that the method of estimating power production captured design trade-offs, such as that between the size of the WEC (and therefore capital cost) and the power production. It also captured the fact, while avoiding the intricacies of wave mechanics, that the type of wave motion converted by a WEC would also influence the power production.

During the workshop, Dr. Bryony DuPont and I acted as stakeholders for the designers. At the end of the workshop, designers were also asked to fill out a post-workshop survey. Authors Dr. Benjamin Maurer and Dr. Rob Cavagnaro performed TPL assessment of each concept. The assessors were not aware of which group generated which concept(s). The Technical Submission Form and the questions that make up the TPL assessment were altered and simplified to match the customer requirements presented to designers shown in Figure 3.4. The designers were only assessed based on those customer requirements rather than the full taxonomy of requirements included in the TPL assessment version 3.01. The sections were weighted according to the number of questions and the flexibility indicated on the taxonomy. We chose the requirements based on what the designers could comprehend and address given the time constraints, and what could be assessed in low-fidelity concepts. We focused on the first two capabilities of the TPL assessment: "Have a market- competitive cost of energy," and "Provide a secure investment opportunity."

3.4.2 Workshop Constraints and Limitations

The workshop functioned as a proof-of-concept for the SBD design method rather than an accurate representation of how SBD would be applied in industry. The time constraints and lack of background of the participants led us to scale the problem significantly. Typically, given a new design methodology, the methodology should dictate the time taken to produce concepts, and this type of concept generation is conducted on the order of days, and not hours. In this workshop, we constrained designers in both the methodology and time. The limited sample size and the time constraints preclude any determination of which design approach is best in industrial application.

Given the alterations done to the TPL assessment and submission form to better align with the scope of the workshop, the TPL scores presented should only be considered relative to one another. They should not be compared to assessments done on other devices using different versions of the assessment. The nature of the TPL assessment is not entirely objective, especially for such low fidelity concepts.

3.4.3 Workshop Results

Group C1, tasked with putting forth one WEC concept, ideated several concepts to begin the workshop. After ideating a set of general concepts, they settled on one concept to move forward with. Feedback from the group indicated that they did not consider the design requirements again until after they had chosen a concept, at which time they used the requirements as a guide when adding detail to their design. They submitted one concept as requested. It received TPL scores of 4.3 and 3.9.

Group C2, tasked with producing three concepts, followed a similar methodology as C1. They ideated 11 initial concepts, and then selected from those 11 the three they would like to further develop. They did not use any quantitative assessment when choosing the three concepts they would develop. They proceeded to develop the concepts one at a time, like C1, using the requirements as a guide when adding detail. C2 did not submit 3 concepts as requested. Rather, they submitted one highly developed concept. It received at TPL score of 4.0 and 3.3.

Group W1 ideated an initial set of concepts, but unlike C1 and C2, they narrowed that set down to five rather than one. With the five concepts, they identified how each concept performed each function. They presented those five concepts in the first stakeholder meeting. Although they were assigned to follow the presented SBD method, they were still inclined to indicate their favorite concept to stakeholders at the first meeting. The stakeholders reminded them that their task was not to choose one concept right away. In the first stakeholder meeting, W1 focused on telling stakeholders how each concept performed each function. They did not give information on costs, availability, uncertainty, or survivability. After the meeting, they continued to follow the iterative steps of SBD, though they did not input intervals into the design matrix. Instead, they entered a single, scaled value. Set B consisted of three concepts, narrowed by two from Set A. They refined those 3 concepts then held another stakeholder meeting. At this meeting, scores in each attribute category were presented to the stakeholders, and W1 converged on a final set. Set C contained 2 concepts which they submitted, indicating the one concept which they assessed to be superior (the "final concept"). The final concept scored 4.3 and 3.5, while the second concept scored a 3.4 and 3.0. Interestingly, the concept that W1 indicated to be their favourite in the first stakeholder meeting did not end up being their final concept. This indicates that SBD succeeded in increasing designers' understanding of the problem and that the method of eliminating inferior concepts rather than choosing one single concept to refine and develop is promising for WEC design.

<table>
<tr><th></th><th colspan="3">C1 Concept 1</th><th colspan="3">C2 Concept 1</th><th colspan="3">W1 Concept 1</th><th colspan="3">W1 Concept 2</th></tr>
<tr><td>CapEx</td><td>4.3</td><td rowspan="4">4.1</td><td rowspan="6">4.3</td><td>3.7</td><td rowspan="4">4.2</td><td rowspan="6">4.0</td><td>4.3</td><td rowspan="4">4.5</td><td rowspan="6">4.3</td><td>4.2</td><td rowspan="4">3.8</td><td rowspan="6">3.4</td></tr>
<tr><td>OpEx</td><td>3.7</td><td>4.5</td><td>4.3</td><td>3.4</td></tr>
<tr><td>Electricity</td><td>4.4</td><td>6.0</td><td>6.0</td><td>5.3</td></tr>
<tr><td>Availability</td><td>4.0</td><td>3.6</td><td>4.0</td><td>2.7</td></tr>
<tr><td>Uncertainty</td><td>3.6</td><td rowspan="2">4.5</td><td>4.3</td><td rowspan="2">3.6</td><td>3.9</td><td rowspan="2">4.0</td><td>2.6</td><td rowspan="2">2.8</td></tr>
<tr><td>Survivability</td><td>5.7</td><td>2.8</td><td>4.3</td><td>3.1</td></tr>
</table>

<table>
<tr><th></th><th colspan="3">C1 Concept 1</th><th colspan="3">C2 Concept 1</th><th colspan="3">W1 Concept 1</th><th colspan="3">W1 Concept 2</th></tr>
<tr><td>CapEx</td><td>3.3</td><td rowspan="4">3.6</td><td rowspan="6">3.9</td><td>3.1</td><td rowspan="4">3.2</td><td rowspan="6">3.3</td><td>3.5</td><td rowspan="4">3.4</td><td rowspan="6">3.5</td><td>3.0</td><td rowspan="4">3.1</td><td rowspan="6">3.0</td></tr>
<tr><td>OpEx</td><td>3.9</td><td>3.1</td><td>3.4</td><td>3.3</td></tr>
<tr><td>Electricity</td><td>4.6</td><td>4.6</td><td>4.3</td><td>3.9</td></tr>
<tr><td>Availability</td><td>3.1</td><td>2.3</td><td>2.6</td><td>2.4</td></tr>
<tr><td>Uncertainty</td><td>3.5</td><td rowspan="2">4.3</td><td>3.7</td><td rowspan="2">3.4</td><td>3.2</td><td rowspan="2">3.6</td><td>2.6</td><td rowspan="2">3.0</td></tr>
<tr><td>Survivability</td><td>4.9</td><td>3.2</td><td>3.9</td><td>3.3</td></tr>
</table>

Figure 3.6: Workshop concept scores

The scores in each category by both assessors are shown in Figure 3.6. For both assessors, the range of scores across concepts is 0.9. The difference between scores for a single concept between assessors ranges from 0.4 to 0.7. When working on a scale from one to nine, using an assessment method that has some reliance on expert knowledge, and assessing concepts which were generated in an extremely limited amount of time, we cannot attribute any statistical significance to these small ranges. Despite this, we can make some interesting observations that influence how we move forward in WEC design and assessment.

For three of the four concepts, the assessors scoring differed by greater than one in the electricity generation category. It is reasonable that some of the greatest differences occur in this category given that knowledge of electricity generation for new WEC concepts is heavily dependent on numerical modelling. The work by Babarit on capture width ratios across many types of WECs does significant work in the direction of synthesis and parameterization of WEC power estimates, but with such differing concepts (both in type and TRL) across the industry, hydrodynamic modelling is essential even in early stages [12]. The score in the electricity category is higher than the score in any other category across all concepts and both assessors. This indicates that the designers likely put the most emphasis on this category. Seven of the eight concepts score lowest in either uncertainty or availability. This indicates that issues of availability and uncertainty may be most difficult to incorporate into early design.

3.4.4 Workshop Conclusions

In this work we identified the need and supported previous calls for more structured practices in WEC conceptual design [5]. We also suggested a method for doing so. Along with the set-based method for conceptual design, this work provides a rudimentary example of its application. The application shows that SBD theory can be applied to WEC design problems. The scale at which we tested the methodology could not effectively prove all our hypotheses regarding how SBD can improve WEC conceptual design and ultimately WEC performance, but our findings indicate that we should continue developing the design methodology. The feedback from designers in the workshop as well as their submitted concepts made it clear that the conflicting requirements of WEC design create a need for a methodological conceptual design approach which guides them in understanding the problem and the trade-offs as they refine concepts. So far, our research shows that SBD could provide the necessary guidance.

The workshop results and feedback show that further work on WEC conceptual design methods should include work on tools which can help designers consider uncertainty and availability in early design stages. We should also work to include specific modeling strategies which are appropriate at the different levels of concept definition. Group W1 showed that SBD and utility analysis can guide designers in comparing multi-attribute imprecise WEC concepts, but as concepts increase in detail and fidelity, the tools implemented in the methodology should also increase in detail and fidelity. Concept evaluation methods must be able to account for significant imprecision.

Conceptual design methods, especially SBD, depend on strong concept evaluation methods. The TPL Assessment methodology was unable to help experts make any valuable distinctions between concepts. This product evaluation method proved to be insufficient for concept evaluation. The decision matrices and utility analysis used by W1 showed that the information content of TPL may be able to be used by designers during conceptual design. It will be important that researchers and designers continue to work toward coherence between concept evaluation methods and product evaluation methods such as TPL. Working toward this coherence stands to improve conceptual design methods, product evaluation methods, and our overall understanding of WEC performance parameters. For new, complex technologies such as WECs, design and assessment methods must be developed concurrently. A design method is necessary to develop high performance concepts, but an assessment method is necessary to know that they are high performance. At the same time, testable concepts are necessary to ensure that the assessment accurately reflects reality. The close relationship between design and assessment highlighted in Chapters 2 and 3 indicates that in order to understand and improve design methodologies, we must also work with assessment methodologies. In Chapter 4, I discuss my work with the TPL Assessment.

Chapter 4: Improving the Technology Performance Level Assessment

In this Chapter, I describe my work with the TPL Assessment, which was created by researchers at the National Renewable Energy Laboratory and Sandia National Laboratory. The assessment is currently in its fifth version and has moved from an Excel spreadsheet to a digital platform. Our goals in working with the assessment were to better understand the role of such an assessment in the conceptual design stages and how it could be improved to help designers during conceptual design.

4.1 Purpose of TPL Assessment

The purpose of TPL "is to provide a comprehensive and holistic measure of a wave energy converter's (WEC's) techno-economic performance potential" [3]. The assessment is meant for use with designers, developers, funders, and strategic investors at various stages of WEC design and development.

The TPL Assessment is based on a stakeholder analysis completed by researchers in the WaveSPARC program using a systems engineering approach [2]. They carried out the stakeholder analysis to determine what the important capabilities of a wave energy farm are. They then organized those capabilities into multiple levels of sub-capabilities, from which they developed the question-based

TPL Assessment. The assessment is intended to be completed by a third party expert along with input from designers. The expert(s) and designer(s) work together to fill out a Technical Submission Form, which prompts them to collect all of the information that will be necessary for the expert to perform the assessment. Once the information has been collected, the expert steps through each individual question in the assessment, giving the wave energy project a score of 1-9 for each question. Each question has a rubric of sorts which guides the scoring, describing the characteristics that could lead to a low, medium, or high score.

Once the expert has assigned a score for each question, the platform (originally in Mircosoft Excel, but now available online) calculates scores in seven different capability areas (cost of energy, investment opportunity, grid operation, societal benefit, permitting and certification, safety and function, and global deployment) as well as various sub-capabilities within each capability. The final score of the TPL assessment contains a significant amount of uncertainty, both due to the uncertainty of inputs to each question and the uncertainty built into the model by the weights assigned at the sub-capability and capability levels. The TPL Assessment score provides designers and decision makers with a more holistic measure of performance than a single qualitative measure such as levelized cost of energy (LCOE), but the acceptance of such a metric requires widespread use and tested outcomes. TPL has not yet reached this point of acceptance in industry.

4.2 Experience with TPL Assessment

I was introduced to TPL in the Fall of 2018 and visited NREL in December 2018 for a kick-off meeting with the WaveSPARC team. The meeting involved a detailed discussion of the TPL assessment as well as a more general overview of the WaveSPARC project goals and work to-date. At the time, I was working with TPL version 3.01 and was able to bring up some of the major questions I had regarding the assessment and the role of design methods within WaveSPARC. Following the meeting, I used TPL Version 3.01 in the WEC design study which I discussed in Chapter 3. Through this study, I observed some of the challenges of integrating TPL into conceptual design.

I used the TPL Assessment Version 4 to assess a higher TRL industry device. I worked with a developer to fill out the technical submission form. Once complete, I, along with other researcher working on this project, completed a TPL assessment of the industry device using the fourth version of the assessment. Along with our varied use of the TPL assessment, we all participated in a webinar during which we discussed the newest, digital version of the assessment as well as current and future improvements. Through this work we became familiar with the assessment's use for well-defined devices, recognized improvements between the TPL assessment versions, and gained insight to the usability if the technical submission request form and the TPL scoring tool. By using the assessment as intended, attempting to retrofit it for use in conceptual design, communicating with its creators, and examining its documentation, I was able to make recommendations for improving the assessment for use in conceptual design. In future work, I will be implementing at least three of these recommendations.

4.3 Strengths of TPL Assessment

As mentioned, the TPL assessment gives developers and investors a means of quantifying, though somewhat subjectively, a WEC Farm's performance in terms of a well-researched and well-organized set of requirements. This is its primary strength compared to other metrics of success– its breadth. The assessment handles questions of power production and questions of impacts on local communities in the same way, whereas other metrics might calculate a power production or capture width ratio quantitatively and leave concern for community impacts up to qualitative arguments. By addressing questions of power production and social impact within the same assessment structure, the TPL assessment could help to move wave energy in toward recognizing the importance of and designing for each of these requirements.

The body of knowledge contained in the TPL assessment– the stakeholder analysis used to create it– helps designers understand the important features and capabilities of a wave energy project. They can use this information in the product definition stages of the design process when they are defining the customer requirements, engineering specifications, and functional requirements of the project. Examining the capabilities, sub-capabilities, and individual questions in the TPL assessment can bring designers' awareness toward important aspects of design or potential trade-offs. The extent to which that awareness changes designer behavior in a meaningful way has not been tested, and will be discussed further in the following sections. By participating in a TPL Assessment, designers may identify areas of improvement for their devices or major showstoppers.

Version 4 of the TPL assessment included significant improvements from version 3, especially for low TRL devices. The version 4 submission form organized data in a much more assessor-friendly way and reduced the frequency with which similar data was repeatedly requested. Version 4 also removed the requirement for a site location response and decreased the number of questions that the assessors needed to answer, which is especially relevant for low TRL devices which may not have a specific location in mind for development.

Since the submission of the report upon which this Chapter is based, the WaveSPARC team has created a fifth, digital version of the assessment (which was one of our major recommendations). In Version 5, the assessor selects a score from a dropdown menu and also selects a confidence level of high, medium, or low. They also have the option of adding a justification. Each question includes both "question guidance" and "scoring guidance" [209]. Since this work was completed prior to the creation of Version 5, I will try to point out relevant changes, but have not yet worked with the newest version enough to fully integrate it into this Chapter. Even as I write this, Version 5 has not been widely distributed as it is still under construction.

4.4 Areas of Improvement for TPL Assessment

While completing much of the work in this thesis, we remained in communication with, but not in collaboration with, researchers within the WaveSPARC project. Therefore, there are a set of recommendations for improvement of the TPL assessment that we have identified with the WaveSPARC team. Most of these improvements have to do with usability and improving model-based uncertainty. Beyond that, there are areas of improvement that we have identified independent of the WaveSPARC team. These recommendations are related to changes in the assessment could make it more useful to designers during conceptual design.

4.4.1 Identified by WaveSPARC Team

1. **Subjectivity and dependence on expert knowledge** There are a few factors which contribute to the subjectivity of the assessment. Given the number of decisions that impact the performance of a WEC and the many uncertainties in the field, a truly objective assessment would be extremely difficult to create. Nonetheless, both teams agree that embedding knowledge from research and testing to minimize subjectivity is a worthy endeavor. The subjectivity of the assessment impacts its usability. The more knowledge and experience needed by the assessor to perform the assessment, the less widely it will be adopted. Allowing for assessor bias decreases the amount of trust people can put in the assessment thereby limiting the potential benefits it could bring to the industry. For that reason, as noted by the national labs

team, the assessment should be done by multiple assessors.

2. **Time requirements** Decreasing the time it takes to fill out the submission form and perform the assessment can make it more appealing to developers.

3. **Continuous improvement with new information** As more devices are tested and research is completed throughout the industry, we will gain a better understanding of what makes a device "high-performing." Even after a public, usable assessment is released, new versions will need to be continuously updated with emerging knowledge in the field. It is important, therefore, to keep track of the information that has been integrated into TPL and how it was integrated.

4. **Weighting** The assessment can have permanent weights, default weights, changeable weights, or weights that are assigned by the designer or the assessor. Weighting different areas of the assessment can make a significant difference in the outcome. The effects of each of these weighting approaches should be understood, and any permanent or default weights should be defended using empirical research and observations. Weighting plays a role in early design, guiding how designers distribute their efforts. Therefore, the weighting methods of the TPL assessment, from individual questions to capabilities, must be well-researched to understand their impacts on design.

5. **Transfer of information from submission form to assessment** To aid in the assessment of the WEC device, reduce the time demand, and decrease

subjectivity, the WaveSPARC team improved version 4 of the submission form such that is has a parallel structure to the assessment. Continued improvement, such as including tables requesting specific quantities such as watch circle, capture width ratio, and number of conversion steps, could still be made. With this in mind, we are aware of the pitfalls of making the transfer of information too explicit. For example, if the assessor only considers information under the "benefit to society" portion of the submission form when answering the "benefit to society" capability questions, they might miss relevant information contained in the "Operational Costs" or "Installation" section. These pitfalls can also be addressed in the "how-to" documentation for the assessment.

6. **Digitization** The WaveSPARC team is currently working on a digital version of the assessment coded in python. This could significantly increase the useability of the assessment.

7. **H-M-L ranges** The WaveSPARC team is continuously working to improve the justification, calibration, and appropriateness or the high-medium-low values used to guide TPL scoring [4]. We agree that this continuous work is necessary, especially as we gain a better understanding of changing stakeholder requirements and the state-of-the-art improves.

4.4.2 Identified by PMEC Team

1. **Embedding trade-offs** The TPL documentation emphasizes that "trade-offs are embedded" in the TPL assessment. A question regarding a particular design parameter could be considered under multiple capabilities, as an asset to one capability and a handicap to another. We are concerned that this acknowledges trade-offs but may not effectively embed them. Embedding the trade-offs would mean that the relative impact of a design decision within different capabilities could be understood by the designer, and the assessment would indicate when an effective balance between capabilities is reached. We outline a way to test this in the recommendations section.

2. **Creating awareness in design** The WaveSPARC team discusses the ability of assessment to make designers aware of things that they may have neglected in the earlier stages of the design process. Though this is anecdotally true and has been the consistent feedback provided by users of the tool, they have not published statistical evidence to support it. More importantly, we have not seen whether or not that awareness changes a developer's design trajectory. Since the TPL assessment is not meant as a design tool, this is understandable, but the language surrounding it must be clear, As we will discuss in the next section, there are types of design tools that could be structured using the information in the TPL assessment for the very purpose of creating awareness that is reflected in the design trajectory. There are also ways to test those tools. Given the anecdotal success that TPL has had

creating awareness, we think it would be useful to create this sort of design tool.

3. **Use in conceptual design** In our work with TPL, we found that the assessment was not able to distinguish between multiple low-fidelity concepts. To be able to distinguish between these low fidelity concepts, the requirements of concept evaluation must be discriminatory- they must be able to pick out differences between concepts. We believe that a concept evaluation tool made using the knowledge in the TPL assessment could be more appropriate for conceptual design than the full assessment. An example of a difference between this sort of tool and the TPL assessment might be that instead of asking for details on how the designers plan to install the WEC, designers are presented with the known best practices for installing a WEC and some constraints that go along with those best practices, and instead are asked if the WEC is able to meet those restrictions. This could help orient designers to the state of the art, give them the background knowledge necessary to effectively engage with other stakeholders (such as vessel providers in this case), and teach them about what design specifications impact a certain requirement. Given that there are many areas where the state-of-the-art need to be improved upon, a tool like this would need to be tested so that it does not lead to design fixation or stifle innovation. It must be clear that the purpose of such a tool would be to communicate information about a baseline capability that must be achieved so that designers and developers can improve upon it.

4. **Testing and Language** TPL, if adopted as an assessment for widespread use, would have significant influence on the wave energy field. For that reason, it should be more vigorously tested to show that it possesses the intended effects and uses. This means that, in the development stages of the assessment, care should be taken to use appropriate language when testing the assessment. Until TPL has gone through the necessary testing to prove it is an accurate reflection of performance, it should be clarified to any designers that are beta testing the assessment that the results of the assessment should not be used to encourage investment or as part of a media strategy for new device designs. They language used when testing TPL with developers will be important to ensuring that there is continued interest and willingness to use the tool, which is important because it is the best holistic assessment available.

4.5 TPL Assessment as Part of a Design Process

The TPL assessment, though designed as an assessment tool not a design tool, has been discussed as a means of making developers aware of areas of design which they have not addressed. We understand this outlook, but know that awareness of downstream information must be coupled with tools to embed that information during the early design stages in order to be effective. If, for instance, a developer using the TPL assessment recognizes their lack of knowledge, data, or planning in the area of WEC farm layout, what are the next steps that they should take to address that gap in knowledge? Does recognizing it through the TPL assessment change how they proceed? We believe that to gain all the benefits of TPL-driven awareness, we need to provide designers with tools that help them address the weaker elements of their concepts while also integrating the capabilities and functional requirements into a design process such that they are given attention from the very beginning. During the workshop we conducted, we found that the submission form was not used to guide design, but rather something that designers tried to complete after having made most of their design decisions. In this case, in the areas in which designers had not yet made thoughtful design progress, they made decisions on the fly to be able to fill out the form. These design decisions made with imprecise knowledge are exactly what we are trying to avoid by creating and implementing a formal design process. If we can integrate information from the TPL assessment into a design process, we can help designers avoid making decisions based on imprecise knowledge. Furthermore, if TPL is embedded into early design, the time it takes to the actual assessment could be decreased.

If TPL is to become a standard, widely used method of assessment, then it would be used by designers to guide design decisions. Therefore, TPL should not be developed as something separate from design, but rather as a tool that stands to heavily influence WEC design. With that, it should subject to long-term testing of its uses and impacts to understand how scores change as more information becomes available and see how changes in design impact the whole score. This long-term approach will, in the end, provide much more trustworthy understanding of how well TPL works and how reflective it is of performance. The kind of testing that we think TPL should be subject to is discussed in our recommendations. The TPL assessment should provide users with a measurable level of certainty, consistency, objectivity, and an accurate reflection of reality.

4.6 Final Recommendations

1. **Test how well trade-offs are embedded** To do this, bring several assessors to a workshop, with some of them being given a reference model to assess, and others would be given a similar WEC, but with one major change that represents a specific trade-off (if there are enough assessors, testing multiple changes would be ideal). For example, members of one group would each receive a submission form filled out for the RM3, while the other assessors would receive a submission form filled out for the RM3 made of a higher-performance, but more expensive material. All assessors would complete a TPL assessment, and then we would compare the scores for the two similar WECs, trying to understand how the trade-offs were embedded in each.

2. **Test how designers use** TPL We must be cognizant that the way industry comes to use TPL may be different from its intended use, especially if we do not consider the other purposes for which TPL might be used. This is especially important given the dependence of the assessment on a third-party expert assessor in its current state. It could be beneficial to test how a group of designers score their own concept versus how third party experts perform the same task. There are many ways to better understand how designers

use TPL and how the presentation/instructions of the assessment influences that. Consistent documentation of the data is crucial to this understanding with data being collected in various forms, such as surveys, observation, etc. Whether data is taken by survey, observation, or otherwise, it is important to document use of the TPL assessment consistently.

3. **Host long-term test to see how TPL tracks development** (look for TRL dependencies that might alter the theoretical possibilities of following the innovation curve) We propose a long-term industry partnership to test TPL, in which the assessment is done regularly as changes are made in a concept's design and new knowledge is gained. The scores can be compared with the qualitative narratives of progression to see how they represent it. We could also use it as a way to see how the company is progressing along the TPL-TRL curve [5].

4. **Test whether participating in a TPL assessment actually changes design trajectories by making designers aware of previously unconsidered topics** To do this, we could write a survey for developers to take before participating in a TPL assessment, immediately after participating, and 6 months after participating. The survey would determine what areas the developers were concerned about and focuses on before and after the assessment and also if they actually changed their design trajectory following the information gained in the assessment.

5. **Identify case studies to make TPL more quantitative less subjec-**

tive There are a number of questions in the TPL assessment which, though based on research or expert knowledge, could benefit from being investigated further in a case study. For example, one question in the Cost of Energy capability reads "for cable based mooring systems: what is the ratio of the expected watch circle (largest characteristic excursion of WEC) to the expected footprint (length to anchors, L)?" and gives specific ratios in the high-medium-low categories. Some background for this question is supplied, but the assessment would be improved if a study specifically relating the watch circle to footprint ratio to capital expenditure was conducted. It would be beneficial for the PMEC team and WaveSPARC team to work together to assemble a list of the studies of this type that could benefit the assessment most.

6. **Determine relationship between engineering specifications** The WaveSPARC team has outlined the capabilities and functional requirements of a WEC designed for grid operation. In Quality Function Deployment for project definition, the next step is to determine how the design specifications are dependent on one another. Creating a spreadsheet that shows that positive and negative dependencies of each specification could inform the TPL assessment questions and weightings.

7. **Test how TPL is impacted by designer uncertainty and explore the possibility of assessment with range inputs** This could be done through long-term testing of TPL. Quantifying the impact of uncertainty in design

on the TPL score is important to determining who should use the assessment when. If there is a point at which the assessment uncertainty becomes too high for concepts with high design uncertainty, which we suspect there is, then we should consider the possibility of a version of the assessment where a range of inputs is allowed, using similar methods to those outlined by Malak et. al. in Multi-attribute utility analysis in set-based conceptual design [88] and discussed in Chapter 3.

8. **Create a clear stage gate for TPL deployment** Discuss among WaveSPARC team, and PMEC team what we would like to see from TPL before it is presented as an assessment tool for widespread use. This is not to say that versions of the tool should not be released throughout the process or that improvements on the TPL assessment should eventually stop (in fact, we do not think wither of these things is true), rather, we are saying that there should be agreed upon thresholds to be passed for each release, and documentation of those thresholds should be published along with a new version of TPL. The potential tests outlined above can help to determine this threshold and move toward the long term goals of the assessment.

One of the most important aspects of this exercise, along with carrying out some of the tests discussed above, is publishing the results. TPL stands to shape the way that the wave energy industry develops. In order for it to be embraced by others in the field and to increase its chances of having a productive impact, its developers must be diligent and methodological in testing the assessment and be transparent about the results. It should be noted that effective publication of these tests can be done without threatening the anonymity of participants and without sharing concepts. Recruiting for design studies can be difficult, especially where participation takes time and requires participants to have specific knowledge or skills sets. For this reason, we recommend that the WaveSPARC and PMEC teams discuss the ideal participants for each test, the potential incentives we can supply, and the ways we can strategically host tests to maximize the information we can derive without impacting the quality of that information. The above recommendations have been discussed with the WaveSPARC team, and we look forward to carrying them out together.

Chapter 5: Assessment of Emerging Market Devices

The TPL assessment is primarily a tool for evaluating the performance capabilities of a grid-scale WEC concept. Since its introduction, it has focused, as the wave energy industry has, on the grid-scale energy market. The recent broaden of interested to include non-grid-scale applications has led to the anticipatory need for a tool similar to the TPL assessment for evaluating the performance capabilities of WECs meant for non-grid-scale (emerging) markets. This chapter outlines what needs to be done to create such an assessment. To increase the relevance of the TPL assessment for alternative, non-grid-scale, markets, we look to how the TPL assessment was created. The TPL assessment is based on a stakeholder analysis which includes stakeholder interested or involved in grid-scale electricity production [2]. In this work, perform a parallel stakeholder analysis for alternative markets to recommend modifications to the existing TPL assessment to enable their use in powering the blue economy.

To perform our stakeholder analysis, we followed the first several steps of Quality Function Deployment (QFD). QFD is a product definition process meant to help designers understand and organize a design problem. It is a stakeholder-focused methodology that encourages designers to consider what the stakeholder needs are and how they are reflected in a concept. The first step in QFD is to identify all potential customers. Customers are not limited to the end users of a product or system, rather, they are anyone who interacts with the system at any of its lifecycle stages. Next, we identify the customer requirements and categorize what is important to each customer. Depending on the system, some customers' preferences are more important than others; therefore, we can weight the customers' preferences accordingly. We then determine design specifications and the relationship between those design specifications and customer requirements. Design specifications are quantifiable measures by which we can meet a customer requirement. For example, if a customer requirement for a WEC is survivability, a corresponding design specification may be the maximum expected load on the WEC. From here, to complete the QFD process, one would develop targets for the engineering specifications and determine the interdependence of the engineering specifications [18]. In completing this stakeholder analysis, we identified many— but not all— design specifications for WEC design, such that we could create a roadmap for the adaptation of the current TPL assessment tool to emerging markets. In that roadmap, we suggest the continuation of the QFD process.

In this Chapter, I present our stakeholder analysis for three promising emerging markets and review the specific questions in the grid-scale TPL assessment and their relevance to emerging markets. From these studies I present a final roadmap intended for use in modifying the TPL assessment into an assessment for WECs for emerging markets.

5.1 Stakeholder Analysis

For the stakeholder analysis we determine (1) who the stakeholders are, (2) what the stakeholders' requirements are for the system, (3) how much each stakeholder cares about each requirement, and (4) how important each stakeholder's preferences are. We do this for three emerging wave energy markets identified in the Powering the Blue Economy report chapters two, three, and seven, Ocean Observation and Navigation, Underwater Vehicle Charging, and Desalination [8]. For emerging markets, it is important to note the uniqueness of potential stakeholders. For example, wave energy systems for ocean observation and AUV recharge might be relevant to academic ocean science researchers, while large-scale desalination systems would not. Stakeholders include purchasers, federal and local policymakers, manufacturers, installers, developers, and investors.

To create a list of stakeholders, we review the lifecycle stages of a device for each emerging market and identify the entities involved at each stage. We compare our list to the stakeholders mentioned in the Powering the Blue Economy (PBE) [8] report and use the report to help us create the initial list of customer requirements. We consider the customer requirements at each life cycle stage as well as different stages of operation. We benchmark alternatives by researching the current methods of providing energy to each of the emerging markets. This helps us refine the list of customer requirements because we know that in order for purchasers and/or policymakers to select an EM-WEC concept, it must meet the same requirements as the most viable alternative. Once we complete a list of customer requirements, we gather feedback from key stakeholders who have varied research and development interests in the three identified emerging markets.

Based on feedback from stakeholders, we score the importance of each customer requirement to each stakeholder on a scale of zero to six, zero meaning that the customer does not care about the particular customer requirement, and six meaning that it is very important to them. When assigning scores, we consider 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.

For our analysis, the individual stakeholder weights ranged from 0.05 to 0.25. We weight most heavily the stakeholders who have the power to choose other forms of energy for their end use; wave energy must prove itself to be advantageous over its alternatives from the perspective of these stakeholders. The stakeholders who take the greatest financial risk when choosing a wave energy system are also weighted heavily. The mid-weighted stakeholders are stakeholders who assume some financial risk and/or have some power to prevent an installation. The low-weighted customers 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 multiplied the importance score according to each customer by that customer's weight and summed the scores over all the customers. The overall importance scores range from 1.85 to 4.5 on the 0.0

to 6.0 scale. The stakeholders and their assigned weights can be seen in Table 1. The customer requirements for each market ordered by importance score is shown in Table 2. In the following sections, we present and discuss the results of the stakeholder analysis for large-scale desalination, ocean observation and navigation, and AUV recharge.

5.1.1 Large-Scale Desalination

Desalination is the process by which we can convert seawater (or brackish water) into fresh water 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. Today, most desalination systems for drinking water production run reverse osmosis, which discharges high salinity brine discharge that can be damaging to ocean environments. Wave power may be an attractive option for powering large-scale desalination operations because the energy resource is close to large coastal populations which are likely to face greater water insecurity in the future due to climate change. Wave energy powered desalination could reduce the environmental impact of the high energy consumption of desalination [210], and may provide new opportunities in brine disposal. The U.S. Department of Energy has identified two distinct markets for wave energy powered desalination, utility scale and distributed systems [8, chapter 7]. We focus on utility scale systems in this section. We chose the large-scale systems because they present different challenges from the smaller ocean observation and AUV recharge markets (the other markets analyzed in this report). Large-scale desalination is the emerging market with requirements closest to those of grid scale devices, and therefore requires the least modification to the most current TPL assessment draft. The important stakeholders for large-scale desalination projects are similar to those for WEC farm projects. Researching Carlsbad Desalination Project, the only utility-scale seawater desalination plant in the U.S., helped us understand the stakeholders involved in a large-scale desalination project [211]. In order of assigned weight, the stakeholders include:

1. project developers (0.25)
2. water utilities/purchasers (0.25)
3. state and federal regulators (0.15)
4. equity investors (0.10)
5. WEC developers (0.10)
6. system operators (0.05)
7. marine contractors (0.05)
8. end water users (0.05)

The project developers are the stakeholders who assume the largest financial risk in a large scale desalination project and make most of the major decisions, 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, and 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 do their jobs properly, and their preferences are weighted the least (0.05) along with the water end users, who may be able to give public comment when the project is being cited, but have little influence afterward. 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) along with the regulators (0.15). Many of these stakeholders have similar requirements for the system. The most important requirements are those that are of the highest importance to the highest-weighted stakeholders. The possible range of overall importance score is from zero to six, calculated by multiplying each individual customer's importance scores with that customer's weight and summing across all customers. The sum of all customer weights equals one. The customer requirements, in order of overall importance score, include:

1. reliable energy production (4.45)
2. serves populations in need of water (3.95)
3. safe (3.90)

4. low capital cost (3.70)
5. produces tens of MW (3.35)
6. low operational cost (3.10)
7. provides a good investment (2.95)
8. low maintenance (2.90)
9. no environmental degradation (2.55)
10. easy to install (2.25)
11. Scalable (2.15)
12. easy to manufacture (1.90)

The potential for wave-powered large-scale desalination plants depends significantly on the cost of the plant, which is extremely site dependent. An ideal location is one where the cost of water is high and the need for water is not currently being met. 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 requirement for low capital and operational costs. The environmental concerns that come with desalination emerge as another barrier. The requirement for the system to reliably produce energy is important to both the financiers of the project and the end users, as well as 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 led to the overall importance score of reliable energy production to be 4.45. The lowest scoring customer requirement was that the system is easy to manufacture (1.9 overall importance score) which is only important to the people involved in making the system and the people in charge of its overall development, marine contractors, project developers, and WEC developers. Though the ease of manufacturing could be related to the capital cost, which has the fourth highest importance score, at this stage in the process we consider the customer requirements to be distinct. The relationship between customer requirements can be quantitatively captured later in the process when we determine measurable engineering specifications and the relationship between those specifications and the customer requirements. We discuss this further in later sections.

5.1.2 Ocean Observation and Navigation

Scientists, sailors, and military groups are constantly increasing the number of sensors, cameras, and navigational aids in the ocean for a wide range of purposes, from collecting data the PH value of the water to monitoring for foreign vessels. The potential of wave energy to power ocean observation and navigation has been explored by researchers at NREL and PNNL [212]. 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 [212]. With more than 80% of the world's oceans remain unexplored, increased interest in the economic and climate-related services of the ocean, and steady use of at-sea weather observation equipment, there will continue to be a demand for power at sea [8, chapter 2]. There is a demand for increased power availability at all depths and distances from shore includes surface, subsurface, landward and seaward of the continental shelf [212].

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, the people in charge of equipment and maintenance at sea, and WEC developers and manufacturers. The end users, being as varied as they are, have a much greater role in dictating the system requirements, as they are the ones driving the need for wave energy devices. As such, the military and NOAA/NWS customers are weighted most heavily at 0.2. Commercial users were weighted at 0.15 and academic researchers on 0.10. The difference in end-user weights is reflective of the difference in predicted size of the future market [212], shown in the list below.

1. Military (0.20)
2. NOAA/NWS (0.20)
3. Commercial Users (0.15)
4. Academic Researchers (0.10)
5. State and Federal Regulators (0.10)
6. WEC developers (0.10)
7. WEC manufacturers (0.05)
8. Ship navigators (0.05)

9. Equipment installers and maintainers (0.1)

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 battery-powered or solar systems. For that reason, reliable power production is again the highest scoring customer requirement with an overall importance score of 4.0. A WEC system needs to allow for longer deployments, greater access to power, and improved spatial and temporal data resolution [212], which lead to the customer requirement for the system to produce power of 10-600W (3.3 overall importance score). Compared to desalination or grid-scale systems which are large and long-term, these small systems are subject to simpler permitting processes, making the regulators a less significant stakeholder (with a weight of 0.10) and thereby reduce the importance of acceptability to other ocean users, which had the lowest importance score of 1.85. The manufacturers, equipment installers, and maintainers are responsible for the continued operation and performance of the systems, so their preferences are considered as well weighted at 0.05 and 0.10 respectively. Our stakeholder analysis shows that an EM-WEC for ocean observation and navigation should meet the following customer requirements:

1. reliable power production (4.00)
2. safe (3.90)
3. survivable (3.90)
4. low operational cost (3.65)
5. cause no environmental disruption (3.45)

6. have low capital cost (3.30)
7. produce 10-600W power (3.30)
8. low maintenance (3.20)
9. flexible in a variety of wave conditions (3.05)
10. Maneuverable (2.85)
11. charge at surface or underwater (2.50)
12. adaptable to charge many instruments (2.35)
13. able to be integrated with other renewables (2.05)
14. acceptable to other ocean users (1.85)

The variety of end users leads to a few customer requirements related to the ability to the device to adapt to varied wave conditions (2.95 overall importance score), to different locations in the water column (2.50), and to many instruments (2.25).

5.1.3 AUV Recharge

AUVs, or autonomous underwater vehicles (sometimes also referred to as unmanned underwater vehicles), are vehicles with onboard computers, sensors, and power sources (batteries or compressed air) 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 [8, chapter 3]. Often, a vessel will retrieve the AUV and use a diesel engine to charge the battery system. The diesel engine can be added to larger AUVs, requiring resurfacing to charge battery systems [8, chapter 3] . In sensitive missions, retrieval or resurfacing can compromise stealth [8, 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 much higher, ranging from 175 to 1250 W [212]. AUVs tend to be more mobile than ocean observation and navigation equipment. Important stakeholders for AUV recharge stations include (in order of importance):

1. Commercial sector (offshore drilling, telecommunications, surveying, etc.) (0.20)
2. Military sector (0.20)
3. NOAA/NWS (0.10)
4. Academic researchers (0.10)
5. WEC developers (0.10)
6. State and federal (0.10)
7. AUV designers (0.10)

8. Marine contractors (equipment installers and maintainers) (0.05)
9. WEC Manufacturers (0.05)

We based stakeholder weights on the impact each stakeholder has on the AUV market. The commercial and military sectors are the primary end users, so we gave each a weighting of 0.20. Scientific end users are mainly comprised of NOAA/NWS and academic researchers, each have different use cases for AUVs. Scientific sectors are also primary end users in this field. Both NOAA/NWS and academic researchers have a weighting of 0.10. Following end users, WEC developers carry a large financial risk, therefore, we gave them a weighting of 0.10. WEC manufacturers, equipment installers and maintainers interact have the lowest weightings (0.05). While manufacturers, installers, and maintainers interact with the charging station and care it is both safe and easy to use, their influence over the charging station design is limited. Regulators must consider the safety and preferences of all parties, ensure project developers and end users are held accountable, and understand the environmental risks of development. They are weighted 0.10. AUV designers also have a mid-weighting of 0.10 as they assume some financial risk and can impact design decisions for a charging station. After identifying stakeholders, we generated requirements for AUV charging stations and ranked these requirements for each customer. Through our stakeholder analysis, we determined the customer requirements for underwater wave powered AUV charging stations include (in order of importance):

1. Operate over a wide range of depths (4.50)

2. Low maintenance (4.35)
3. Easy to dock (4.30)
4. Safe (4.30)
5. Survivable (4.25)
6. Able to dock AUVs in harsh conditions (4.05)
7. Low capital cost (3.95)
8. Store between 66kWh and 2.2 MWh (3.75)
9. Produce between 175 to 1250 W (3.65)
10. Low operating cost (3.30)
11. Easy to install (3.25)
12. Provide data storage (3.10)
13. Maneuverable (2.60)
14. Cause little environmental disruption (2.55)
15. Maintain vehicle stealth (1.90)
16. Able to store compressed air (1.80)

Underwater, wave-powered AUV charging stations have the potential to save hundreds of thousands of dollars [8, 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 [8]. The end user's ability to utilize charging

Table 5.1: Stakeholders and weights for emerging markets

Large Scale Desalination		**Ocean Observation and Navigation**		**AUV Recharge**	
Customer	**Weight**	**Customer**	**Weight**	**Customer**	**Weight**
Project Developers	0.25	Military	0.20	Military	0.20
water utilities/ purchasers	0.25	NOAA/NWS	0.20	Commercial Users	0.20
State and Federal Regulators	0.15	Commercial Users	0.15	NOAA/NWS	0.10
Equity Investors	0.10	Academic Researchers	0.10	Academic Researchers	0.10
WEC Developers	0.10	State and Federal Regulators	0.10	AUV designers	0.10
System Operators	0.05	WEC developers	0.10	State and Federal Regulators	0.10
Marine Contractors	0.05	Equipment installers and maintainers	0.10	WEC developers	0.10
End Users (water)	0.05	WEC manufacturers	0.05	WEC manufacturers	0.05
		Ship navigators	0.05	Equipment installers and maintainers	0.05

stations, regardless of location, leads to *operate over a wide range of depths* to have the largest weighted importance score (4.5). The device *being able to dock AUVs in harsh conditions* (4.05) could be related to operating over a wide range of depths, but at this stage we consider these separate requirements. The process of quantifying these relationships is discussed later. The lowest importance score is the need for the AUV charging stations to store compressed air (1.9), which is moderately important to only academic researchers and commercial users. For all three emerging markets, stakeholders and their assigned weights are in Table 5.1 and the ordered customer requirements are in Table 5.2.

5.1.4 Customer requirements and TPL capabilities

The TPL assessment was developed based on a stakeholder analysis similar to the one we present in this report [2]. The ”capabilities” of the TPL assessment are high-level customer requirements. They include 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 and the grid integration capability should be use integration, specific for each market. The global deployability capability takes on new meaning in markets where there are many potential end users. Global deployability can be understood to mean both geographically global and global among end users. Each of the requirements listed in our stakeholder analysis fits into at least one of the seven capabilities listed in the TPL assessment adjusted for emerging markets. The TPL assessment is organized within the seven capabilities by sub-capability (and sometimes sub-sub-capability) and the questions are based on measurable design specifications that relate to each sub-capability. In Figure 5.1 we organized the customer requirements as they align to the TPL capabilities and list several design specifications related to each. We include any information (capability, sub-capability, or design specification) that is

Table 5.2: Stakeholder requirements for emerging markets

Large Scale Desalination		Ocean Observation and Navigation		AUV Recharge	
Customer Requirement	**Importance Score**	**Customer Requirement**	**Importance Score**	**Customer Requirement**	**Importance Score**
Reliable energy production	4.45	Reliable power production	4.00	Operate over a wide range of depths	4.50
Serves populations in need of water	3.95	Safe	3.90	Low maintenance	4.35
Safe	3.90	Survivable	3.90	Easy to dock	4.30
Low capital cost	3.70	Low operational cost	3.65	Safe	4.30
Produces tens of MW	3.35	No environmental disruption	3.45	Survivable	4.25
Low operational cost	3.10	Low capital cost	3.30	Can dock AUV in harsh conditions	4.05
Provides a good investment	2.95	10-600 kW power production	3.30	Low capital cost	3.95
Low maintenance	2.90	Low maintenance	3.20	Can store 66kWh-2.2MWh	3.75
No environmental degradation	2.55	Flexible in a variety of wave conditions	3.05	Produces power between 175 and 1250 Watts	3.65
Easy to install	2.25	Maneuverable	2.85	Low operation cost	3.30
Scalable	2.15	Can charge at surface or underwater	2.50	Easy to install	3.25
Easy to manufacture	1.90	Adaptable to charge many instruments	2.35	Provide data storage	3.10
		Able to be integrated with other renewables	2.05	Maneuverable	2.60
		Acceptable to other ocean users	1.85	Causes little environmental degradation	2.55
				Maintains vehicle stealth	1.90
				Can store compressed air	1.80

from the TPL assessment in black, and any information unique to the emerging markets in blue. The requirements and specifications in blue should be included in a version of the TPL assessment for emerging markets. We do not divide beyond sub-capabilities to avoid tiered customer requirements. In Figure 5.1, we see that much of the content included in the TPL assessment would be appropriate to include in an emerging market assessment. Unsurprisingly, the capability with the most unique customer requirements and design specifications is *use integration*. This is because the customer requirements and design specifications under *use integration* are specific to the emerging market rather than integration with the electric grid and use integration is a new capability area. The customer requirements and design specifications in Figure 5.1 are not exhaustive, but provide the foundation for an assessment of low-TRL EM-WECs.

5.2 Capturing Design Specifications in TPL Questions

The fourth version of the grid-scale TPL assessment contains 87 questions within 7 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,

Capability	Sub-capability/Customer Requirement	Design Specification
Cost of Concept	Manufacturability Installability Low Capital Cost Low Operational Cost **Easy to Deploy and recover (OO and AUV)** High Performance Good Components ("Design" in TPL)	**Cost/L water (DL)** Sea state range for install **Cost/device (OO and AUV)** Steps in energy conversion Maturity of technology Percent components using specialty material Sensitivity to tides and currents Number of components without load safety margins Number of configurations
Investment Opportunity	Reliable energy production Capex Uncertainty Availability Uncertainty **Serves populations in need of water (DL)** Opex Uncertainty **Large end user market** Maintainability Survivability	Cost of Materials MTBF of components Sea state range for deployment Sea state range for servicing Number of components without load safety margins **Sea state range for recovery (OO and AUV)** Maturity of technology **Predicted devices sold per year (OO and AUV)**
Use Integration	**Easy to dock (AUV)** **Provide data storage (AUV)** **Maintains vehicle stealth (AUV)** **Adaptable to many instruments (OO)** **Can store compressed air (AUV)** **Converted energy is the same order of magnitude as demanded energy**	Energy storage capacity **Sea state range for docking (AUV)** **Compressed air storage capacity (AUV)** Power Output **Data storage capacity (AUV)** **Permanence and seawater exposure of interconnection** Maturity of technology **Range of power output (OO)** **Ratio of energy conversion to energy use**
Benefit to Society	No environmental degradation **Serves populations in need of water (DL)** GHG emissions and pollution	Percent of parts recyclable **Number of compatible instruments (OO)** Noise pollution levels Lifetime of device Length to repay energy debt Light pollution levels Percent of parts reusable
Safety and Function	Safe Maintainability **Maneuverable (AUV & OO)** Easy to Install Survivability	Survivable sea states Safety factor Sea state range for deployment Sea state range for servicing Number of components without load safety margins Losses per annum Number of life cycle steps that pose risk to humans
Permitting	**No permit required for short term deployment (OO and AUV)** No environmental degradation Few area use conflicts Acceptable to other ocean users	Noise pollution levels Light/radar reflector Light pollution levels Area of exclusion zone
Global Deployability	Easy to Install **Can operate over a wide range of depths (AUV)** Survivability **Useful for short and long term deployments (OO and AUV)** **Scalable (DL)** **Easy to recover (OO and AUV)**	Sea state range for operation Noise/ light pollution levels Sea state range of survival Sea state range for deployment **(and recovery)** Depth range **Recovery equip req. (OO and AUV)** Current (sensitivity) range for operation Bottom Type Maturity of technology Tidal (sensitivity) range for operation

Figure 5.1: Capabilities, Customer Requirements, and Design Specifications for Emerging Markets
DL = Desalination, OO = Ocean Observation, AUV = Autonomous Underwater Vehicle

as they relate to grid integration and other concerns 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. The question-by-question breakdown can be found in Appendix 6.

There are some key differences between emerging market and grid-scale WEC design requirements which have implications for the ways we assess performance. Primarily, differences in the scale of costs and investment change who the most important stakeholders are, especially for ocean observation and navigation and AUV recharge. The capital cost for a WEC farm which powers a large desalination plant is estimated to be close to $4 million [210], while to capital cost for ocean observation or AUV recharge EM-WECs should be much less given the reduced power requirements [8, chapter 2]. Typically, in ocean observation systems, the costs of deployment, maintenance, and recovery are far more than the capital cost [212].

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. The same is 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 the project developer. The difference in important stakeholders will lead to a change in the weights of sub-capabilities in the TPL assessment. The demand for WEC developers to make an EM-WEC that is marketable to individual users as a contained system (for ocean observation and AUV recharge) can be captured in the *cost of concept*, *investment opportunity*, and *use integration* sections of the assessment with the additional requirements and design specifications, such as *cost per device* and *adaptable to many instruments*, shown in Figure 5.1. Many of the TPL questions that assume large, power maximizing arrays are labeled scalable or irrelevant due to this key difference in market scales.

The public plays a much smaller role in the small-scale markets (ocean observation and AUV recharge) than in the large development projects. The requirement to get public approval is less important for these markets, and the permitting processes are simpler. This leads the *benefit to society* and *permitting can certification* sections of the assessment to containing different questions and different weights than the grid-scale TPL assessment. As seen in Figure 5.1, ocean observation and AUV recharge systems should be designed to require minimal permitting (though, as the blue economy grows, permitting processes may change). 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. For that reason, we label the environmental impacts questions in the permitting section as scalable to reflect the different measures of environmental impacts that will be required.

Ocean observation and navigation and AUV recharge markets may require systems that are used in many, short term deployments in various places or for long term, stationary deployments. Therefore, those systems need to be designed for short and long term use. This requires scaling of the questions regarding component lifespans, installation, and maintenance. The ease of recovery also becomes much more important and the equipment expected to be available for installation and recovery should scale with the price of the system. The design specifications measuring installability will have different targets for EM-WECs than for grid-scale WECs. Questions measuring installability in the TPL assessment were, therefore, often labeled as scalable questions. In Figure 5.1, we added some measures of recoverability to capture the need for an EM-WEC for ocean observation of AUV recharge to be acceptable for short term deployment.

The questions in the TPL assessment refer to four main subsystems; the subsystem that absorbs energy, converts energy, transports energy, and station keeps. It will be necessary to ensure that the language used to refer to these subsystems and their responsibilities is adapted for each emerging market. Along with having potentially different subsystems, EM-WECs differ from grid-scale WECs in terms of the goal of power production. In grid-scale WECs, power production should be maximized and consistent over time. The TPL assessment reflects this need for power maximization and consistency through questions in the grid integration and cost of energy capabilities. These questions were labeled as irrelevant because the assumed need for maximized, consistent power production may not be valid for EM-WECs. In order to still capture energy production requirements, 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. The use integration section of Figure 5.1 provides requirements and design specifications that can be used to capture this unique need, specifically the ratio of energy converted to energy used by the integrated system.

The design specifications measuring the final output of the system will have different targets for each emerging market. Questions measuring the final output of the system were, therefore, often labeled as scalable questions. The final output of the system changes how we measure its ability to meet customer requirements. For example, the question regarding how long the WEC takes to repay it energy debt is measured differently if the WEC's end product is not energy to the grid. In the case of a WEC system that is sold as a product for ocean observation, this question may be irrelevant. Alternatively, it would need to better define the energy debt- does it include the energy used for multiple deployments? How does it account for energy offsets versus energy supplied for new uses? Answering these questions will change the definition of the energy debt. EM-WECs could output electricity directly to another ocean technology, pressurized water, compressed air, or potentially another innovative form of energy. An EM-WEC performance assessment must account for the ways those differing outputs are reflected in customer requirements and design specifications. We have highlighted some of the important distinctions between grid-scale and emerging markets assessment through the stakeholder analysis and TPL question analysis. To incorporate some of the differences we have identified, Section 5.3 includes a roadmap of the necessary actions for adaptation of the TPL tool for emerging markets.

5.3 TPL Tool Adaptation

The TPL assessment, in its fifth version, is the product of more than seven years of work beginning with the stakeholder assessment. The structure, scoring, and individual questions have seen significant improvements. Though we began our inquiry about adapting the TPL tool for emerging markets by performing a similar stakeholder analysis, we know that the final adaptation of the tool should not need to go through the same iterative process if it does not have to. That said, we have previously made some recommendations for improvement of the TPL assessment (Chapter 4). In this discussion of TPL tool adaptation, we attempt to provide a roadmap which preserves some fundamental structures of the TPL assessment while also addressing some of our previous concerns. Ultimately, we believe that this is the quickest to get the best assessment.

5.3.1 Employing suggestions from Chapter 4

The following suggestions provided in Chapter 4 are relevant in the transfer of information from grid-scale TPL to emerging market performance assessment. We discuss each of those suggestions into this report, and how to implement each in the adoption to emerging markets. We recommended, regarding the TPL assessment,

> ***Determine relationship between engineering specifications*** *The WaveSPARC team has outlined the capabilities and functional requirements of a WEC designed for grid operation. In Quality Function*

> *Deployment for project definition, the next step is to determine how the design specifications are dependent on one another. Creating a spreadsheet that shows that positive and negative dependencies of each specification could inform the TPL assessment questions and weightings.*

For the three emerging markets discussed in this paper, we outline many of the customer requirements and design specifications along with how they relate to the customer requirements and design specifications embedded in the TPL assessment. We also identified how important each stakeholder is and how important each requirement is to each individual stakeholder. We recommend that before those new requirements and specifications are embedded into the current TPL tool, the WaveSPARC or PMEC team continue with the next step in Quality Function Deployment by determining how the design specifications are related. Once this is done, the team could use the Quality Function Deployment House of Quality to approximate the relative weight of each design specification. The House of Quality accounts for the relationships between customer requirements and design specification, the relationships among design specifications, and the relative weights of each customer requirement based on their importance to each customer (and the importance of that customer).

We also recommended regarding the TPL assessment,

> ***Weighting*** *The assessment can have permanent weights, default weights, changeable weights, or weights that are assigned by the designer or the*

assessor. Weighting different areas of the assessment can make a significant difference in the outcome. The effects of each of these weighting approaches should be understood, and any permanent or default weights should be defended using empirical research and observations. Weighting plays a role in early design, guiding how designers distribute their efforts. Therefore, the weighting methods of the TPL assessment, from individual questions to capabilities, must be well-researched to understand their impacts on design.

Subjectivity and dependence on expert knowledge *There are a few factors which contribute to the subjectivity of the assessment. Given the number of decisions that impact the performance of a WEC and the many uncertainties in the field, a truly objective assessment would be extremely difficult to create. Nonetheless, both teams agree that embedding knowledge from research and testing to minimize subjectivity is a worthy endeavor. The subjectivity of the assessment impacts its usability. The more knowledge and experience needed by the assessor to perform the assessment, the less widely it will be adopted. Allowing for assessor bias decreases the amount of trust people can put in the assessment thereby limiting the potential benefits it could bring to the industry.*

Digitization *The WaveSPARC team is currently working on a digital version of the assessment coded in python. This could significantly* *increase the usability of the assessment.*

Time requirements *Decreasing the time it takes to fill out the submission form and perform the assessment can make it more appealing to developers.*

To address each of these suggestions, we should use the weights calculated in the House of Quality for each design specification to guide the weighting of questions in the TPL assessment. If implemented correctly and digitized, this method of weighting would capture the positive and negative relationships identified in the House of Quality, making every question only necessary to ask once. This could reduce the time requirement and decrease the subjectivity of the assessment. A House of Quality should be created for each emerging market.

Once the relative weight of each design specification is determined, questions for the EM-WEC TPL assessment should be written such that each question is a measure of a single design requirement. The questions may be organized into categories according to the capabilities outlined in this report, but the tiered weights of the current TPL assessment [3] will be unnecessary. This is because the importance of each customer requirement is used to calculate the relative weight of each design specification and each design specification is represented by a single assessment question, therefore the relationships that are captured by tiering the requirements are already captured in the relative weights. Once the questions are written, they should be organized into transferable (between all emerging markets), scalable (between emerging markets), and unique (to a single emerging market) and the assessment should be digitized. A digitized version should allow for 1) user input on customer weights and customer needs and 2) user selection of an emerging market with automated question filtering. The transferable questions will be relevant for all emerging markets, and the scalable and unique questions will be programmed to only appear when the corresponding emerging market is selected. By allowing the user to change the default customer weights, the assessment will be able to best reflect a particular market. The digitization based on the House of Quality inputs and outputs would help to decrease subjectivity and reduce the time necessary to do the assessment.

Unlike the current TPL assessment, which uses the answers to each question to calculate sub-sub-capability scores, which are then used to calculate sub-capability scores, which are then used to calculate capability scores, which are then used to calculate the final TPL score, the recommended emerging market adaptation of the tool would give each question an overall weight according to its relationship to each requirement and that score would be used to calculate the final TPL score. The type of scores and feedback that the assessment should give beyond the final TPL score must first be determined before deciding on a way to calculate and present scores in individual categories. The relationships identified between customer requirements and design specifications can be used in a digitized, adapted version of the TPL assessment tool to assign scores in individual capabilities. Since design specifications are the measurable quantities according to which designers can make decisions, and specific assessment questions collect information about individual design specifications, it is likely most valuable for designers to get assessment feedback on the individual question level with an indication of what customer requirements those questions are related to. That would likely be more valuable than scores in each capability and sub-capability without reference to the specific design decisions that can be made to improve those scores.

Finally, once the digitized emerging markets assessment tool is created, it should be tested, compared the grid-scale TPL tool, and used to identify unique, market-specific trade-offs. To test the tool, we recommend incorporating some of our suggestions regarding the testing of the grid-scale TPL assessment found in Chapter 4 with some of the most effective tests used by the WaveSPARC team in while creating the current TPL assessment. This includes (a.) getting feedback from users, both potential developers and assessors, regarding both content and usability, (b.) testing how well trade-offs are embedded, and (c.) testing whether using the assessment leads to changes in design decisions. We can compare the emerging market assessment to TPL, looking for similarities and differences in the way that developers and assessors use the assessment. We can also compare the uncertainty in the assessments. We can test the EM-WEC assessment's ability to embed trade-offs by making small design changes to a concept and tracing the change in the assessment score. Inversely, we may be able to identify trade-offs by understanding how design changes are reflected in each design specification.

5.3.2 Roadmap for an Equivalent Assessment

Throughout this Chapter I identified some key differences and areas for attention when converting the grid scale TPL assessment to a performance assessment of emerging market technologies. To briefly summarize, they included,

- Adjusting weights of requirements and potential assessment question answers to match the scale of the merging market
- Considering marketability of EM-WECs sold as a single, standalone system
- Adjusting customer weights according to stakeholder analysis
- Considering permitting differences within and between emerging markets and grid scale
- Matching question wording to make sense with the end output of the EM-WEC
- Rewording or reconsidering questions that assume that power maximization is desired
- Covering all unique subsystems of EM-WECs
- Considering markets which require multiple deployments and recoveries

The path from the grid scale TPL assessment tool to a similar performance assessment tool for emerging markets is shown in Figure below.

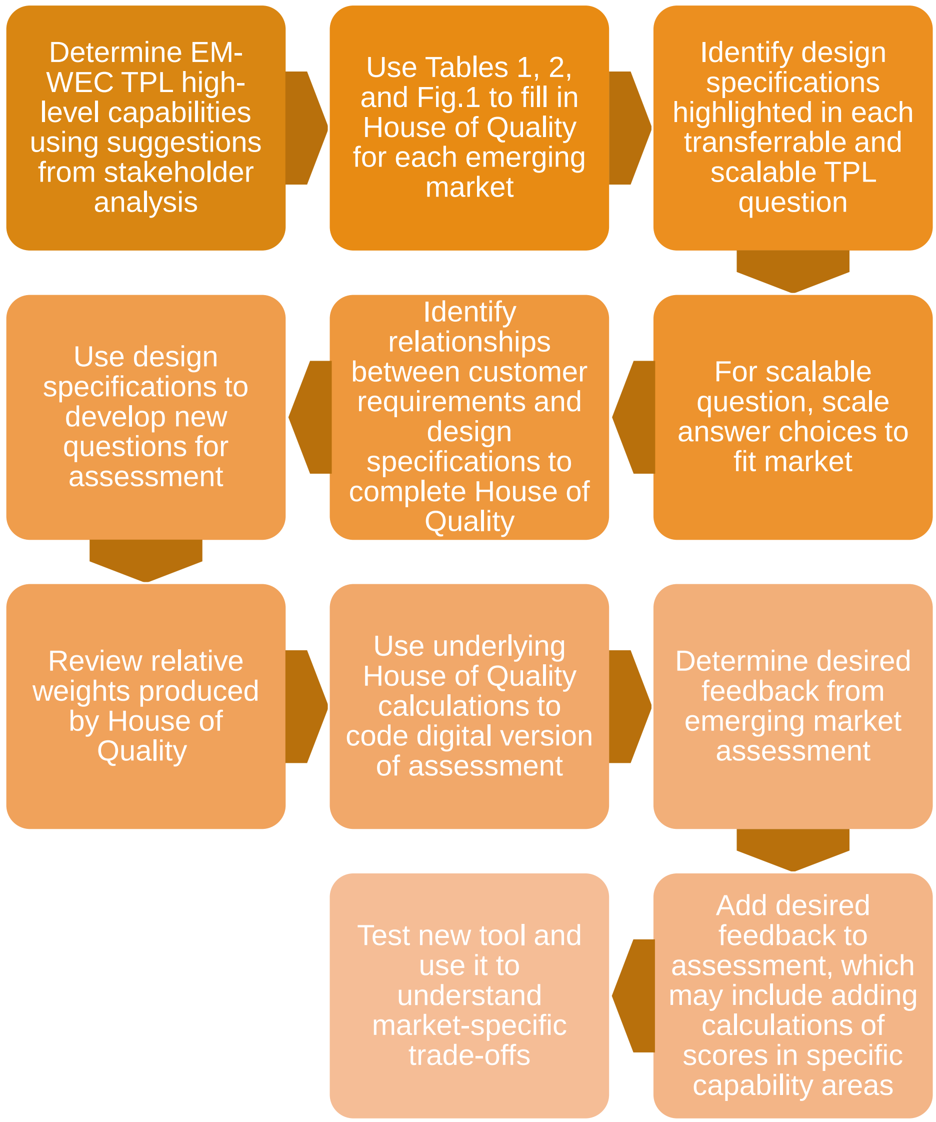

Figure 5.2: Roadmap for adapting TPL for use in emerging markets

Chapter 6: Conclusion

The challenges unique to WEC design make it a design problem that does not fit neatly into product, technology, or systems design. WEC design success is sensitive to the preferences of a diverse set of stakeholders and to the changing environmental and political contexts of our time. With a better understanding of the properties of the WEC design problem, I show that the field is in need of structured design methods to improve performance, reduce costs, and embed the knowledge contained in academic research in the field. The work presented in Chapters 2-4 for this thesis moves the wave energy field toward improved WEC design processes. Though I cannot conclude this work with an ideal design process, I have completed the foundational research that will be necessary for proposing an improved process by reviewing current practices and analyzing those practices and the problem of WEC design in the context of engineering design. Current practices, examined in both research and industry design, are predominantly point-based, iterative design which has been shown to be a sub-standard design practice by metrics of time, cost, and optimality of design [64]. There is a need for improved conceptual design practice that can lead to better initial concepts as well as a need for tools which guide design decisions based on device evaluation. In order to create tools that lead to better design decisions based on evaluation, wave energy researchers need to improve our collective knowledge on the ways that individual design decisions impacts the wide range of WEC design requirements, not just power production or cost.

Set-Based Design and multi-attribute utility analysis are good candidates for application in WEC conceptual design, but empirically examining any new conceptual design methodology will require better methods for evaluating WEC concepts. Currently, the most holistic WEC performance assessment (though a product evaluation method, not for concept evaluation), the TPL assessment, cannot distinguish between early design concepts. Furthermore, it has yet to be shown that participating in a TPL Assessment changes the trajectory of WEC design projects. Creating holistic assessments requires an examination of customer requirements and design specifications. The requirements determined by the WaveSPARC team's stakeholder analysis can be used by WEC designers in the product definition stages of design for grid-scale devices. For emerging markets, the design requirements are different enough from those of grid-scale devices to warrant substantial changes in the content of the TPL assessment if it is to be applied to emerging markets.

Aside from the three federal-level projects in WEC design and development discussed in Chapter 2, academic research on the WEC design process is scarce. Most academic research is not contextualized in the broader WEC design process. This can make pathways in WEC design seem disparate and make it difficult to understand how a particular piece of research is relevant to the design process. Wave energy is not, as it stands, a major part of the suite of potential technological means of addressing climate change [213], and it is difficult to know whether it will become such. Without a clear pathway and a structure for understanding design processes, approaches, methods, and tools, it seems unlikely. In this work, I have offered such a structure as well as several approaches, methods, and tools guided by engineering design research, with which we may understand the many areas of wave energy research and forge a pathway forward.

All together, the chapters of this thesis help us understand the reasons for the slow progress of marine energy thus far and suggests ways that we might be able to speed up progress in technology development. While completing this work, I have noticed a considerable discontinuity between wave energy system design and the ecological problem of climate change which motivates it. In engineering design, arguably the most important and most highly emphasized part of the design process is properly defining the problem which you are trying to solve. By looking at wave energy from the lens of engineering design and the imperative of good problem definition, one will notice that the problem of climate change is neither well articulated in relation to wave energy nor is it central to the design process. I plan to address these shortcomings in future work, by focusing my research on understanding the potential impacts of wave energy on climate change and on applying and developing design methodologies enable the complex web of technological, social, political, and ecological challenges to be integrated into wave energy system design. As action at many levels of citizenry and government builds to address climate change and global ecological crises, examining new energy technologies in relation to these urgent challenges will be important. Critically assessing design practice, which I have done in this thesis, and improving design practice to better align with the problem of climate change, which I hope to do in the coming years, are both actions which may be taken within any renewable energy technology field. Doing so might help us make difficult decisions in the near future about how and from what resources we convert energy for human use.

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APPENDICES

Appendix A

Altered From:
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Technical Submission Form

Altered From: Version 2.01

Diana Bull
Systems Analysis & Decision Support Department

Jesse Roberts
Water Power Technologies Department

Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-127

Kim Nielsen
Ramboll
Copenhagen, Denmark

Ben Kennedy and Ronan Costello
WaveVenture
Cornwall, United Kingdom

Jochem Weber
National Renewable Energy Laboratory
Golden, Colorado

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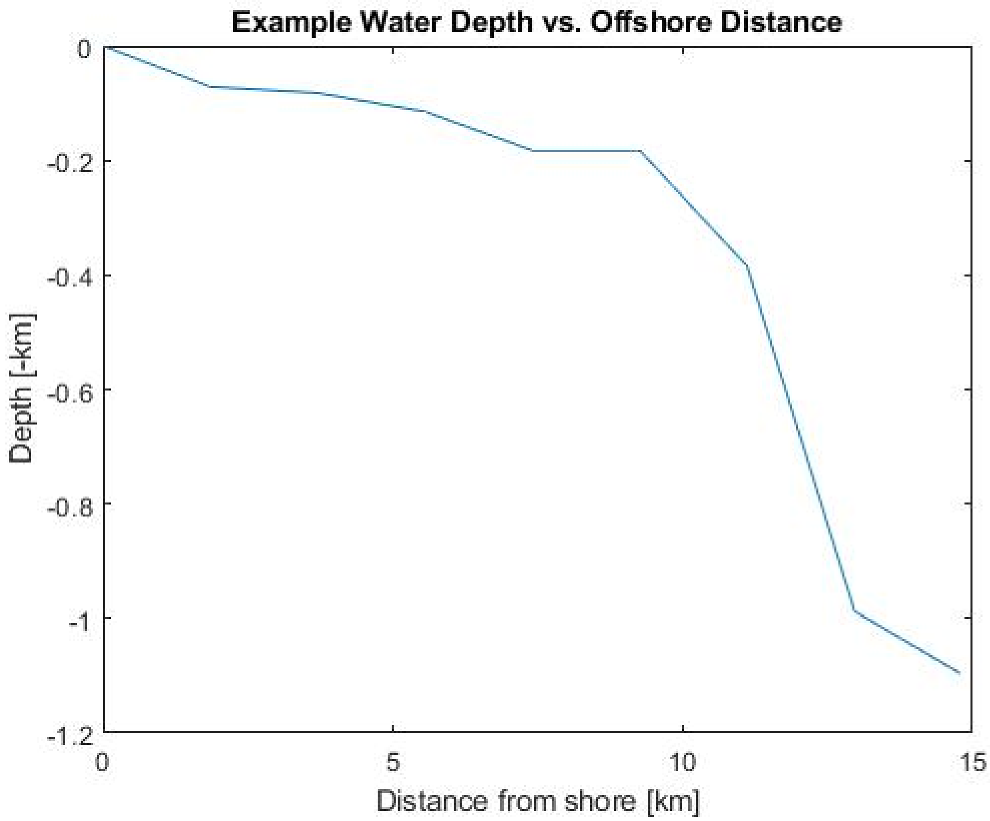
1. DEPLOYMENT LOCATION

Some of the information about the deployment location is provided in this section. We recognize that these are not consistent with a real location. They are simplified for the scale of this workshop.
Wave Resource: 40 kW/m wave crest
Model Spectrum: Pierson-Moskowitz Spectrum
Significant Wave Height: 4m
Peak Period: 8s
Bottom type: sand with some rocky bottom within 1 km of shore, sand further offshore
Other uses: Fishing, Boating, shipping
Species of Concern: Pacific Salmon, Blue Whales, Fin Whales, Humpback Whales, Black Abalone, White Abalone



1.1. Interaction with Surrounding Environment

The purpose of this section is to describe an steps you have taken to avoid negative interaction with the surrounding environment.

Provide:

- Describe any aspects of the design intended to reduce possible environmental impacts of the WEC- including marine life, seabirds, sediment shift, or noise emissions.
- A description of the measures you have taken to avoid collision/ negative interaction with other users of the area (fishing, shipping, recreation, etc.)

2. ID 01 WAVE ENERGY CONVERTER DESCRIPTION

The purpose of this section is to provide a description of the WEC device and the list of identified subsystems.

Provide a short description of sub-subsystems involved in collecting wave power. The table may be adapted and completed to assist with this task.

Table System Identification table for WEC.

ID	Subsystem, sub-subsystem, component	Function	Material	Number per WEC device
01	WEC DEVICE			
0100	Collect Wave Power (Primary Converter)	Collect Wave Energy		
0101				
0102				
0110	Convert Power	Convert Wave Energy		
0111				
0112				
0113				
0120	Supporting structure	Provide structure for support		

2.1. ID 0100 Collect Wave Power (Device Primary Absorber)

The purpose of this section is to provide the information required to understand the primary absorber and to obtain estimates of the power absorption by the WEC device. A guide to making estimates of power absorption is provided in section 11.

Drawings of the device should include representations of each component. Hand- drawn sketches are satisfactory. System ID shall refer to ID numbers in the completed Table with relevant subsystems, sub-subsystems, and components.

Provide:

- A description of the overall working principle in all relevant configurations and modes of operations. Modes of operations should include power generation at rated power and shut down for maintenance purposes.

The description can include illustrations and should include information on:

- o The description of the working principle and modes of operations.

- A description of distinct physical configurations and envelope dimensions.
- The sensitivity to environment parameters (wave direction, tidal, current, wind, etc.).
- Any conditional changes in mode of operation
- Estimate of wave power absorption, and calculations showing how this was attained
- Identification of absolute and/or relative degrees-of-freedom (DOF) and/or modes of deformation and/or modes of operation, if applicable.
- Any other data relevant to estimating/verifying resting position in calm water.

Provide:

- Description of sensitivity to wave power, wave direction, and directional spreading.
- Description of sensitivity to tidal height, tidal current, wind or influence of mooring systems.

Summary Table

Table 7 should be filled in to provide a summary of the information requested in the section above.

Table Summary Table for Wave Power Absorption.

Parameter	**Unit**	**Value**	**Comment**
WEC Device power rating with J=40kW/m	kW		
Characteristic Dimension B	m		Provide note to support claim
CWR	%		Provide support
If applicable, expected effect of stroke limitation on wave power absorption	-	[Low/ Medium /High]	
If applicable, expected effect of tidal height and/or tidal current on wave power absorption	-	[Low/ Medium /High]	
If applicable, expected effect of wind on wave power absorption	-	[Low/ Medium /High]	
If applicable, expected effect of wave direction and directional spreading on wave power absorption	-	[Low/ Medium /High]	
If applicable, expected effect of mooring systems on wave power absorption	-	[Low/ Medium /High]	

2.2. ID 0110 Power Conversion

The purpose of this section is to present at subsystem level the elements involved in converting the captured power to transportable power.

Provide:

- A list of energy conversion steps at sub-subsystem level within ID 01. Include with reference to System Identification table for WEC and provide:
  - Sketches and descriptions of the conversion steps and systems involved
  - Estimate of converted absorbed power. Defend these estimates. You may look up typical efficiencies for the elements you intend to use. (The input power for the conversion chain will be the absorbed power described in the previous section.)
  - Details if the sub-subsystem that converts absorbed power into transportable power plays a role in withstanding extreme loads and responses.

2.3. ID 0120 Supporting Structure

The purpose of this section is to provide the information required for assessment of the structure of the WEC, including both areas that are intended to collect wave power and those that only provide only a structural element (i.e. structural elements whose main purpose is not to provide surface area for wave power absorption).

Provide:

- The mass for structural members that are not intended to collect wave power.
- Specification of quantities and materials types used.
- A description and summary of the overall geometry.
- Details of the connection points of power conversion system to the structure.
- Description of point loads and areas of stress concentrations.
- If applicable describe how strokes are limited (i.e. mechanical).
- Define how many sets of point loads (heave plate, mooring lugs, PTO, end stops) affect the subsystem that collects wave power. Note: Point loads occur when two bodies connect for which the forcing profiles are distinct (general hull withstands hydrostatic pressure combining with the PTO attachment at which thrust forces must be mitigated); special structural solutions may be employed to distribute the point loads across a wider area. Identify the type, number, and accessibility.

Summary Table

Table should be filled in to provide a summary of the information requested in the section above.

Summary Table for the Supporting Structure Data.

Parameter	**Unit**	**Value**	**Comment**
Mass of structure	kg		

Number connection points to Collect Wave Power	-		
Number of connection points to Control Position	-		

3. ID 02 CONTROL POSITION

The purpose of this section is to provide the information relating to the subsystem used to keep the WEC at its proposed position and how it works in the targeted environment.

Provide:

- Design drawings and descriptions of the method of controlling position.
- Specification of the materials used in the control position.
- A description of how the Control Position system is connected to the WEC.
- A description of how the Control Position is monitored.
- Overall dimensions of the mooring system layout
- Identification of connection points of to the WEC structure and seabed.
- A description or illustration of the point loads.
- Illustration and dimensions of the watch circle and footprint of the WEC.

Summary Table

Table should be filled in to provide a summary of the information requested in the section above.

Table Control Position Summary Information.

Parameter	**Unit**	**Value**	**Comment**
Footprint (distance to anchors)	m		
Watch circle diameter	m		
Excursion limit in the direction of prevailing wave direction of the most flexed connection point	m		
Connection points on seabed	No.		
Connection points on a Collect Wave Power	No.		

4. ID 04 ELECTRICAL WAVE POWER DELIVERY

The Electrical Wave Power Delivery system connects the converted power to the main grid at the shore. This can be via a DC or an AC connection – it could be an existing offshore hub – it could be anything that brings the power collected in the aggregation system to the shore. Other means of transporting the power to shore can be identified if appropriate.

Provide:

- The general method of power delivery to grid.

5. SURVIVABILITY AND RISK

The purpose of this section is to provide the information required for a preliminary assessment of the wave energy converter risk. Some of the areas that should be considered are:

- Survivability under extreme events from waves, wind, and current.
- Risk in the case of grid failure, grid loss, or grid interruption.
- Risk in case of collisions.

Provide:

- A description of the most susceptible subsystems (in terms of motions and loads) in the wave energy converter to increasingly energetic conditions and describe how these subsystems react to highly energetic waves or other environmental impacts.
- If those subsystems are impacted by highly energetic seas or other environmental conditions, will they become unsafe? Consider fluid spills, detached equipment, electrical hazards
- Details on the number of subsystems that may be significantly damaged by extreme events, grid failure, or interruption or in case of collisions.
- A description on the monitoring and control of wave energy converter operations.
- A description of any subsystem that is able to reroute power from one source to another.
- A description of how the wave energy converter can easily be detected by other users of the area.

Fill out the Summary Table for Risk below giving the likelihood and penalty of each risk on a scale of 1-5, 1 being low risk/cost and 5 being high risk/cost.

Summary Table for Risk.

Risk	Likelihood	Penalty/Cost of actualized risk

Note: Mechanisms used for signaling to other users of the area as well as the location of the subsystems within the water column should be described with a reference to drawings.

6. RELIABILITY, DURABILITY, AND MAINTENANCE

The purpose of this section is to provide the necessary information required for a preliminary estimate of reliability and durability of the chosen technology involved. The more reliable the less maintenance cost and higher the availability of the wave energy farm.

Technology Class	Definition
1	No new technical uncertainties
2	New technical uncertainties
3	New technical challenges
4	Demanding new technical challenges

Provide the technology classes used in the wave energy farm:

TRL 1-2: subsystems (highest level of the ID table)

Table Identification of Technology Class.

ID	Subsystem, Sub-subsystem, Component	Application		Technology			Technology class
		Known	New	Proven	Limited history	Unproven	
01	WEC DEVICE						
0100	Collect Wave Power (Primary Converter)						
0110	Convert Power						
0111	i.e. Hydraulic rotary motor						
0120	Structure						
02	CONTROL POSITION						
03	WAVE POWER AGGREGATION SYSTEM						
04	ELECTRICAL WAVE POWER DELIVERING SYSTEM						

6.1. Reliability and Durability

The purpose of this section is to describe the reliability of the WEC. This includes assessment of the likelihood of systems, sub-systems, or sub subsystems that could give reason for UNPLANNED maintenance (reliability), as well as identifying systems, sub-systems, or sub subsystems that will require PLANNED maintenance (durability).

Provide:

- Details, for the subsystem and sub-subsystem, of the well-known possible failure modes caused by circumstances such as: shock, chemical attack, corrosion, wear, fatigue, thermal, abrasion, corrosion, thermal overload, clogging, and photolysis, other.
- Details of the life time of subsystems (here the table below was useful).
- A ranking of the subsystems, sub-subsystems, and components according to the frequency and cost of both planned and unplanned maintenance on the same 1-5 scale as above

Table Ranking of Maintenance Frequency and Cost

ID	System, Subsystem, Component	Planned Maintenance		Unplanned Maintenance	
		Frequency	Cost	Frequency	Cost

01		WEC DEVICE				
	0100	Collect Wave Power (OWC)				
	0110	Convert Power (air turbine / generator)				
	0120	Structure				
02		CONTROL POSITION				
	0200	Pile Anchors				
	0210	Mooring lines				
03		WAVE POWER AGGREGATION				
	0300	Dynamic electrical cables				
	0310	Sub-sea hubs				
	0320	Intra-array electrical cables				
	0330	Substation/Platform				
	0340	Trafo station				
	0350	Intra-array electrical cables				
04		ELECTRICAL WAVE POWER				
	0410	Substation/Platform				
	0420	HVDC Trafo station				
	0430	HVDC cables				

6.2. Maintenance Process and Requirements

The purpose of this section is to present a storyboard description of planned and unplanned maintenance activities for the wave energy farm. This information is required for a preliminary estimate of the wave energy farm maintenance cost.

Provide:

- A description of maintenance strategies, processes, limitations, and timelines.
- A description of key systems and subsystems that require maintenance.
- Details of required equipment and infrastructure (ships).
- The quantities, size, and masses of items being maintained.

7. AVAILABILITY

The purpose of this section is to provide information on the availability of the wave energy converter. Availability factor expresses on an average annual basis how much power is lost due to planned and unplanned maintenance.

Provide:

- Details of the target availability for the overall wave energy converter.
- Details of subsystems with failure modes with consequent reduction in power production.
- A description of any redundancy in the subsystem.

- A list of the top 10-15 failures along with their likelihood and cost ranked on the 1-5 scale

ID		System, Subsystem, Component	Failure		Unplanned Maintenance	
					Likelihood	Cost
01		WEC DEVICE				
	0100	Collect Wave Power (OWC)				
	0110	Convert Power (air turbine / generator)				
	0120	Structure				
02		CONTROL POSITION				
	0200	Pile Anchors				
	0210	Mooring lines				
03		WAVE POWER AGGREGATION				
	0300	Dynamic electrical cables				
	0310	Sub-sea hubs				
	0320	Intra-array electrical cables				
	0330	Substation/Platform				
	0340	Trafo station				
	0350	Intra-array electrical cables				
04		ELECTRICAL WAVE POWER				
	0410	Substation/Platform				
	0420	HVDC Trafo station				
	0430	HVDC cables				

8. MANUFACTURING AND TRANSPORTATION

The purpose of this section is to provide a storyboard description of the key stages of the manufacturing and production and transportation processes involved in building the wave energy converter.

Provide:

- A description of the production processes and facilities, key activities at factory, at harbor or in the ocean (final assembly).
- Details of subsystems of technology class 3 & 4 that need to be custom-manufactured and the quantity.
- A description of the transportation process.
- Key dimensions and masses of subsystems being manufactured.
- Envelope dimension of parts that need to be transported to the installation staging point.
- Safety concerns in manufacturing and transportation and any steps you have taken to mitigate these in your design

9. INSTALLATION

This section describes how the subsystems of the wave energy farm will be installed. The installation process must consider the weather conditions, the required time to complete each part of the installation, maximize the use of readily available vessels, and minimize the need for skilled workers.

Provide:

- A description of the key stages and activities of the installation process.
- A description of assembly points and connections.
- Details on the required equipment and infrastructure (types of installation vessels & ships).
- The masses and envelope sizes of subsystems being transported to and maneuvered within the installation area.
- Safety concerns in installation and any steps you have taken to mitigate these in your design

10. POWER SUMMARY

The purpose of this section is to summarize information related to power throughout the entire wave energy farm.

Provide:

- The expected WEC rated power.
- A description of any aspects of the system that could decrease power production.
- Any data relevant to estimating/verifying power absorption or transfer. Defend your estimate of CWR
- Details of each stage of Power Conversion and the losses expected at that stage

11. POWER ABSORPTION CALCULATIONS

The power absorption of your device will be highly dependent of the wave distributions at the sight. We have simplified these calculations so that you do not need to deal with the wave distributions when making calculations. Despite this, the distribution of wave heights and frequency provided in Section 1 should be qualitatively considered when designing your WEC. That qualitative description is required in Section 2.1

In Section 2.1 you are ask to provide 3 quantities: WEC device rating (absorbed power P at wave resource J=40 kW/m) , Characteristic dimension B, and Capture Width Ratio CWR.

P=J*B*CWR

First find B for your device, then use the look-up table below to estimate CWR, then calculate P.

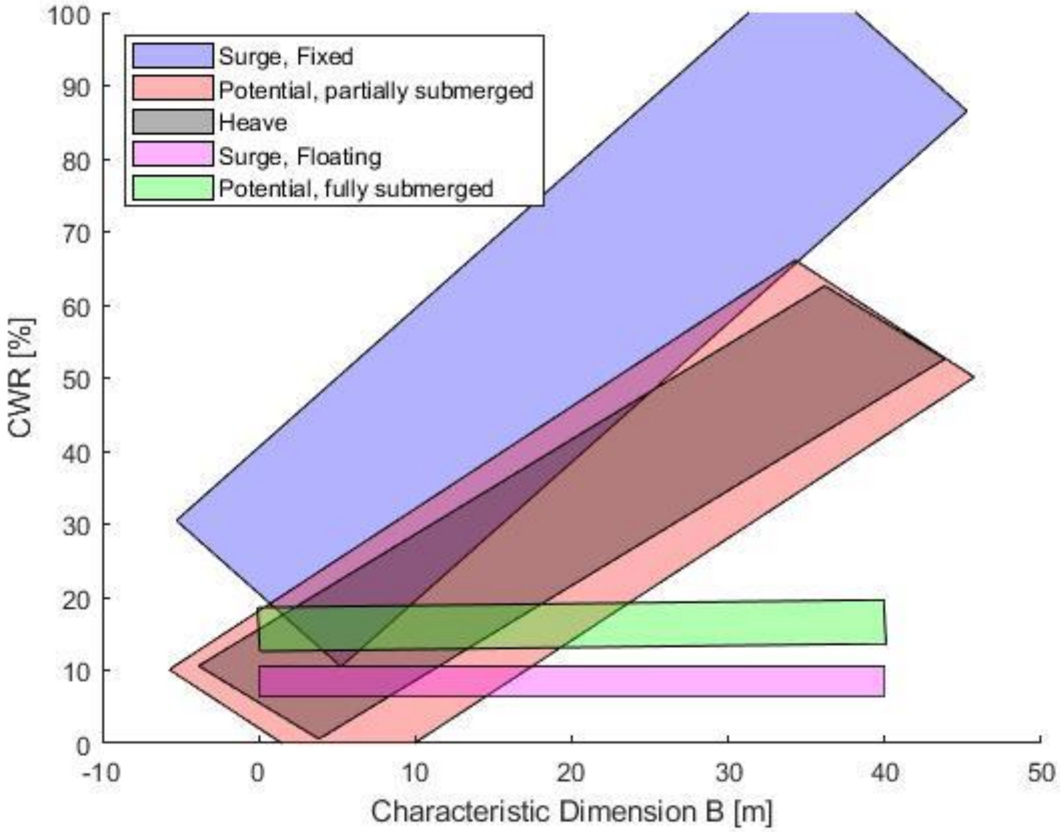
The characteristic dimension B depends on the type of wave motion that is being exploited for capture (surge, heave, wave height/potential).

For surge and potential devices: B= width of the components active in primary absorption

For heave devices: $B=\sqrt{\frac{4A}{\pi}}$ where A=the horizontal cross-sectional area of primary absorption components

Once you have estimated B and identified the type of wave motion you are working with, use the look-up table below to estimate CWR. The table also makes some distinctions based on whether the device is partially or fully submerged or if the device is fixed or floating (a device which is attached to the ocean floor via moorings for station keeping is not considered "fixed"). If you have any trouble figuring out where your device falls, ask your stakeholders!

LOOK-UP TABLE FOR CWR
***questions for where you device is on this table can be directed to stakeholders**



Within the approximations given by the look-up table, you may also consider other indicators to approximate power absorption (such as limits to swept volume or influences of other subsystems on power absorption).

12. REFERENCES

1. D. Bull, R. Costello, A. Babarit, K. Nielson, C. Bittencourt Ferreira, B. Kennedy, R. Malins, K. Dykes, J. Roberts, J. Weber, "Technology Level Performance Assessment Methodology." SAND2017-4471. Sandia National Laboratories, Albuquerque, NM, April, 2017.

Appendix B

TPL Question Relevance- Cost of Energy

Cost of Energy Capability Question	Relevance
For the system used to transport power from the WEC to the grid, is the system reasonably priced and does it scale well with distance and array size?	3
How efficient is the device at absorbing wave energy? Calculate the capture width ratio for two specified spectrum and average the results. The rules for the spectrum are on line 60 of the TPL scoring worksheet of this spreadsheet. Capture width (CW) is the power divided by the resource (kW/ (kW/m)). Capture width ratio is CW/B where B is the characteristic dimension (diameter for a point device).	2
Is the theoretical limit for energy absorption by the wave power collecting systems units large (# of DoFs and types, orientation, Budal limit)?	3
If applicable, how is the motion and range of the absorbing elements of the wave power collecting systems mechanically limited?	3
In production volumes what is the estimated manufactured and assembled cost of the WEC device in dollars per rated MW? This is for the WEC device only and does not include any balance of station or development costs. Rated power is defined here are the maximum sustained output of the WEC device to the collection system.	3
Does the device need to have multiple configurations to limit stress in high energy situations, increase energy capture, or for another reason? How much additional equipment (actuators, sensors, etc.) and structure, beyond what is needed for energy capture in a static configuration, is required to support the transformation?	2
Can the WEC device absorb energy effectively over a wide range of wave resources that are expected for early development? Is the WEC insensitive to wave direction.	2
What is the cost of the system that converts mechanical power to usable power?	2
What is the cost of power conditioning equipment such as inverters and transformers or pumps and accumulators?	2
For the controller, how much additional equipment (actuators, sensors, etc.) and structure, beyond what is needed for energy capture in an uncontrolled configuration, is required?	2
What type of installation vessels will be needed for 1 MW of capacity? This can include multiple devices up to 1 MW if they can be deployed in one trip. Guidance should scale for larger devices	2
What is the most difficult remove and replace maintenance task expected/likely on the WEC during its operating life, either due to mass and size requiring a crane or due to the coordination of divers and lift equipment that is expected to take place during the life of the WEC?	2
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)?	1
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?	1
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)?	1
For an expected depth, is the station keeping system inexpensive and relatively simple	1
Does the cost and complexity of the station keeping design scale well with depth?	1

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.	1
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.)?	1
What expertise is needed from the workforce (dependent upon: material type, level of tolerances that must be achieved, specialized safety, customized molds, etc.)?	1
Are any of the major structural or shell components complex to form?	1
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 (i.e. they cannot be transported on conventional trains or trucks)? I.e. they are not available from a shore side manufacturer.	1
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?	1
How fast can the WEC be transported from the dock to the installation site and how weather/sea-state dependent is the tow?	1
What are the weather window requirements for installation?	1
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?	1
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?	1
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?	1
Is the energy absorption by the wave power collecting systems sensitive to tidal height, tidal current, or wind?	1
What is the influence of the station keeping system on energy absorption?	1
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? What is the design average combined energy conversion and transmission efficiency? This does not include the efficiency of converting wave energy to mechanical energy. Use average energy input over average energy output over a year of operation in the design operating resource.	1
Within the WEC, what is the target ratio of instantaneous peak to mean power for the energy conversion drive train? Instantaneous peak power is defined here as the maximum output of the energy conversion component. For mean power calculate the power based on rules provided on the TPL scoring worksheet of this spreadsheet line 60.	1
How many conversion steps are there after the output from the individual WEC device to the POC (point of connection)? What is the design combined average energy efficiency of the conversion steps? So from the energy leaving the WEC device to the POC. Loses in the WEC are not included here	1
For each part of the power collection system, what is the target ratio of peak to mean power? Are peak power surges smoothed within the WEC device or is the power collection system required to handle the peak values? In this question peak power is instantaneous power during the wave cycle and mean power is the average power as defined on line 60 in the TPL scoring worksheet of this spreadsheet.	1
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?	1
What are the limiting sea states that allow maintenance access?	1

TPL Question Relevance- Investment Opportunity

Investment Opportunity Capability Question	Relevance
Can the WEC device absorb energy effectively over a wide range of wave resources that are expected for early development? Is the WEC insensitive to wave direction? Was the performance modeling done with validated tools that give a high confidence in the projected performance?	3
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?	1
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?	1
Are new manufacturing capabilities and/or new workforce expertise needed to construct the WEC?	1
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? .	1
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?	1
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? .	1
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?	1
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?	1
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?	1

TPL Question Relevance- Grid Operations

Grid Operations Capability Question	Relevance
Can the WEC device absorb energy effectively over a wide range of wave resources that are expected for early development? Is the WEC insensitive to wave direction.	2

TPL Question Relevance- Benefit to Society

Benefit to Socitety Capability Question	Relevance
How many operating jobs (life of the project) will the WEC contribute to the local community where it is deployed in a farm, in units of FTE/GW (the full time equivalent jobs per GW installed capacity)?	2
How many construction/manufacturing jobs will the WEC contribute to the local community where a farm is located during farm construction, in units of FTE years/GW (the full time equivalent job years per GW installed capacity)? This includes local manufacturing and assembly if that is normally able to be done locally.	2
How many jobs will the WEC contribute to the local community where it is manufactured, in units of FTE/GW (the full time equivalent job years per GW of manufactured WECs)? This includes local manufacturing, logistics, engineering, design, management, administrative, etc. This does not include jobs local to the installation site if some manufacturing is done locally to the WEC installation.	2
How long will it take for the WEC device to repay its energy debt? Include energy for the material production, manufacturing of components, procurement, construction and decommissioning.	2
What is the expected lifetime of the WEC device?	2
Is the WEC and its components recyclable?	1

TPL Question Relevance- Safety and Function

Safety and Function Capability Question	Relevance
For the WEC, are subsystems at risk of damage by grid failure, grid loss or grid interruption?	3
Does loss of grid result in a safe state for the WEC device? Can it continue to protect itself and be in a state that is safe for extreme conditions?	3
Can a WEC operate without the grid even in a reduced capacity and power other WECs?	3
Does the design require personnel to work in or under the sea? (e.g. divers)	2
Does the device need to have multiple configurations to limit stress in high energy situations, increase energy capture, or for another reason? If so how complex (Risky and or slow) is the transformation? A change in depth is a simple change. Even so it should be evaluated for reliable (i.e. how many points of failure and are they reliable or redundant) or failsafe operation. A change in orientation (for instance vertical to horizontal) of the WEC or a major part of the WEC is complex and requires careful evaluation of risk.	2
Has a safety philosophy been incorporated into the design process? (E.g. Adopt best practice and appropriate formal standards at design stage. Appoint a responsible person to take charge of safety. Review design for safety early, design out risks early. Design in mitigation for risks that cannot be eliminated. Ensure designers are suitably qualified and trained. Keep appropriate records...)	1
Is there a threat to human health and safety during any of the life cycle stages? (Consider all life stages from design, manufacturing, assembly, lifting, transport, installation, operation, maintenance, removal, decommissioning etc.)	1
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?	1
Is any lifting by crane done at sea?	1

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)	1
What is the design probability of WEC loss?	1
Can the WEC be easily detected by other users of the area?	1
In the event of a collision, is the WEC able to mitigate damage?	1
For all expected orientations and configurations other than during operation and survival, is the WEC as safe and survivable?	1
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?	1

TPL Question Relevance- Permitting and Certification

Permitting and Certification Capability Question	Relevance
Given the desired farm rated power along with the expected footprint what is the proposed area the farm will occupy per rated farm power? Use the layout of a typical array and the dimensions from the outside of the outermost anchor to the outermost anchor on the other side in both directions to calculate the footprint area. Use the rated power of the WEC devices times the number of devices for the denominator.	2
Are there any characteristics of the system and its impact on the environment that restrict its application in environmentally sensitive locations?	2
Are there any characteristics of the system that produce an impact on wildlife that would restrict its application where threatened or protected species exist? For instance whales and other marine mammals.	2
Can the technology form a farm that could co-exist with other potential users of the area? (e.g. fishing fleet, surfers, shipping, sailing area, etc.).	1

TPL Question Relevance- Globally Deployable

Globally Deployable Capability Question	Relevance
What is the minimum feasible wave resource for attractive LCOE?	3
What is the theoretical global wave energy capacity that is suitable for capture by the WEC farm (estimated global size of the resource that can be exploited by the WEC farm taking into account physical site conditions, manufacture and installation logistics and port infrastructure)?	3
Can manufacturing, construction, assembly, and installation capability and infrastructure be found or easily developed at many coastal locations, as needed, to develop a farm?	2
What is the water depth requirement to deploy the WEC farm?	1
What geophysical conditions are required to deploy this concept?	1
What is the sensitivity tidal range?	1
What is the sensitivity to current?	1
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.)?	1