A conceptual design tool for high-performance wave energy converters for Blue Economy applications

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***Abstract*—Much like wind energy in its early years, marine energy has vast potential, and wave energy converter (WEC) concepts are constantly in development. Consequently, wave energy faces many challenges for expansion and has a wide-ranging design space of WEC concepts. The large design space demands new methods for understanding the potential performance of early-design stage concepts. The Technology Performance Level (TPL) metric has been a proposed method for early-stage concept assessment. However, previous research has shown that the TPL is not designed in such a way that it is able to distinguish between multiple early-stage, low-fidelity concepts. We created a conceptual design tool to complement the TPL assessment to help wave energy developers during the design stage, rather than a quantitative assessment metric. The tool guides marine energy developers during the conceptual design of a wave energy converter by presenting designers with established practices, asking if their concept can meet these practices and constraints, and providing design feedback based on the answers. In this paper, we document the architecture, content, and results from our first tests of the tool. While limited in the number of participants, this study serves as a proof of concept of the tool's ability to impact design decisions during concept generation. These results also provide insight for further improvement of the tool's structure and content. Creating awareness of oversights early in the design process will help wave energy developers effectively engage stakeholder requirements, increasing the appeal of a wave energy converter concept to marine energy stakeholders.**

***Index Terms*—conceptual design, design tool, engineering design, wave energy converter.**

I. Introduction

In response to the global climate crisis and ever-increasing global energy consumption [1], renewable energy sources such as marine energy continue to be developed. Wave energy does not require significant land use compared to other renewable energy technologies [2] and can provide a reliable carbon-free energy source to remote coastal communities and other Blue Economy applications [3]. Blue Economy applications often refer to non-grid markets like aquaculture, desalination, and ocean observation. These sectors are particularly interesting for wave energy as they provide an opportunity to develop competitive, carbon-free energy technologies. Despite this potential, there are still gaps in knowledge that researchers and developers need to overcome to make this a economically viable alternative.

In wave energy converter (WEC) development, significant effort is put into problem definition through resource assessments, economic analysis, and local community surveys. Similarly, a great deal of time is put into product development through hydrodynamic modeling and scaled tests. Literature suggests that few developers are conducting concept evaluations before model validation [4], [5], and that many wave energy developers commit to an archetype before conceptual design begins [4]. This may limit developers to the overall performance constraints of the initial concept. According to Weber [6], this behavior is because the key to funding in the wave energy sector is fast demonstrations of technological readiness. The limited selection of early concept evaluation tools for wave energy may also help explain this phenomena. As we discuss in Section II-B, these tools are indeed helpful for developers, but have some limitations. Discovery of a major problem late in design can lead to longer development, costly redesign, and lower technological performance. Individual setbacks stall development of the marine energy sector as stakeholders may lose trust in the robustness of marine energy.

Previous work demonstrates that design tools and guidelines can help increase a designer's focus on goals and requirements [7], and that better design practices lead to better products [8]. We are aware of little work to date that applies these findings to wave energy, indicating a need for more research in wave energy on best practices that enable the design of high-potential WEC concepts. Identifying oversights early in the design process will help wave energy developers effectively engage stakeholder requirements – increasing the appeal of a wave energy converter concept to marine energy stakeholders. In this paper, we propose the Blue Economy Quiz, a conceptual design tool to help wave energy developers embed stakeholder and industry knowledge at the concept generation phase. The Blue Economy Quiz employs a similar methodology to an existing sustainable product design tool that increases sustainable design decisions during concept generation [9], [10]. Through the research and testing

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of the Blue Economy Quiz, we hope to increase design decisions during concept generation - providing developers more opportunities to integrate stakeholder and industry knowledge into their designs. Section II of this paper reviews the existing literature and tools. Section III presents the Blue Economy Quiz and initial testing with Oregon State University's Marine Energy Collegiate Competition team. Section IV presents and discusses the results of the tests, and section V provides concluding remarks and a discussion on future work.

II. Literature Review

A. Concept evaluation tools in engineering design

From product discovery to end of life, engineering design encompasses techniques enabling high-quality and cost-effective products [8]. Engineering design research includes varying definitions of product design stages, but all have a similar focus on the early design phase of product discovery [8]. Conceptual design is one phase in this process, covering the steps of concept generation, concept evaluation, and concept selection. The impact of the early engineering design process may seem insignificant, but design decisions made during concept generation contribute a decrease in manufacturing costs while comprising only a fraction of the manufacturing budget [8]. Thus, it is crucial that designers actively focus on the way they think about and engage with early design as these methods help create successful complex mechanical products.

Before proceeding, it is important to define *concept evaluation*. In engineering design, concept evaluation often makes comparisons between multiple concepts against the requirements of the project, providing designers with a method for selecting a concept. These evaluations can be used to make design decisions, allowing the designer to refine or improve a concept. These comparative methods are numerous, including Pugh charts, concept screening, fuzzy set theory, and utility analysis [11]. In this paper we will examine individual concept evaluation tools that are used to improve design decisions during concept generation.

Design for X (DfX) is the application of design processes toward typically later-design-stage objectives, allowing designers to focus on a particular objective or set of objectives. These categories can cover many areas such as Design for Manufacturing (DfM), Design for Environment (DfE), Design for Assembly (DfA), and Design for Reliability (DfRL) [12]. Many DfX tools integrate the knowledge of a specific area into preexisting methods to help designers achieve the goals of said area. Novel methods are also developed, though Benabdellah et al. [12] found that many novel methods are complex, time consuming, and often do not consider the entire life cycle of a product.

As an example DfX approach and as a close analogy to the consideration of diverse design objectives in the design of wave energy converters, Design for Environment research has focused on these issues as they relate to product design [9], [13]–[16]. DfE studies find that early incorporation helps reduce the environmental footprint of a product [15]. DfE specifically integrates knowledge that helps reduce environmental degradation caused by poor design decisions. Tools for DfE fall into many categories, the most recognizable being the life-cycle assessment/analysis (LCA). LCAs are used in many industries and help designers understand the overall environmental impact of an existing product. While the LCA is helpful in understanding the detailed impact across the product's life, the need for a completely finished product does not make this a good early concept evaluation tool. Other engineering design work investigates incorporating LCAs earlier in product development, yet these are still completed after establishing a concept [13] and cannot be used during the concept generation phase.

Other DfE tools include guidelines and checklists which are generally comprised of generic information that designers can apply to their concept. One popular version of this tool is "The Ten Golden Rules," which is a tool that covers holistic life cycle aspects designers should consider [16]. These types of tools are useful for designers because it prompts them to apply these rules to the specifics of their product and can be used multiple times during conceptual design [16]. The issue here is that designers often need some experience to apply these guidelines and develop solutions for their concept [16].

The GREEn Quiz (Guidelines and Regulations for Early design for the Environment) is a novel DfE tool for helping designers integrate knowledge at the concept stage [9], [10]. This tool compiles DfE knowledge from multiple sources, like established DfE checklists and guidelines, into an accessible concept evaluation tool for designers of all skill levels. The GREEn quiz uses a search tree to prompt designers with multiple choice questions about established DfE knowledge and, based on the answers selected, provides a feedback report [9]. The feedback presents the designer with recommendations on how to make the concept more sustainable [9]. This methodology was compared against using no tools or even using established DfE checklists and guidelines, with the results demonstrating a positive impact on the number of deliberate sustainable design decisions designers make during concept generation [9], [10].

The positive impact of the GREEn Quiz falls in line with other studies demonstrating that structured design tools help increase a designer's focus on goals and requirements [7]. This effect can be explained through priming, a subject studied extensively in engineering design and other fields [17]–[19]. Priming is a psychological method that presents information that engages a mindset impacting a subsequent activity [20]. In engineering design, many studies look at how priming can be used to effect the concept generation process and find that priming helps generate innovative designs with no decrease in feasibility [21].

B. Wave energy design and concept evaluation

There is a large potential set of complete solutions—commonly called the *design space*—for wave energy converters. Each WEC archetype harnesses the ocean's energy differently, and each design concept within that archetype can use different kinds of wave motion. This variety already implicates a large number of research and development topics such as shape, controls, mooring, and electricity conversion. Wave energy developers must embrace innovation and economic value while simultaneously considering numerous stakeholder requirements in order to become a competitive energy alternative. When this already-complex design space is combined with growing interest in Blue Economy applications, it is clear there is a need for design strategies that aid developers in tackling these challenges. Research groups like the WaveSPARC (Systematic Process and Analysis for Reaching Commercialization) and DTOcean/DTOceanPlus projects seek to provide the industry with development methodologies and tools that enable innovation.

The WaveSPARC project is comprised of teams at at the National Renewable Energy Laboratory and Sandia National Labs and is funded through the United States Department of Energy. The goal of this project is to provide industry with tools and methodologies to develop high performance wave energy converters that also integrate stakeholder requirements [6]. The WaveSPARC teams developed the Technology Performance Level (TPL) assessment to quantify how well a technology performs in relation to its holistic economic capability [6]. The TPL assessment requires an assessor to answer questions about seven distinct categories, with each category addressing aspects impacting the techno-economic performance of a wave energy converter (WEC). Each of these categories were determined by identifying customer requirements through a stakeholder analysis. These categories are [6]:

1) **Cost of Energy:** Entails the factors that contribute to a competitive energy cost, such as capital expense and operating expense.
2) **Investment Opportunity:** Includes the uncertainty associated with the cost of energy and factors relating to how well a WEC can survive at sea.
3) **Grid Operations:** Answers the question, "Will the WEC be good for grid-scale use?"
4) **Benefit to Society:** Incorporates the impact on local communities and environmental impact over the entire life cycle of the WEC.
5) **Permitting and Certification:** Determines the environmental and ecological impact and the ability of the WEC to coexist with other ocean users.
6) **Safety and Function:** Discusses the safety over the entire lifecycle of the WEC.
7) **Globally Deployable:** Determines the conditions that determine where the WEC can be deployed.

The questions in the TPL assessment require extensive information from developers in order to choose accurate responses. This information is submitted prior to the evaluation, allowing for a WEC expert assessor to review and ask for any additional information they may need to accurately score the technology.

The Technology Readiness Level (TRL) metric determines how ready a technology is for the market by measuring the maturity of the technology, or how far along it is in development. The creators of the TPL assessment employ it alongside the TRL metric to help drive WEC technology to high-performance at early readiness levels [22]. Starting early development at a high TPL will provide wave energy developers with a footing to reach the highest TPL by the time the WEC is ready for market entry [6].

The TPL assessment report is designed to help developers identify areas of improvement and increase the performance of the device through redesign. As previously discussed, early guidance helps designers create better concepts. However, the complexity of the WEC design problem requires the evaluation and feedback to be more tailored to the design stage. Previous research dictates that early concept changes have a low impact on the TRL, and that while using engineering design methods during concept generation can increase the technological performance level, the TPL assessment doesn't quantitatively differentiate between multiple low fidelity designs [23]. This is due to the amount of technical information that is required by TPL assessment to complete the evaluation and is not an issue inherent to the TPL assessment.

The DTOcean and DTOceanPlus projects are comprised of international teams of academic, government, and private researchers and are funded through the European Union's FP7 and Horizon 2020 program, respectfully. The goal of these projects is to provide open-source design tools for the "development and deployment of ocean energy systems, aligning innovation and development processes with those used in mature engineering sectors" [24] across all stages of WEC development. There are many modules of DTOceanPlus, with the tools relating to concept evaluation being:

1) **Structured Innovation tool:** This uses established design methods to help with concept generation and selection [25].
2) **Assessment Design tools:** These calculate parameters used for technology benchmarking [26].
3) **Stage Gate tool:** This uses metrics to evaluate technology development [27].

Like the TPL assessment, the Stage Gate and Assessment Design tools are very helpful for the development of a concept because they accumulate wave energy design knowledge into a set of tools. However, these are used during product development, meaning these are used for a single, refined design [26], [27]. Thus, these tools could also have trouble differentiating between low fidelity designs.

DTOceanPlus' Structured Innovation design tool combines Quality Function Deployment (QFD), the Theory of inventive problem solving (TRIZ), and Failure Modes and Effects Analysis (FMEA) into a design tool for the sector [25]. The FMEA portion has users enter all information needed for the analysis and the results page tells the user which failure modes need to be redesigned [25]. The QFD/TRIZ portion of the tool has users enter all information for QFD and uses the functional requirements of QFD for TRIZ and benchmarking against current solutions [25]. This design tool is still in development and shows promise for wave energy developers, as it is applying widely successful engineering design methods. One limitation that arises with user-driven input is the potential oversight of stakeholder requirements and functional requirements. If the developer accidentally overlooks requirements during the project definition stage, this tool will not catch the mistake. These oversights can lead to low-performance concepts and potentially more negative public perception of wave energy.

III. Methodology

Performance evaluations for WEC design often require extensive information on a concept. This information can include anything from deployment plans to the maximum power capture or a combination of maximum power capture and a proxy for cost, such as device volume. Such evaluations require models and simulations, and sometimes tank testing validation. At the early design phase, developers may not have clarified details to calculate maximum power or considered details such as installation and deployment.

As part of our collaboration with the WaveSPARC team, we suggested the creation of a conceptual design tool that employs the knowledge of the TPL assessment to help developers embed crucial design knowledge early in WEC design. Instead of asking designers how they plan to deploy a WEC and then provide feedback based on the answer, a concept-phase WEC design tool should present designers with the restrictions of established practices and ask if their concept is able to meet these restrictions. This format is more accessible to designers of all skill levels and provides fast feedback during the early design stage. As previously stated, the early incorporation of guidelines helps designers focus on goals during design without reducing originality and feasibility. Catching oversights early in the design process will help designers effectively engage stakeholder requirements and increase the appeal of a wave energy converter concept to parties involved in the marine energy sector.

A. Software

The Blue Economy Quiz is a tool which reflects knowledge from both the Systems Engineering approach to grid-scale WEC design conducted by the WaveSPARC team and an emerging market stakeholder analysis performed by this research team at the Pacific Marine Energy Center (PMEC). The tool that provides designers of varied skill levels with the knowledge needed to improve low-fidelity concepts for emerging market applications. The Blue Economy Quiz is not an assessment tool for emerging markets, but a design tool for marine energy developers that can be used alongside other design methods.

The Blue Economy Quiz follows the format of the aforementioned GREEn Quiz, asking designers questions about their concept and providing design feedback based on the answers provided. This format enables understanding the extent that users are engaging stakeholder requirements, and is accessible to users of all skill levels as potential responses are pre-populated.

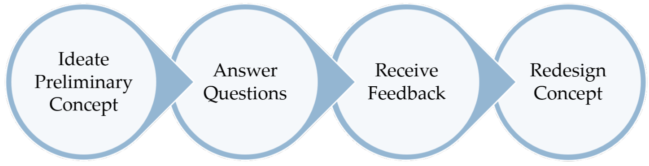

Fig. 1. The intended use of the Blue Economy quiz is to provide designers with a tool that can help increase the performance potential of their concepts early in the design process. It achieves this function by presenting multiple choice questions related to established design practices and asks the user to pick how well their concept meets the requirement. These answers determine a feedback report to help redesign the concept.

Fig. 1 illustrates how the tool is designed to be incorporated into concept generation. Questions are divided into six categories related to the Blue Economy:

1) Cost of concept
2) Investment opportunity
3) Use integration
4) Benefit to society
5) Safety and function
6) Permitting and global deployability

These sections generally align with the categories of the TPL assessment, with some notable distinctions. One new category, *Use Integration*, covers features that increase the capabilities of a WEC. We chose to combine the *Permitting and Certification* and *Globally Deployable* sections of the TPL assessment because these topics extensively overlap.

Through our collaboration with the WaveSPARC team, we conducted a stakeholder analysis for Blue Economy emerging market WECs (EM-WEC) [28]. This stakeholder analysis followed the first few steps of Quality Function Deployment [8] to define the stakeholder requirements of an EM-WEC in ocean observation, desalination, and autonomous underwater vehicles. More information about this evaluation can be found in [28]. The results of the analysis, alongside our research formed the basis for many questions in the Blue Economy Quiz. Some questions in each section are also transferable questions from the TPL assessment. These questions are not solely applicable to grid-scale devices and will be useful for all Blue Economy WEC developers [28]. Clarifications and definitions are included within the question prompt to provide the user with more comprehensive knowledge. Each question is paired with a set of user responses that indicate how well the concept satisfies the question, with some questions including an option of not having considered the topic. The number of responses varies for each question, with responses tailored to both the question's topic and the complexity of how a designer may have incorporated the idea, as seen in Table I. These answers are scored on a scale from zero to one, with zero indicating the designer has not considered the requirement or has not incorporated the requirement into their design, and one indicating the designer has fully incorporated the requirement. In this paper we refer to the zero scoring answers as "low" scoring, the answers between zero and one as "medium" scoring, and the one scoring answers as "high" scoring.

TABLE I: An example question from each section of the Blue Economy Quiz

Category	Question	Answer	Score	Feedback
Cost of Concept	Is the concept easily deployable by a common workboat?	We have not considered deployment of the concept	0	Outline the deployment (and maintenance) process early in design such that adjustments can be made to ensure that the device is deployable by common workboat. For the field in which you are working, determine limits for volume, weight, and mobility of a device.
		The concept is not deployable by a common workboat	0	Outline the deployment (and maintenance) process early in design using storyboarding techniques. You might consider adding modularity, switching to lighter material, changing mooring design, or making the device tow-able by boat. It may be beneficial to reach out to experts early in the process, such as the crew on ocean research of installation vessels. Reduce the costs of renting or buying specialized equipment. DTOceanPlus offers a Logistics and Marine Planning tool that you may find helpful later in the design process.
		The concept has few components with life spans shorter than that of the device	0.5	–
		The concept has no components with life spans shorter than that of the device	1	–
Investment Opportunity	Are most of the components of the system technologies which are already used in the marine environment?	Few/none of the components of the system are already used in the marine environment	0	Consider replacing some components with others which are already used successfully in the marine environment. These could be identified by looking at existing marine industries. Meeting with stakeholders such as marine contractors could help you identify components that could be replaced.
		Most of the components of the system are already used in the marine environment	0.5	–
		All components of the system are already used in the marine environment	1	–
Use Integration	Can the concept provide real-time data to operators?	We have not considered provide real-time data to operators	0	Determine if providing real-time data would increase the capability of the system. Meeting with stakeholders such as purchasers and operators could help with this decision. Looking at existing marine devices that provide data, such as ocean observation buoys, could help with the determining needed systems. When considering the system, remember to determine the energy needs of electronics.
		The concept cannot provide real-time data to operators	0	Consider whether the adding the ability to provide real-time data to operators could increase the capability of the system to perform its intended functions (within the design requirements). Meeting with stakeholders such as purchasers and operators could help with this design decision.
		The concept can provide limited real-time data to operators	0.5	–
		The concept can provide real-time data to operators	1	–

TABLE I: (continued)

Category	Question	Answer	Score	Feedback
Benefit to Society	Will the device lead to a reduction in carbon emissions during the early life cycle (manufacturing, assembly, lifting, transport, installation) of the device?	We have not considered the reduction in carbon emissions	0	List all life stages (from design, manufacturing, assembly, lifting, transport, installation) and consider sources of carbon emissions. Try replacing unsustainable materials with environmentally friendly alternatives and reducing reliability of harmful manufacturing practices, Involving manufacturers and marine contractors can provide important insight into how to make your system environmentally friendly. For more information regarding environmentally friendly design, refer to literature on Design for Environment and Design for Sustainability.
		The device will not lead to a reduction in carbon emissions	0	Consider ways to reduce carbon emissions during the early life cycle of the system. Try replacing unsustainable materials with environmentally friendly alternatives and reducing reliability of harmful manufacturing practices. For more information regarding environmentally friendly design, refer to literature on Design for Environment and Design for Sustainability.
		The device will lead to a reduction in carbon emissions	1	–
Safety and Function	Can the concept be detected by other vessels/people at sea?	The concept cannot be detected by others	0	Consider redesigning your system so that it is easy to detect by marine vessels or other people at sea. Interviewing other marine environment users may help you ideate ways to improve the system's ability to be detected. You may find common concept generation methods such as brainwriting or morphological matrices to be helpful with this redesign.
		The concept can be detected by others	1	–
Permitting and Global Deployability	Can the concept be disassembled/easily distributed?	We have not considered disassembly of the concept	0	Create a storyboard the disassembly of the process. This may help you understand potential issues that need redesigned. Replace components that cannot be disassembled or easily distributed with more mobile, modular components. Try to design components that require no advanced or uncommon manufacturing techniques and can be disassembled for transportation. Standardize dimensions and refer to Design for Assembly and Design for Manufacturing literature for further guidance.
		The concept cannot be disassembled or easily distributed	0	Consider replacing the components that cannot be disassembled or easily distributed with more mobile, modular components. This can be achieved by designing components that requires no advanced or uncommon manufacturing techniques and can be disassembled for transportation. Standardize dimensions and manufacturing steps, and refer to Design for Assembly and Design for Manufacturing literature for further guidance.
		The concept can be partially disassembled but requires oversize vehicles for distribution	0.5	–
		The concept can be disassembled and easily distributed	1	–

When a user takes the quiz, questions are served to them by category and the answers to each question are saved. Once a user has answered all the questions, the quiz compiles the scores for each category and normalizes the scores to ten, with higher scores indicating that a concept embeds more stakeholder requirements. The quiz provides designers with section scores and feedback if they selected low scoring answers - meaning they have either not considered or have not incorporated a stakeholder requirement. The design tool does not provide feedback for all answers, and is limited to the most relevant information that will improve the user's concept. The initial feedback page shows only the two lowest scoring categories for this same reason. Our experience with engineering design and the guidelines, rules, and feedback of other engineering design studies – discussed in section II-A – formulates the basis for the feedback. The feedback includes:

1) **Design strategies:** These are specific improvements designers can make to their system.
2) **Suggestions:** These are broad recommendations designers can make for improvement.
3) **Design methods:** These are actions designers can take to reach certain performance requirements.

Users also have the option to view feedback for the entire quiz, which is downloadable as a PDF for later viewing. The initial feedback page is cached so users can revisit the feedback page and download their feedback later if needed. Through the feedback, the tool will help designers identify specific changes and actions they can take to improve their system.

The Blue Economy Quiz is currently hosted [29] using the free web-hosting service Heroku and functionality is achieved through the open-source Django application *django-quiz* [30]. This package is a Django application we built, providing users with the functionality to build similar concept stage design tools and host the tool online. We update this package concurrently with the Blue Economy Quiz to maintain feature parity.

B. Experiment

The version of the tool presented in this paper is still in the early stages of development and there are planned improvements to the structure, content, and implementation. Nonetheless, it is important to investigate the efficacy of the current version of the quiz - in order to see how well the tool can help designers identify and make changes to their design. As the validity of this approach has been demonstrated in the product design space [9], [10], it is important to determine whether or not this methodology can be an effective tool for the wave energy sector. To test this, we hosted a design workshop for members of Oregon State University's (OSU) Marine Energy Collegiate Competition (MECC) team. We also worked alongside the OSU and University of Washington's MECC teams to get user feedback on potential improvements for the tool.

The MECC program funded by the United States Department of Energy and run by the National Renewable Energy Laboratory that tasks multidisciplinary teams of graduate and undergraduate students with designing, testing, and pitching a marine energy device for a Blue Economy application [31]. The purpose of the design workshop was to test the efficacy of the Blue Economy Quiz during concept generation. In the workshop, participants were paired into four groups and tasked to sketch a design of a wave-powered device for large scale desalination that satisfied a given a set of design objectives and constraints. After completing the concept, each group used the Blue Economy Quiz to get feedback that they used to redesign or improve their concept. Finally, each group was asked to use the Blue Economy Quiz a final time to evaluate their revised concept. From this workshop, we can make initial observations about the impact that the Blue Economy Quiz has on design decisions.

IV. Results and Discussion

A. MECC Workshop Limitations

This design workshop functioned as a proof-of-concept and user experience test for the Blue Economy Quiz. The limited sample size does not permit a statistical study of the tool's effectiveness or a comparison with existing methodologies. In this case, the workshop was hosted for two and a half hours. The time constraints of the workshop limited the feedback that could be acted upon during the redesign. For instance, one question suggests the designer complete a functional decomposition to reduce operational redundancies. Since the workshop was a few hours total, it would be difficult to fully follow this feedback for informed design decisions. Ideally, the start of the workshop would include an introduction to the design methods mentioned in the quiz's feedback and provide ample time for the design activity. Despite these potential shortcomings, the workshop successfully provided a preliminary test of the Blue Economy Quiz and helped to steer development plans and testing of the tool.

B. MECC Workshop

The setup of the workshop allows for measuring the decision-making ability of each group before and after taking the Blue Economy Quiz. Prior to using the Blue Economy Quiz, few groups addressed design decisions relating to the Blue Economy Quiz categories in their initial concept. An example of a design decision could be a unique feature or a text annotation, like in Fig. 2, that explains the function of the device.

The results of the design workshop with members of the Oregon State University MECC team are shown in Fig. 3 and Fig. 4. Fig. 3 shows the number of groups that reference a category within the Blue Economy Quiz, both before (Red) and after (Blue) using the tool to evaluate their concept. A group is only counted once per section, even if they referenced multiple aspects within a category.

Fig. 4 shows the change in answer composition by category of low scoring, medium scoring, and high scoring questions. As seen in Fig. 3, all categories expect permitting and global deployability had a design

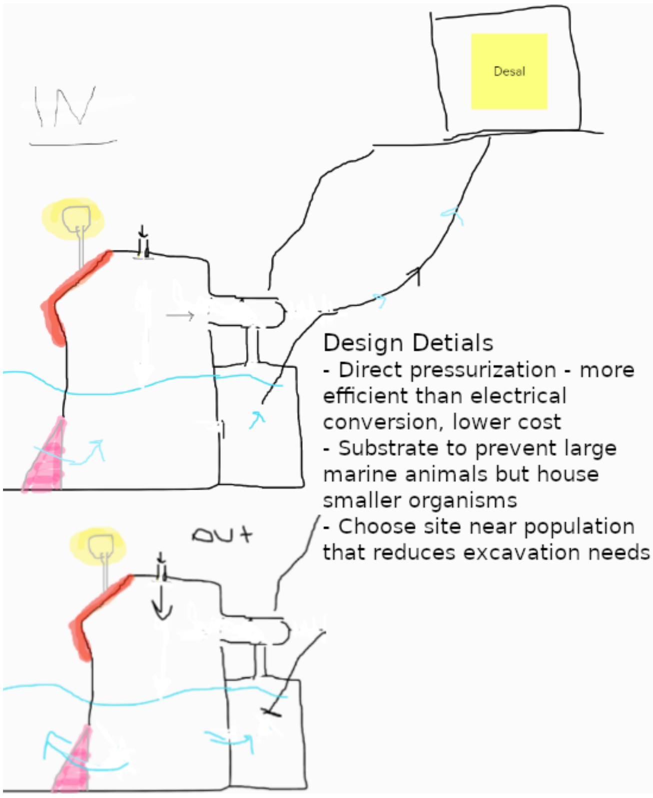

Fig. 2. A sketch of a WEC concept from the OSU MECC design workshop, before taking the Blue Economy Quiz. This group provided text callouts to help explain multiple design decisions. Note: the "Design Details" text of the image was enhanced to improve legibility.

decision by one group in the initial design. Four of the six category design decisions were made by one group, with all other groups only making one design decision in the initial design. After taking the quiz, three out of the four groups mentioned at least one design decision relating to every category. This indicates that even with limited time to process the tool's feedback, the knowledge is in a format that is easy to translate into design decisions. Furthermore, these results indicate that the questions of the Blue Economy Quiz cover topics that the designers had not initially considered. While the increase in design decision breadth follows the results found by tests of the GREEn Quiz [9], it is clear that we need more testing of this tool to determine the tool's effectiveness across a broad range of designers and a broad range of Blue Economy emerging markets.

As seen in Fig. 4, we see that the participants decreased the proportion of low scoring answers in each category. On average, increased the medium and high scoring answers through their redesign. These results are expected as low scoring answers often include an option for not considering the requirement presented. Nonetheless, this further indicates that the Blue Economy Quiz helps designers consider how they can refine their design to incorporate the requirements presented. While these results are not statistically significant due to the small sample size, the group choices can provide insight regarding focused testing and development of the quiz. It is important to note that each category does not have the same number of questions, so this analysis is only on the evolution of answer composition on a per-category basis and is not intended to compare answer composition between categories.

Based on these preliminary results, we could consider developing feedback for mid-level answers when a category score reaches a certain score threshold. This would help improve designs during structured concept generation methods, like Set-Based Design. Designers often refine concepts a few times in these methods, so providing mid-level feedback after a certain score threshold may help concepts reach a higher performance level. Future testing could incorporate a longer study, which could allow us to investigate not just if the feedback for low and medium scoring answers impacts a change on the design but also if that change is beneficial to the performance and stakeholder satisfaction of the design.

As discussed in Section II-A, engineering design studies show that early incorporation of guidelines helps prime designers to focus on goals during design while maintaining originality and feasibility. Since the Blue Economy Quiz appears to achieve our goal of helping designers incorporate requirements, it is important that we are vigilant in keeping these stakeholder requirements current. Incorporating dated or incorrect information may decrease the overall performance of a design and could be detrimental to the stakeholder's perception of a concept.

C. User Feedback

During the workshop we also received feedback on the Blue Economy Quiz's user experience. Workshop participants stated that the topics and feedback of the quiz is helpful, as it reveals topics they had not considered during initial concept generation. The OSU MECC team said this feedback impacted conversations the team had throughout the rest of the competition. The workshop participants also stated that some questions were hard to answer for their concept, either because the question did not directly apply or because they did not have enough information to answer the question. Currently, the quiz delivers the same question set to each participant regardless of the project, WEC archetype, etc. This is a limitation of the tested build, as not all projects have the same requirements. If the wrong requirements are presented to designers, this could lead to bad design decisions that may hinder the performance and stakeholder satisfaction of the WEC.

We can ensure that the right requirements are present to the user by incorporating filtering questions. These filtering questions will change the structure of the quiz to a search tree, allowing us to deliver more specific questions to the user and provide further clarification on restrictions of established practices. These filtering questions alongside a weighting system to help designers know which stakeholder requirements are the most important to incorporate. Additionally, some users stated that features to track progress may be helpful, which aligns with literature on user-focused survey design [32]. These improvements will ensure that taking the quiz is an effective use of time and will keep users engaged.

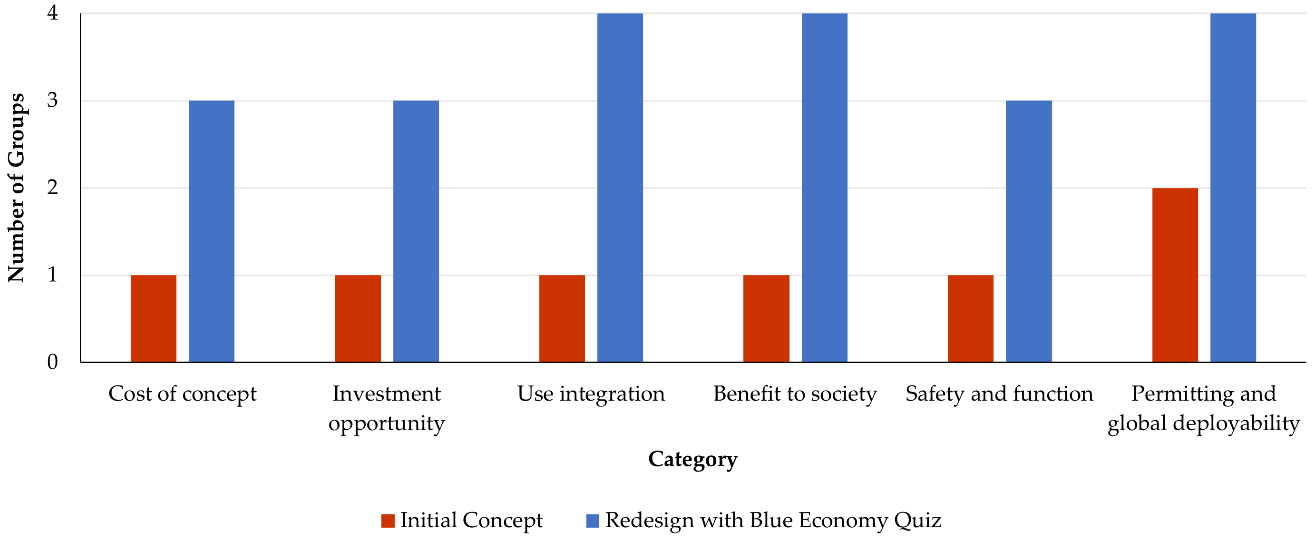

Fig. 3. Design decisions referenced in the concept sketch for each category, before and after taking the Blue Economy Quiz. These design decisions were only counted once per group in a section, even if they referenced multiple aspects within a category in their sketch.

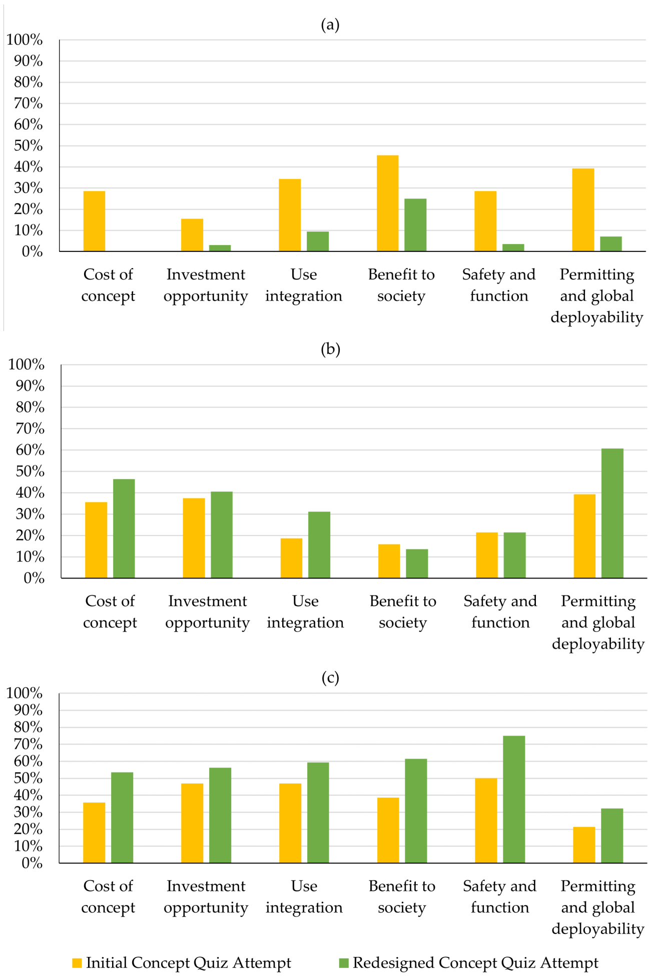

Fig. 4. Division of score breakdown by category before (yellow) and after (green) taking the quiz for: (a) low scoring questions, (b) medium scoring questions, and (c) high scoring questions.

V. Conclusion

In this paper, we present an early-design-phase wave energy converter design tool that presents designers with known practices for designing for Blue Economy applications and provides design feedback based on user answers. The tool is based on existing product concept generation tools that successfully help designers make sustainable design decisions - addressing a need for more early concept evaluation tools identified in previous work [4], [23]. The proposed tool provides designers with actionable feedback that helps designers improve their designs to better satisfy stakeholder requirements. Our initial case study shows a positive relationship between using the Blue Economy Quiz and making design decisions that capture a wider breadth of stakeholder requirements. These results indicate that such a tool may be helpful for wave energy developers in emerging markets.

Future work on this tool will incorporate feedback from the OSU MECC team, most of which aligns with existing literature on survey design to increase participant engagement [32]. We also plan to make the quiz more versatile by adding filtering questions. Filtering questions allow us to serve an initial set of high level questions to determine what detailed questions should be asked of the concept. This will change the structure of the quiz from a more general survey to a search tree structure. The search tree will eliminate asking questions that are irrelevant to a design's application and could reduce the number of questions a user needs to answer. For instance, if a concept has functionality currently on the market, we should ask if the designer has benchmarked the concept against competition. Additionally, we will continue to update the contents of the tool to reflect current literature on stakeholder requirements in emerging markets. This is important as stakeholder needs change over time. We plan to add more user-friendly features, such as a progress bar that designers can view as they take the quiz. We hope to test this tool with a larger group to have a more detailed investigation on the impact of the tool during concept generation. It would also be interesting to test what kind of feedback and what amount of feedback is most helpful during concept generation. After more development and testing, it is pertinent to conduct longer tests with the Blue Economy Quiz where we have participants complete all design stages up though concept selection. After concept selection, we can then evaluate concepts that used the Blue Economy Quiz and concepts that followed traditional design methodologies. Estimating manufacturing costs, performance, and stakeholder acceptance of these concepts will help us understand the impact of the Blue Economy Quiz on WEC development. This research will help us provide a tool for wave energy developers that makes their concepts higher-performing and engages all stakeholders.

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