An Early Design Phase Method for Characterizing and Comparing Wave Energy Converter Archetypes

Aeron L. Roach, Moira Meek, Raza Syed-Muhammad Ali, Bryony DuPont, and Bryson Roberston

Abstract—**Wave energy converters (WECs) hold promise for powering blue economy applications, but their success relies on their ability to survive in the highly energetic ocean climate. Existing approaches for understanding WEC functional benefits often occur during detailed design, which can lead to crucial functional decisions based on archetype selection rather than design goals. This paper presents a methodology that leverages functional decomposition for identifying high-level overlaps between WEC archetypes during early design stages. Functional decomposition is a method for analyzing complex systems and tracking energy, information, and material flows. We apply this method to seven fully submerged WEC archetypes. This process provides helpful information for understanding the necessary functions of a submerged WEC. The methodology and case study results will help communities advance their efforts to combat climate change by selecting the best device for their application and location in the blue economy. Better identifying functional overlaps between WEC archetypes will help researchers and developers generate effective designs that build resilient coastal communities.**

Index Terms—**functional decomposition, submerged wave energy converter, engineering design, archetype comparison**

I. Introduction

The ongoing effects of climate change threaten the resiliency of coastal communities that rely on the ocean for survival. These communities engage with many sectors that have the potential to be powered by renewable energy technologies, such as aquaculture, desalination, and ocean navigation. These applications are called the blue economy [1]. The blue economy encourages the equitable development of applications that contribute to the resiliency of coastal communities. Governments and communities worldwide are identifying wave energy converters (WEC) as a potential part of their renewable energy portfolio in efforts to develop the blue economy [2]. WECs have the potential to produce renewable energy from ocean waves, which can significantly reduce reliance on fossil fuels and help mitigate the impact of climate change on coastal communities.

Survival of WECs in the highly energetic ocean climate is crucial to the success of the technology [3]. Contrary to this contradicts is the ability to extract power from the most frequent conditions. Understanding how WECs function and interact with the ocean environment is critical for developing effective designs that can withstand these challenges. In addition, different WEC archetypes have various functional benefits, and it is crucial to understand these benefits when selecting the most appropriate WEC for a given application.

Existing approaches to understanding the functional benefits of WEC archetypes include numerical modeling and experimental testing of the entire WEC system and various subsystems. Numerical modeling methods employ many tools such as boundary element method (BEM) solvers to help capture the hydrodynamic characteristics integral to WEC performance. Experimental testing then helps validate the previous results and provides more detailed insight into the performance of WEC prototypes [4].

While these efforts help understand specific devices' performance, they often occur during stages where researchers are fine-tuning subsystems. At this stage of the process, we have set the WEC's general design (archetype, configuration, etc.), and making fundamental changes will incur significant costs. The findings of Trueworthy et al. [5] may reveal that over half of WEC developers start with an idea for a device that determines the archetype [5]. While this is common for emerging technologies, we must learn from other technological development paths to be a viable climate change solution. Rushing through early design stages often means crucial functional decisions are automatically made based on a single concept rather than comparing which archetype best satisfies the requirements of a project. The gap lies in the early stages of the design process, where only some methods exist for comparing functional overlaps between WEC archetypes [6].

This paper proposes a methodology for identifying and comparing functional overlaps between WEC archetypes during early design stages, which leverages functional decomposition for identifying high-level functions and analyzing information, energy, and material flows through a WEC archetype. Functional

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decomposition is an established methodology employed by other fields, helping designers understand what a product does and what functions contribute to the overall operation of the product [7]. Using this approach, we can extract the high-level processes and evaluate how well archetypes satisfy various criteria.

To demonstrate our methodology, we apply it to the analysis of submerged WECs. The blue economy has seen a recent surge of interest in submerged WECs for applications that aim to support coastal communities and contribute to a sustainable future. Our methodology analyzes seven submerged WEC archetypes and identifies nine high-level functions. These functional overlaps provide helpful information for understanding the necessary processes of a submerged WEC, which will help future designers ideate high-potential concepts. Our approach offers a unique way of conceptualizing and evaluating the functional benefits of WEC archetypes during early design stages.

This paper is organized as follows: Section II gives an overview of existing engineering design methods, their application in WEC design, and related studies. Section III outlines our methodology for identifying, evaluating, and comparing archetype functionalities. In Section IV, we discuss submerged WECs and their advantages and disadvantages. Sections V and VI present our methodology's application and the ensuing discussion of results. Our objective is to offer a valuable strategy for selecting the most suitable device for blue economy applications. This method and the knowledge from our case study will help blue economy communities advance their efforts to combat climate change.

II. Background

Engineering design encompasses decision-making processes that enable designers to generate effective products. Generally, the engineering design behind products is defined as a six-stage process [7], illustrated in Figure 1. During these steps, researchers and developers employ methods that refine their concepts to generate more information that characterizes the system. The engineering design methodologies help designers across many sectors, like automobile and consumer product design, ideate successful ideas. Following these processes can help ensure a concept satisfies the needs of all parties. Moreover, market research demonstrates that these methods can help designers reduce long-term costs, such as manufacturing costs [7]. These cost reductions are because each approach encourages increasing functional reasoning and exploring concept changes during early development when changes cost less [8].

At each engineering process step, designers conduct tasks that refine the design and provide information that characterizes their product. For this paper, we define *product characterization* as methodologies that provide users with an understanding of a system's functions. These methods help researchers and developers identify a system's inputs and the processes creating the desired output [8]. By employing these methods during early design stages, WEC researchers and developers may augment existing processes and produce higher potential WEC designs.

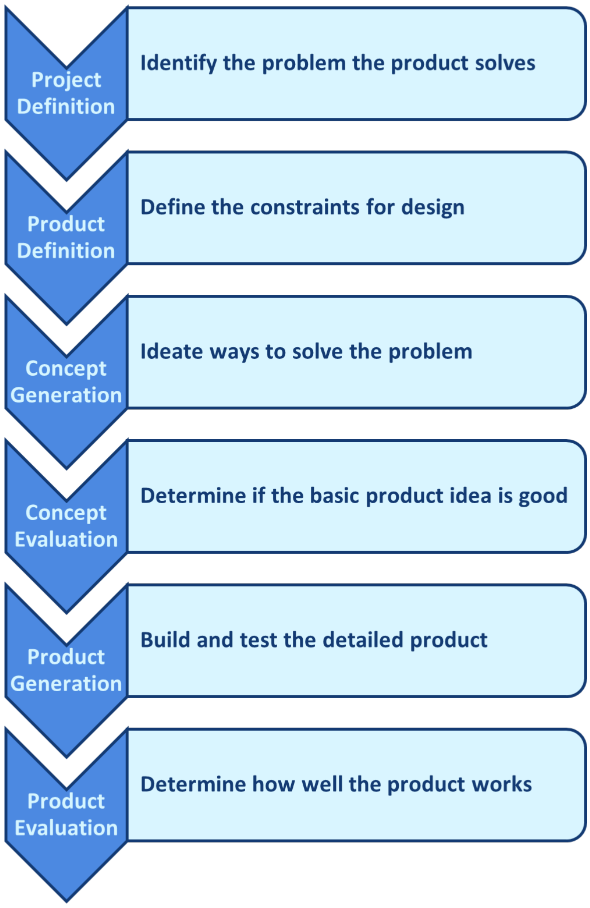


Fig. 1: A generalized definition of the engineering design process, as defined in [7]

A. Current Paradigms for Characterizing Wave Energy Converters

Numerical methods for characterizing WECs include time-domain and frequency-domain approaches. Frequency methods utilize linear potential flow theory to calculate device hydrodynamics and response based on frequency. These methods rely on BEM Solvers such as Capytaine, WAMIT, and NEMOH, but have simplified assumptions and limited capturing of higher-order terms. Time domain models capture nonlinear aspects of designs, such as PTO dynamics and drag effects, enabling a better understanding of nonlinear behavior.

While both time domain and frequency domain modeling helps characterize detailed WEC designs, problems arise when translating these methods to early design stages. For instance, Barbarit et al. [9] compare the mean annual power absorption of eight WEC archetypes using wave-to-wire modeling. This research provided foundational knowledge of power performance and an understanding of the working principles of WEC archetypes. However, the specific designs in this study mean the results only apply to that device. Robertson et al. [10] expand upon prior work and propose an archetype-agnostic model, enabling users to compare the power performance of various WECs at a resolution suitable for utility Integrated

Resource Planning [10]. Wave-to-wire models are crucial for understanding power performance. However, both methods rely on specific device configurations for comparing performance. In early design, the number of particular device configurations a group can analyze is limited by the time available.

An alternative to numerical modeling is the analytical method proposed by Bubar et al. [11], which solves for optimal linear power capture by treating the WEC as a mechanical circuit. This approach provides insights into maximum theoretical power capture in early design but remains dependent on specific configurations. The problem with particular configurations is that these contain preexisting functional decisions and are only sometimes optimal for a specific deployment. Thus, using these configurations at early stages limits the ability of designers to understand which archetype best satisfies project requirements.

WEC designers face limitations in comparing designs beyond numerical modeling, often relying on device-specific tools. The WaveSPARC (Systematic Process and Analysis for Reaching Commercialization) team at the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL) is developing a Technology Performance Level (TPL) assessment to understand techno-economic performance [12]. The TPL assessment achieves this by evaluating how a WEC satisfies the functional requirements established by Barbarit et al. [9]. The current TPL assessment focuses on technology readiness levels 1 to 3, assessing devices based on a holistic set of functional requirements but challenging its adaptation for archetype-level comparisons. Similarly, Blue Economy Quiz serves as a design tool for blue economy WEC applications [13], facilitating knowledge embedding during concept generation and evaluation, drawing from both TPL knowledge and a stakeholder analysis [14]. While both the TPL assessment and the Blue Economy Quiz face challenges in archetype-level comparisons due to their device-specific focus, they contribute functional requirements that can establish criteria for such comparisons.

The DTOceanPlus project offers multiple tools for supporting WEC designers [15]. The Structured Innovation design tool [16] combines Quality Function Deployment (QFD) and the Theory of Inventive Problem Solving (TRIZ) for ocean energy applications. Ruiz-Mingeula et al. [17] propose integrating Axiomatic Design [8] into this tool to emphasize critical system aspects during early-stage design. This structured approach facilitates connecting stakeholder requirements with measurable values, although it does not specifically compare WEC archetypes. Nonetheless, the results of the systems engineering approach can be integrated with other archetype comparison methods. In their work, Tiusanen et al. [18] introduce an archetype-agnostic methodology focused on enhancing reliability in WEC design, using the wave roller device as a case study. Functional decomposition is employed to analyze the device, but the resulting function block diagrams are used solely to identify potential failure modes for a single device.

B. Engineering Design Methods for Characterizing Mechanical Systems

Engineering design presents many methods for characterizing complex mechanical systems. Quality Function Deployment (QFD) occurs at the project definition stage [7], [8], [19]. This method is a customer-focused methodology that helps designers focus on *how* to satisfy *what* the customer wants out of a product. The result of this method is a ranked set of engineering specifications that characterizes the functionalities most important to the customers. This method helps the designers to obtain direct knowledge of customer requirements early in the design process, allowing them to generate a good design. QFD can be time-consuming, and understanding the relationships between customer requirements and engineering specifications is often more complex than initially thought. The process only offers designers insight into the metrics a design should achieve. QFD is unsatisfactory at characterizing WEC archetypes as it does not provide insight into the underlying functions.

Another method often used by designers when characterizing a product is functional decomposition. This method has users create a function block diagram that maps information, material, and energy flow [7], [8], [19]. This method enables the user to understand a system's inputs and outputs and the processes used to transform the inputs into the desired output — allowing for a clear understanding of how a system functions. Designers must be consistent across device characterizations because each function block often splits into multiple subfunctions, leading to a long process of refining the function block diagram with no clear end goal.

III. Methodology

We intend to employ a methodology that enables the easy characterization of all WEC archetypes based on their underlying functions. By leveraging established engineering design methodologies, this WEC archetype characterization methodology enables us to perform a functional analysis of each archetype. We intend this methodology for use during the product definition design phase. The output of this method will help designers and communities understand how WEC archetypes function, and help them determine in what scenarios specific archetypes may be beneficial. This will make designers aware of the complete functionality of a WEC archetype, ensuring that they are considering all functional requirements during concept generation.

A. Prerequisites

Before beginning the functional analysis, we recommend that users either utilize an existing review or a review of the WEC archetypes. This review allows an understanding of the state-of-the-art technologies and provides insight later when comparing archetypes. Understanding the customer requirements and engineering specifications of the deployment application is also essential, as it provides the necessary criteria for comparison. Customer requirements are what the product must be, and engineering specifications are the measurable metrics the design must achieve to satisfy customer requirements. All engineering specifications should incorporate the International Electrotechnical Commission's (IEC) guidelines from technical specification (TS) 62600-100 [20].

B. Archetype Analysis

The functional analysis contains four main steps:

1) Perform high-level functional decomposition
2) Perform refined functional decomposition
3) Derive elementary functions from refined functional decomposition
4) Construct Pugh Charts for comparing WEC Archetypes

The first step of the archetype analysis is creating a high-level functional diagram of each WEC archetype. A function diagram represents the entire WEC functionality, with each function expressed in a function block. The arrows in the diagram illustrate the flows of information, material, and energy. The inputs and outputs of the system go at the beginning and end of the function diagram. For all inputs and outputs, use arrows with dashed lines to differentiate where the system begins. We recommend dividing the WEC functions into as few function blocks as possible for this step. Once each archetype has a high-level functional decomposition, review phrasing among all functions and ensure it is uniform. This step ensures we can compare the functional overlaps.

After completing the high-level diagram for each archetype, initiate a recursive functional decomposition process. Split each main function block into multiple subfunction blocks that achieve the high-level function, focusing on general functionality and avoid naming specific mechanisms. Once complete, revise the diagrams to ensure uniform phrasing among all function blocks. Then use the refined functional decompositions to derive elementary functions across the WEC archetypes, either as common function blocks or high-level functions encompassing multiple functions.

To compare archetypes, employ the Pugh Chart methodology for benchmarking alternative concepts against a selected datum [7]. This approach facilitates a quick understanding of how well an alternative concept performs against criteria. We apply the same structure when comparing archetypes for deployment applications by using two Pugh Charts to gain more thorough insights into the benefits and drawbacks of each concept. Establish the criteria for the Pugh Charts based on customer requirements, engineering specifications, and elementary functions derived from the decomposition. We recommend choosing the most concept-rich archetypes from the state-of-the-art review as the datum for the Pugh Charts.

Next, evaluate how well each archetype satisfies the criteria compared to the datum, assigning scores of *much better (+2), better (+1), the same (0), worse (-1), or much worse (-2)*. During this process, utilize the functional decomposition and elementary functions to ensure consistency in the comparison. Sum the scores for each archetype in the two to get the final results, where higher scores indicate greater suitability for the intended deployment application. Note that while the datum comparisons in the two Pugh Charts are opposite, the remaining archetype comparisons are not, as each archetype is only compared to the current datum, not the previous one.

IV. Case Study: Submerged WECs

Early WEC design prioritized surface-piercing devices to maximize power performance for utility-scale applications. However, these designs pose two significant challenges. Firstly, surface-piercing devices face risks of damage or loss due to the chaotic nature of the ocean, necessitating careful consideration of survivability. Secondly, ensuring coexistence with other ocean users becomes crucial for community acceptance, as surface-piercing devices require others to avoid the deployment area, leading to use conflicts [21].

To address survivability, researchers suggest submerging WECs in extreme events as a favorable approach [3]. Submerging the WEC reduces the wave force exponentially with depth, decreasing the likelihood of collisions with other ocean users. While this enhances survivability, it also results in lower power ratings due to the exponential energy decay in the water column. However, this trade-off makes submerged WECs well-suited for blue economy applications, where coexistence with other users is crucial and power requirements are lower than utility-scale [1].

Through a state-of-the-art review, we identified 27 devices in academia and industry. Overall, development is occurring on only 14 of the 27 devices. These devices span technology readiness levels 2 to 8 with no devices commercially deployed. These concepts span seven archetypes:

- Point absorbers (PA)
- Oscillating surge wave energy converters (OSWEC)
- Oscillating water columns (OWC)
- Planar pressure differentials (PPD)
- Horizontal pressure differential (HPD)
- Flexible membrane (FM)
- Bulge wave (BW)

Existing WEC reviews and methodologies compare WEC archetypes, but no literature currently investigates submerged WEC archetypes. This knowledge gap obscures the advantages and disadvantages, making submerged WECs an ideal case study for our methodology. For this paper, we assume the use case of the submerged WEC to be for ocean observation and navigation in deep water.

V. Results

A. Functional Decomposition

After reviewing the function of all the known submerged WEC archetypes, we observed a trend that each device undergoes a variation of the functional decomposition in Figure 2. First, the device transfers

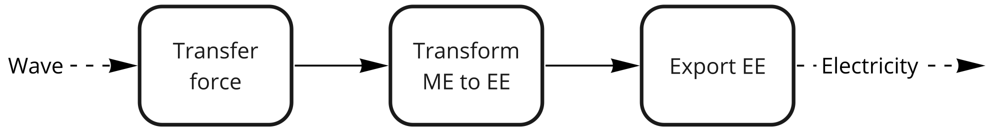


Fig. 2: Simple Functional Decomposition of Submerged WEC

the force of the wave to the device's subsystems. The subsystems convert this mechanical energy into electrical energy and export it to the desired application subsystem. While each device uses different mechanisms to achieve this process, we see this trend across all submerged WEC designs.

This simple functional decomposition enables us to proceed to the next step and conduct refined functional decompositions of each submerged WEC archetype. Point absorber devices extract energy from the ocean's waves through a body reacting against a reference structure, requiring the device to maintain its position during deployment. The wave forcing on the body transforms forces and energy into electricity. We describe this process through the functional decompositions in Figure 3b. From the incoming wave, the device first *transfers* the force from the wave to the WEC. Then, the WEC *transforms* the force into the necessary translational or rotational force needed to *transform mechanical energy to electrical energy*. These devices often operate in all degrees of freedom, but the design can restrict energy extraction. Additionally, these devices have the ability to monitor incoming wave conditions for regulating internal force transformations.

Oscillating surge wave energy converters extract energy through the relative motion between a free body and a fixed body that relies on the device maintaining its position. The wave forcing on the free body drives the free body in surge, transforming forces and energy into electricity. The functional decomposition of the OSWEC, seen in Figure 4b, captures this function of the archetype.

Oscillating water columns use wave forcing to pressurize a chamber. Under the wave peak, the water is driven through the power take-off system (PTO), compressing the air. The pressure decreases under a wave trough causing the air to expand and move the water through the PTO. The PTO transforms the energy into electricity. The functional decomposition of the OWC, seen in Figure 5b, captures this function of the archetype.

Planar pressure differential devices extract energy through a wave-induced pressure differential between two bodies. This pressure differential induces a force on one of the bodies, driving the conversion of mechanical energy to electrical energy. The functional decomposition of the PPD, seen in Figure 6b, captures this function of the archetype.

Horizontal pressure differential devices use the dynamic pressure field for driving an alternating compression and expansion cycle. The wave's force directs an internal fluid through a subsystem that transforms the mechanical energy into electrical energy. The functional decomposition of the HPD, seen in Figure 7b, captures this archetype's function.

Flexible membrane devices use the dynamic pressure field to transform the energy of the wave field into mechanical and potential energy. The system converts this mechanical potential energy into electrical energy. As the dynamic pressure field changes, the potential energy transforms back into mechanical energy, which is converted again into electrical energy. The functional decomposition of the FM, seen in Figure 8b, captures this function of the archetype.

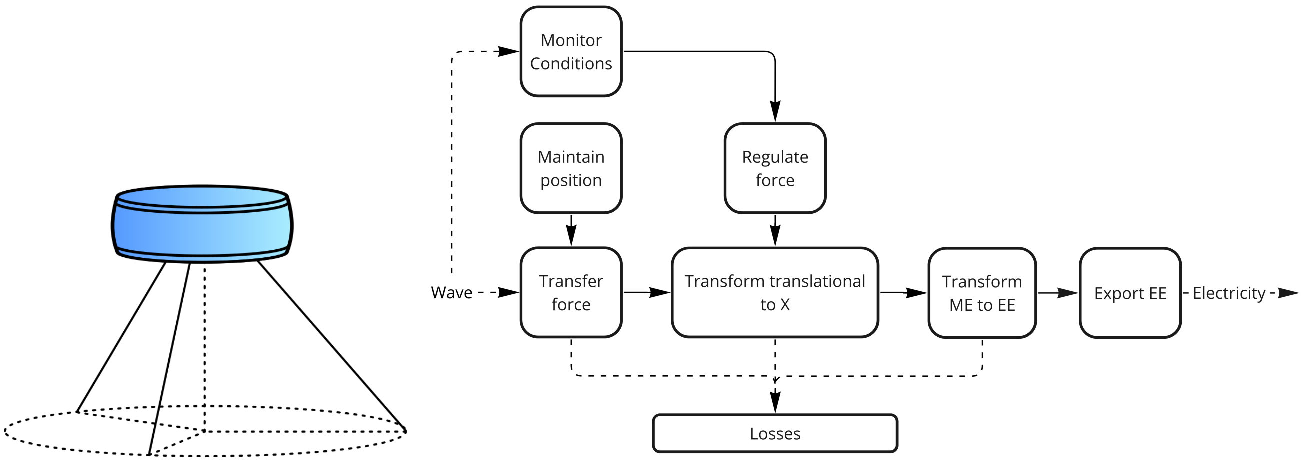
Bulge wave energy converters employ the bulge wave generated as the wave passes over the length of the device. These devices are unique from other submerged WECs as there are two categories (or subarchetypes). The first subarchetype, labeled *(1)* in Figure 9b, has the force of the wave transform the electrical capacitance of the device, which induces a current to generate electrical energy. The second subarchetype, labeled *(2)* in Figure 9b, has the force of the wave directly moving an internal fluid that drives the conversion of mechanical energy to electrical energy. The functional decomposition of the BM, seen in Figure 9b, captures this function of the archetype.

B. Elementary Function derivation

We can observe some overarching functions from the previous section's functional diagrams. In our case study of submerged WECs, we identify nine high-level functions across the archetypes. The first function is *absorb wave energy*. This elementary function deals with transferring force from the wave to the device. Next, the device must *maintain position* for effective operations. We split the monitor conditions block in the functional decomposition into two elementary functions, *monitor wave conditions* and *monitor body position*. These elementary functions deal with collecting the information for determining device controls. The *control related modularity* elementary function controls the internal device mechanics. After the transfer of wave force, submerged WECs undergo several force transformations: they convert the translational force into translational, potential, or rotational energy. The mechanical energy behind the force then converts to electrical energy. Outside of the elementary functions necessary for energy conversion, we observe that each submerged WEC archetype contains the *maintain body position* function.

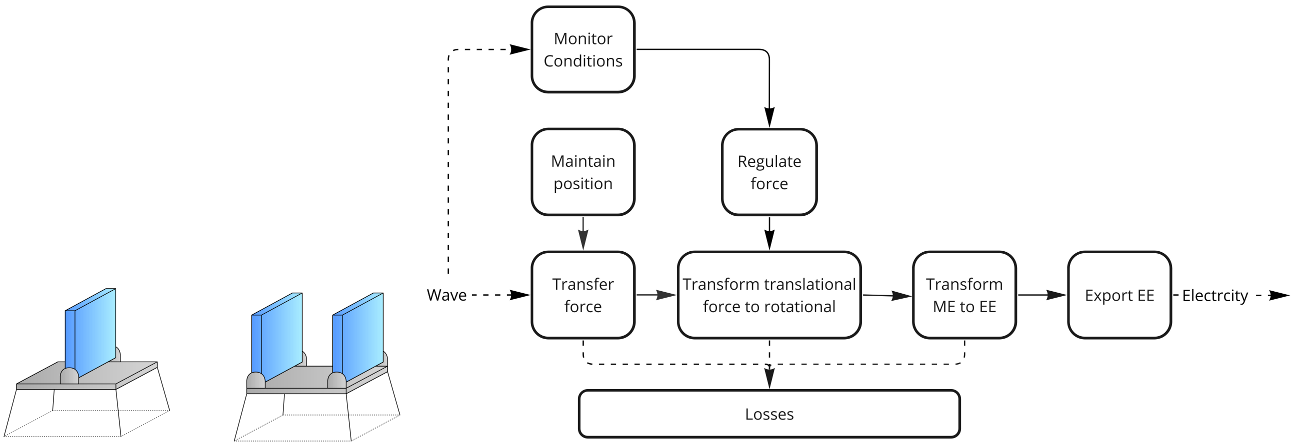
C. Archeytype Comparison

As stated in Section IV, we assume ocean observation is the deployment application. Stakeholder analyses of



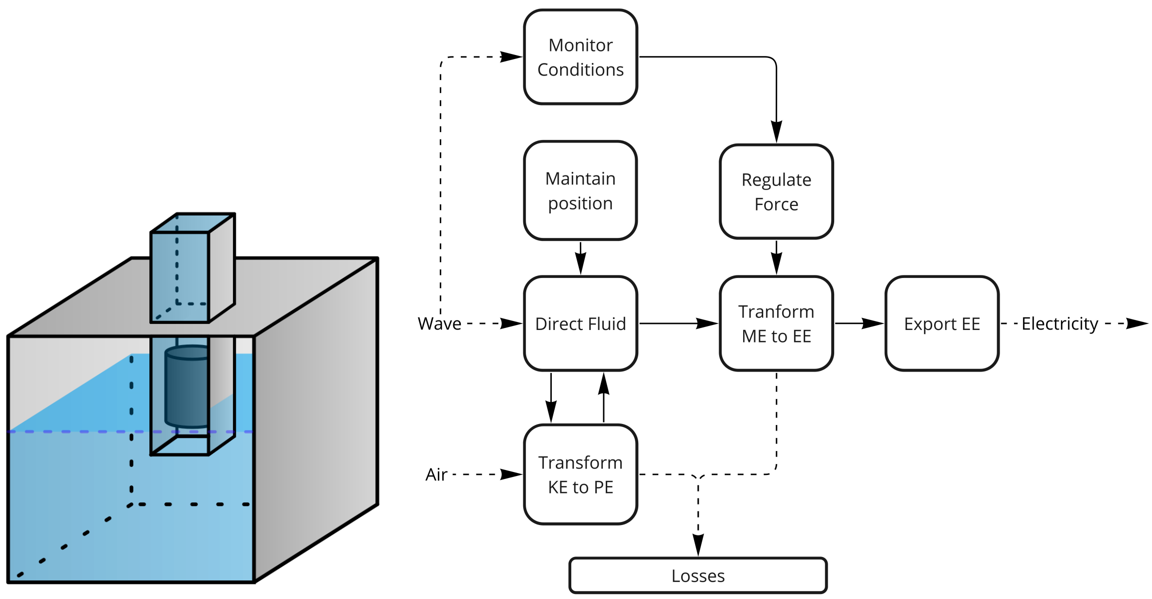
(a) (b)

Fig. 3: (a): Illustration of PA archetype (b): Refined functional decomposition of a Point Absorber



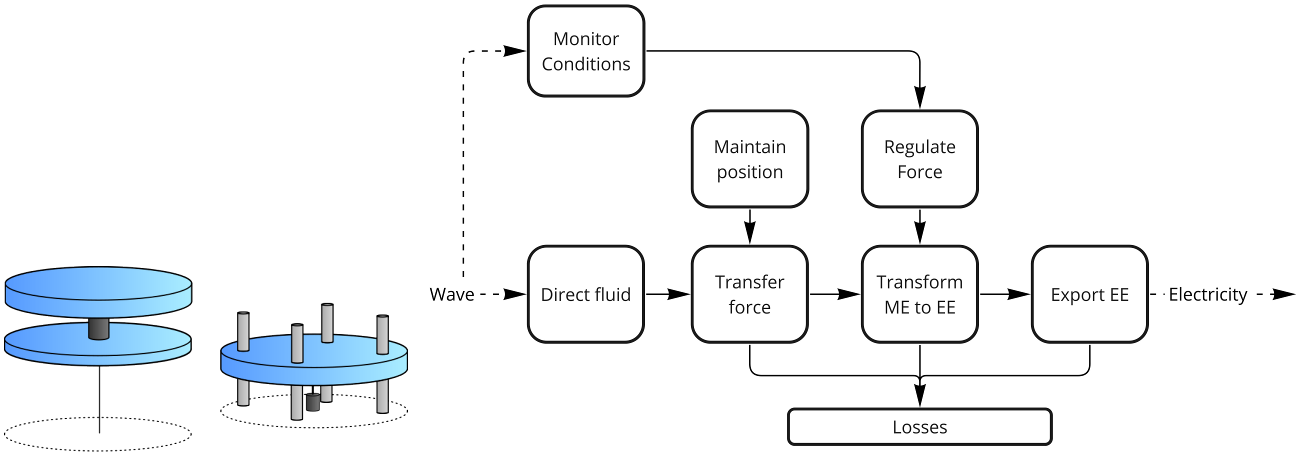
(a) (b)

Fig. 4: (a): Illustration of OSWEC archetype (b): Refined functional decomposition of an Oscillating Surging Wave Energy Converter



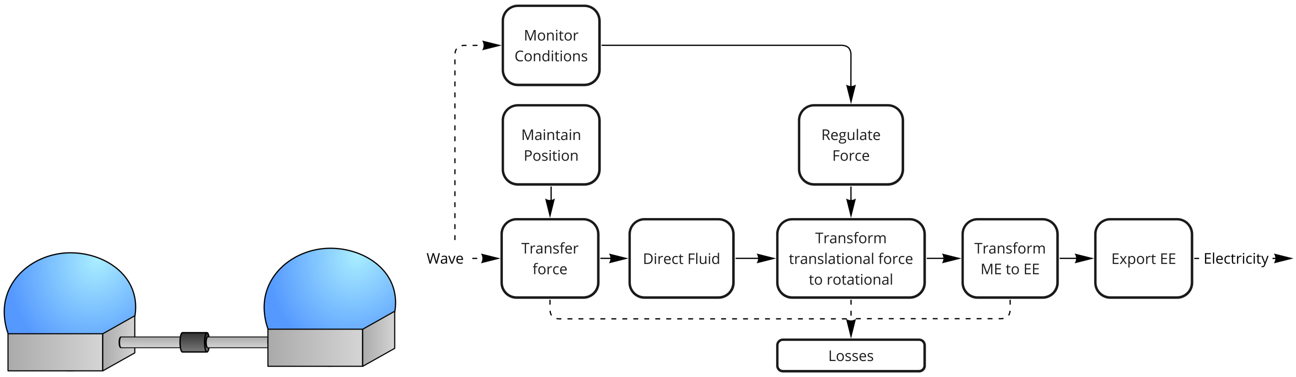
(a) (b)

Fig. 5: (a): Illustration of OWC archetype (b): Refined functional decomposition of an Oscillating Water Column



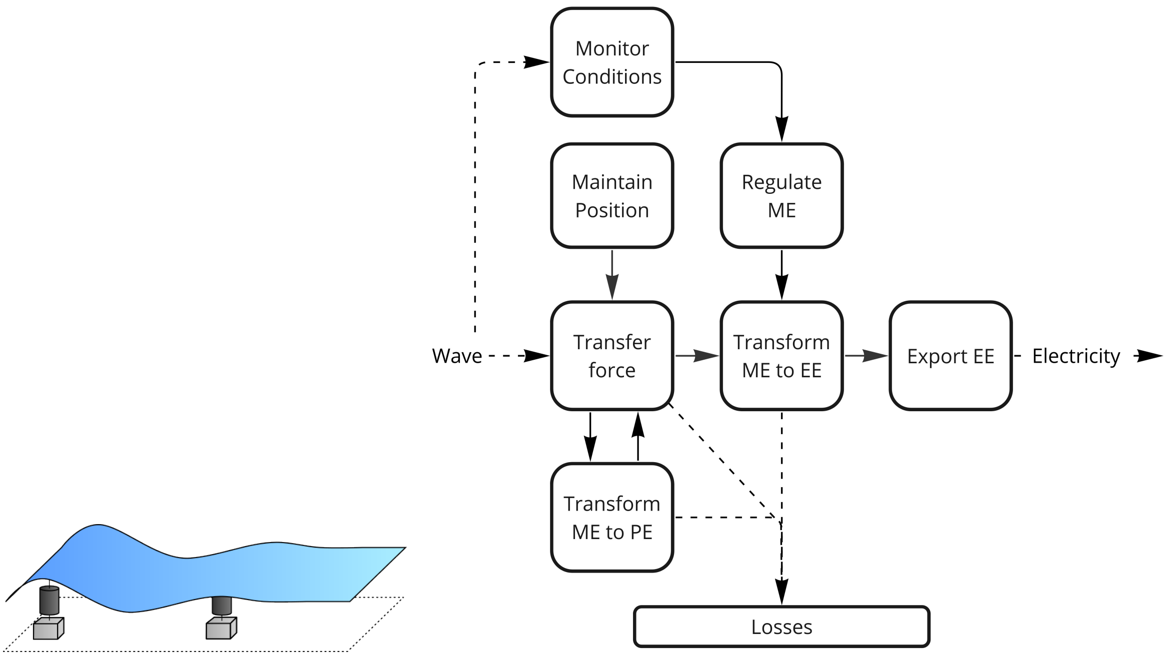
(a) (b)

Fig. 6: (a): Illustration of PPD archetype (b): Refined functional decomposition of a Planar Pressure Differential



(a) (b)

Fig. 7: (a): Illustration of HPD archetype (b): Refined functional decomposition of a Horizontal Pressure Differential



(a) (b)

Fig. 8: (a): Illustration of FM archetype (b): Refined functional decomposition of a Flexible Membrane

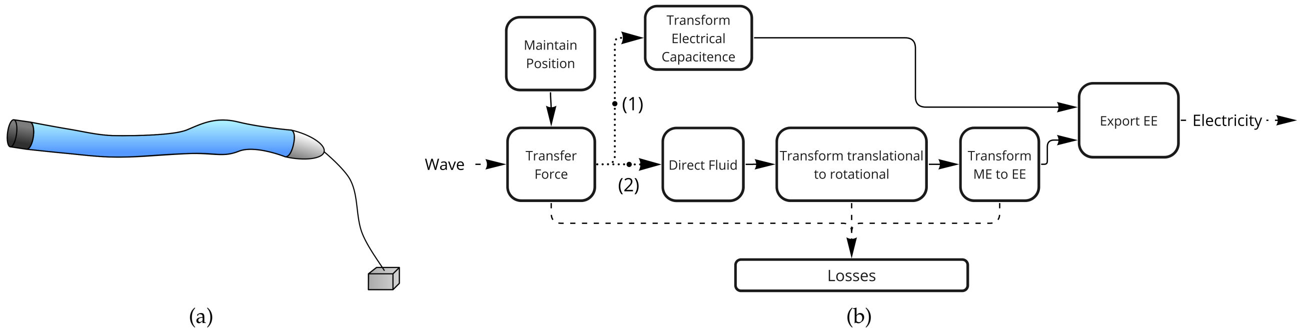


Fig. 9: (a): Illustration of BW archetype (b): Refined Functional Decomposition of a Bulge Wave. Note that for this functional decomposition, there are two sub-archetypes, labeled (1) and (2)

		Archetype						
		OSWEC	PA	OWC	PPD	HPD	FM	BW
Elementary Functions	Absorb wave energy	X	X	X	X	X	X	X
	Convert translational to rotation	X	X			X		X
	Convert translational to translational		X		X			
	Convert translational to Potential			X			X	
	Convert ME to EE	X	X	X	X	X	X	X
	Maintain Position	X	X	X	X	X	X	X
	Monitor Wave Conditions	X	X	X	X	X	X	
	Monitor Body Position	X	X	X	X	X	X	
	Control Related Modularity	X	X	X	X	X	X	

TABLE I: Elementary Function Overlap of Submerged WEC Archetypes. PA = Point absorber, PPD = Planar Pressure Differential, HPD = Horizontal Pressure Differential, FM = Flexible Membrane, BW= Bulge Wave

ocean observation state that these devices must: reduce costs, have a consistent power source available, and be easy to install and recover [22], [23]. The ability to support a variety of sensors is also important. However, for this investigation, we assume sensor modularity will depend on the specific device design and not the archetype selection. Thus we select ease of manufacturing, simplicity, estimated cost, number of stock components vs. custom components, estimated power efficiency, and sensitivity to wave direction as our criteria. We select the OSWEC and the Point Absorber for the datum because these archetypes comprise a significant portion of the state-of-the-art.

This comparison between archetypes relies on engineering reasoning and our knowledge of archetype performance from the state-of-the-art review. For example, with the OSWEC we know that the reliance on flaps minimizes the WEC's ability to generate electricity in deployments with high variance in wave direction. Thus we determine that the OSWEC performs *worse than* the Point Absorber for *sensitivity to wave direction*. The full results for the Pugh Charts are in Table II. From this, we see that the point absorber best satisfies our criteria, followed by the planar pressure differential and the OSWEC. In contrast, the bulge wave, flexible membrane, and horizontal pressure differential perform worse than both datum.

VI. Discussion

While this methodology will help designers understand the characteristics of WEC archetypes during product definition, it is crucial to understand the limitations. Since our method is for early design phases, the results provide a qualitative understanding of archetype performance. Nevertheless, a literature review of archetypes can enhance this qualitative understanding and enable designers to make informed functional choices during the early design stage. Another area for improvement is that the analysis cannot capture unique innovations of specific designs. A potential solution is creating a functional decomposition for each distinct design. However, we stress caution with this as it could lead to analysis paralysis and limit time during concept generation.

Nonetheless, we can begin understanding which submerged WEC archetypes may perform the best for deep-water ocean observation. If we consider each set of criteria equally important, the point absorber is the best for our deployment application. This result is because the point absorber archetype can capture an omnidirectional wave resource and relies on a relatively simple design for wave energy capture. We summarize the final total scores across the two Pugh Charts in Table III. Surprisingly, the planar pressure differential and the OSWEC archetypes rank equally as the second best. This may be due to the similarities between the functionality of the point absorber and planar pressure differential. However, more criteria will clarify the results as we can compare the planar pressure differential and OSWEC more thoroughly. It is important to note that since this comparison is for a specific application, this is not a definitive determination on which WEC archetype will perform the best. Additionally, as unique materials' manufacturing capabilities mature, other designs like the bulge wave archetype may see an improved performance against the datum. Again, this method aims to assist designers in gaining insight into the archetypes with the highest

	Archetype						
Criteria	OSWEC	PA	OWC	PPD	HPD	FM	BW
Ease of manufacturing	DATUM	+1	-2	+1	+1	-2	-2
Simplicity		+1	-1	-1	-2	-1	0
Estimated cost		0	0	0	-1	-1	-2
No. stock components vs custom		0	+1	+1	-1	-1	-1
Estimated power efficiency		+1	-1	-2	0	+1	+1
Sensitivity to wave direction		+1	0	0	+1	+1	+1
$\sum$ **Total**	-	+4	-3	-1	-2	-3	-3

(a)

	Archetype						
Criteria	PA	OSWEC	OWC	PPD	HPD	FM	BW
Ease of manufacturing	DATUM	-1	-1	0	-1	-2	-1
Simplicity		-1	0	+1	0	-1	-1
Estimated cost		0	0	-1	-1	-1	-1
No. stock components vs custom		0	0	0	-1	-1	-1
Estimated power efficiency		-1	-1	-2	-1	0	0
Sensitivity to wave direction		-1	-1	-1	-1	0	-1
$\sum$ **Total**	-	-4	-3	-3	-5	-5	-5

(b)

TABLE II: Pugh Charts for comparing submerged WEC archetypes for deep water ocean observation. (a): OSWEC as datum, (b): Point Absorber as datum. PA = Point absorber, PPD = Planar Pressure Differential, HPD = Horizontal Pressure Differential, FM = Flexible Membrane, BW= Bulge Wave

	Archetype						
	PA	OSWEC	OWC	PPD	HPD	FM	BW
Pugh Chart #1	+4	-	-3	-1	-2	-3	-3
Pugh Chart #2	-	-4	-3	-3	-5	-5	-5
Total	+4	-4	-6	-4	-7	-8	-8

TABLE III: Summary of Pugh Chart comparison in Table II. PA = Point absorber, PPD = Planar Pressure Differential, HPD = Horizontal Pressure Differential, FM = Flexible Membrane, BW= Bulge Wave

chances of success and require further investigation during early design.

Even though our process stops with the Pugh Chart comparison, the outputs can help designers during concept generation and evaluation. From the functional decomposition, we can easily interpret the system's functionality and how subfunctions interact to generate electricity. The structured approach provides the opportunity for identifying functional overlaps between WEC archetypes. Suppose researchers and developers refine the functional decompositions. In that case, they can identify opportunities within these functional overlaps to learn and explore innovative solutions to functional problems in WECs. For instance, the planar pressure differential scores better than the point absorber for *simplicity*. If we determine which functions contribute to that score, we can innovate when designing a point absorber. While the subsystem may not be directly transferable between archetypes, these overlaps could inspire innovative solutions. Other methods, such as the theory of inventive problem solving (TRIZ), could take contradictions in the functional decomposition and inspire ways to overcome operational challenges.

Additionally, researchers and developers can employ the elementary functions from this method during concept generation. For example, morphological matrices have users ideate different mechanisms that solve a single function. Combining solutions for each function becomes the start of a concept [7]. The elementary functions from the functional comparison can directly transfer to a morphological matrix for concept generation. The function blocks from this methodology also provide researchers and developers with categories for evaluating WEC concepts during early design. For instance, if the elementary function *Maintain Position* heavily influences a deployment, a team could determine related metrics such as the risk of loss, risk of collision with marine wildlife, and risk of collision with maritime vessels. The team can then evaluate concepts using these metrics and select the idea that best maintains position. During detailed design, the functional decomposition could also provide insights on how to improve a specific design. The systematic approach to mapping out the function of their design can help designers identify operational improvements in an existing design. It could help groups quickly iterate changes and understand what changes will impact the device's functionality.

VII. Conclusion

Wave energy converters (WECs) hold promise for powering blue economy applications. The success of WECs relies on the technology's ability to survive in the highly energetic ocean climate while extracting enough power to meet demands. Balancing this contradiction requires a thorough understanding of the functional benefits of WEC archetypes. Existing approaches for understanding the functional benefits of WEC designs often occur during detailed design, when fundamental changes to the archetype have high temporal and financial costs. The early commitment to an archetype inadvertently makes crucial functional decisions for designers. This paper presents a methodology that leverages functional decomposition for identifying and comparing the functional overlaps between WEC archetypes. Functional decomposition is a well-established engineering design method for breaking down complex systems into constituent subfunctions and tracking energy, information, and materials flows.

We apply the method to seven fully submerged WEC archetypes and identify nine elementary functions. The process provides helpful information about the functionality of submerged WECs and enables us to conduct a Pugh Chart comparison on submerged WECs for deep-water ocean observation. The methodology and case study results will help communities advance their efforts to combat climate change by providing insight into which archetypes have higher chances of success and warrant further investigation during the early design phase. By better identifying the functional overlaps between WEC archetypes, researchers and developers can generate increasingly effective designs that build resilient coastal communities and combat climate change.

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