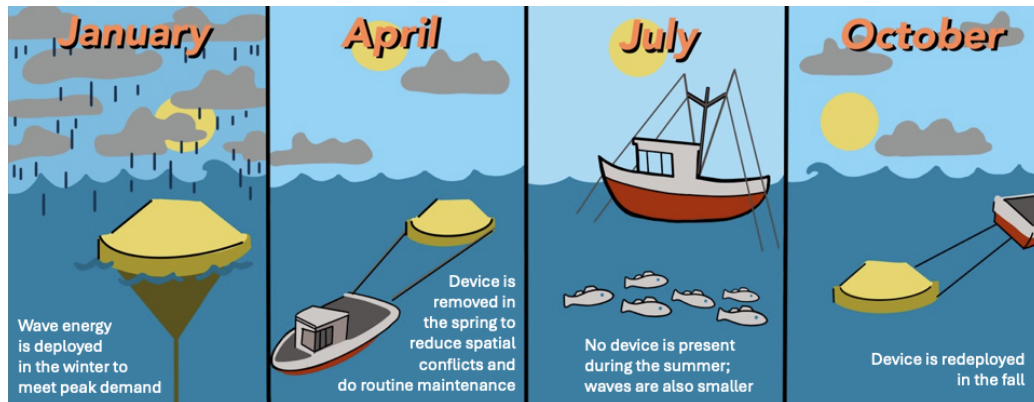


Graphical Abstract

Wave Energy In Season: A Comparative Approach to Feasibility of Seasonal Deployments for Remote Coastal Communities

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Highlights

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- Presents a holistic, comparative approach to feasibility investigations
- Assesses the potential impacts of seasonal wave energy deployments
- Compares operations and maintenance costs and their localness
- Optimizes negative spring wave energy converter for Sitka, AK

Wave Energy In Season: A Comparative Approach to Feasibility of Seasonal Deployments for Remote Coastal Communities

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Abstract

Remote coastal communities, who could be early adopters of wave energy projects, have concerns over costs, conflicts, and potential risks of development. Designers and developers are challenged to address those community concerns as they continue to develop wave energy technologies. One potential means of reducing cost, conflicts, and risks, especially for demonstration and pilot-scale projects, could be planning a deployment that operates for only a portion of the year—a seasonal deployment. In this paper we look at the impacts of a season deployment in terms of cost, electricity production, operations and maintenance, environmental impacts, and community benefits. We take a holistic, comparative approach to feasibility that can be replicated for other comparative studies. We estimate electricity production using a point absorber WEC modeled near Sitka, AK, USA and optimized for the given sea conditions. We determine that, for remote community sized projects, seasonal deployments could result in small cost savings (less than 10%), but larger decreases in annual energy production (around 30% for our case study area). Seasonal deployments could be preferable in places with seasonal energy needs, if failures and device access become a major hindrance to wave energy technology development, or as a cautionary approach to introducing new technology to the oceans. We also determine that a highly seasonal wave resource is not necessarily a requirement in order for seasonal deployments to be considered. Seasonal deployments are an alternative to year-round deployments that can be considered in places where marine spatial conflict is a seasonal concern.

Keywords: wave energy deployment, operations and maintenance, WEC optimization, control co-design

1. Introduction

Remote coastal communities have received special attention as groups that might benefit from and serve as an important testing ground for early wave energy deployments [1]. As an emerging technology that converts energy from ocean waves, wave energy is currently too costly to compete in continental grid markets, but it has shown potential in remote coastal communities with a high cost of energy [2]. As communities become more central to early development, and a variety of policy and social science studies highlight the need to engage the public in energy decision making and design [3; 4; 5; 6; 7; 8], technical researchers and developers are challenged to integrate community perspectives. This is especially true in remote coastal communities where electricity is generated locally and, therefore, changes to the energy systems are of broad public concern. For marine renewable energy, concerns over potential spatial conflicts with fisheries, recreation, and various marine species are common among coastal communities [9]. These conflicts are often seasonal, especially in the mid-latitude, western coasts where wave energy resources [10] and marine activity (both human and non-human) differs significantly between summer and winter [11; 12].

In this paper, we examine one possible way designers and project developers of wave energy systems could reduce costs, conflicts, and risks for communities and developers while addressing spatial conflicts: deploying wave energy devices on a seasonal basis. Seasonal deployments could be a way to address the inherent risks of demonstration projects and ocean spatial conflicts. We investigate if, and under what conditions, a seasonal deployment might be preferable for a coastal community, considering conditions related to both project and place. Our aim is to qualify the potential benefits and drawbacks of seasonal deployments for remote coastal communities, knowing that these will be different for different communities.

To consider the variety of differences between seasonal and year-round deployments while also acknowledging differences across communities, we take a multi-method approach to our investigation. After reviewing literature related to wave energy in remote coastal communities in Section 2, we examine the requirements of a successful wave energy project in Section 3.

From that examination, we choose which aspects of a wave energy project we will compare between seasonal and year-round deployments. For some aspects, like energy conversion and operations and maintenance (O&M) costs, we choose to create detailed models. For other aspects such as component costs, environmental impacts, permitting and monitoring costs, and conflict and community benefit we take a qualitative approach. In Section 4 we introduce our case study location, Sitka, AK, USA. Sections 5, 6, 7, 8 describe our comparisons of seasonal and year-round deployments according to the power conversion, costs, environmental impacts, and community impacts, respectively. In Section 9.1, we discuss the overall feasibility of seasonal deployments given each comparison along with what local conditions might justify consideration of seasonal deployments. We also discuss the implications of the results of our WEC optimization, then reflect on the wider usefulness of our comparative, multi-disciplinary approach to feasibility and its limitations.

2. Wave Energy for Remote Coastal Communities

Building off of other research on marine energy for remote coastal communities, ours is the first systematic look at seasonal deployments. Research by Beatty et al. (2010) [13], Fadaeenejad et al. (2014) [14], and Robertson et al. (2020) [2] all show potential pathways for wave energy to become feasible and beneficial for remote communities. Beatty et al. (2010) estimate the electricity conversion of a 100kW heaving point absorber WEC near St. George Island in the Bering Sea. They compare the time series of wave energy conversion to the community’s electrical demand and estimate that the WEC could supply 9% of the island’s demand. Notably, they suggest that seasonal WEC control strategies be adopted in order to align WEC energy conversion with grid needs [13]. Ciappi et al. (2022) also argue for seasonal control strategies to improve power performance for a WEC in the Mediterranean Sea [15]. As suggested by these papers and others, we allow for different control parameters during different months of the year, however, in addition, we optimize PTO parameters seasonally. An important distinction here is that control parameters are software-based, meaning, they can be changed after a WEC is built and a single WEC can operate multiple control strategies. PTO parameters, on the other hand, correspond to physical, unchangeable design decisions and have yet to be optimized seasonally. This is despite knowledge that control and PTO parameters are dynamically coupled [16].

Kim et al. (2012) evaluate the compatibility of wave energy with other marine and coastal uses including fishing, transport and shipping, tourism, recreation, and other related uses[17]. They use spatial analysis and a synthesis of existing ocean uses for a site off the Pacific coast of Canada to show that there are high-value wave energy sites that only minimally conflict with other uses. They propose a stakeholder engaged approach to siting that considers the variety of ocean uses. While they acknowledge the seasonality of available wave energy, they do not consider the seasonality of other ocean uses or the potential for seasonal deployments.

Fadaeenejad et al. (2014) summarize the applied research on wave energy for island communities, bringing together a dozen individual studies published prior to 2014. Although their synthesis of those studies is limited, they note that wave energy could be a part of sustainable development for island communities [14]. Various other studies in coastal sciences and coastal management discuss the potential of marine renewable energy to improve sustainability and resilience of coastal communities [18; 19]. Manasseh et al. (2017) look at the potential benefits of wave energy in terms of energy security and coastal protection [20]. They argue for the combination of marine renewable energy with coastal-protection infrastructure. Caballero et al. propose a framework for "meaningful MRE development" that can help to guide community engagement and trust building around marine renewable energy projects [21]. We use their work as a guide in our discussion of community impacts, but the framework is not directly applicable for comparing projects.

Robertson et al. (2020) use an allowable-cost methodology to estimate how much a marine energy system could cost in order for it to be preferable for remote communities, an approach that avoids dealing with the cost uncertainties of nascent technologies [2]. They determine that, for a remote community in Canada, wave energy has an allowable cost of \$0.59/ kWh, however that number is community-specific. This approach to cost estimation is considered a "bottom-up" approach [22]. For wave energy, where costs are uncertain, bottom-up approaches provide an opportunity to consider costs related to individual design decisions rather than an entire device or system [23; 24]. In our study, we use what Giglio et al. (2023) would call a hybrid approach: we choose a few significant aspects for which we make detailed comparisons, then we put those estimates in the context of overall costs using estimates of cost percentages published in top-down studies. Making whole project cost estimates is not the focus of this study, however,

being able to contextualize cost differences as a portion of the total cost is important.

Together, these studies show that marine renewable energy has the potential to provide benefits to coastal communities in terms of electricity, environmental impacts, and social dimensions. Despite that, motion toward wave energy deployments has been slow for several reasons, including the lack of field tested technologies, the need to integrate community concerns into technology development, potential ocean spatial conflicts, and other social and economic dimensions in remote coastal communities. This paper fits into work being done to bridge these barriers.

3. A Comparative Approach to Feasibility

Babarit et al. (2017) outline design requirements for a wave energy project, their respective sub-requirements, and each sub-requirement’s relative importance based on an industry stakeholder analysis [25]. Their analysis is one of the most systematic and comprehensive characterizations of what a wave energy system needs to achieve to be successful. We use their analysis to guide our choices (outlined in Figure 1) about what aspects we compare between seasonal and year-round deployments.

In Table 1 we show each requirement and sub-requirement from Babarit et al., the importance of the requirement, the expected level of difference between seasonal and year-round deployments according to the requirement, the reasons for that difference, and the related local characteristics. We use that information to determine which requirements we examine and the level of fidelity (last column) with which we examine them. The process for making that determination is detailed in Figure 1. Babarit et al. indicate the level of flexibility in each sub requirement, and we translate that into a relative importance (I) where ”no flexibility” translates to high importance, and so on. We indicate the level of difference (D) we expect in that sub-requirement between a seasonal and year-round deployments on a high-medium-low scale. The level of difference is a coarse determination we made based on the reasons for potential difference and the local characteristics that might impact the requirement.

We use the information in Table 1 to decide if and to what fidelity of detail we will compare deployment schemes according to each requirement, indicated in the final column as H (high), M (medium), L (low), or N/A (not applicable). Our final decision about whether or not to include an individual

Table 1: Factors impacting the performance of a wave energy project. Column 3, labeled "I/D" shows the importance and expected difference between seasonal and year-round for a sub-requirement, estimated as high, medium, or low. we then give the reasons for the expected difference, the related local characteristics, and the level of fidelity with which we estimate the differences in the upcoming sections.

Requirement	Sub-Requirements	I/D	Reasons for difference	Related Local Characteristics	Fidelity
Cost of Energy	Power conversion	H/H	Operating timeframes	Sea conditions	H
	Availability	H/M	Fewer failures for devices removed and maintained yearly.	Sea conditions, weather conditions, workforce availability	L
	Device components	H/M	Cheaper components for shorter term deployments, optimal device designs	Preference toward local manufacturing	M
	CapEx				
	Infrastructure, mooring, installation	H/L	N/A	Existing infrastructure, local vessel and workforce availability	N/A
	CapEx				
	Design, site assessment, etc. CapEx	M/L	N/A	N/A	N/A
	O&M OpEx	M/H	O&M strategies	Local workforce availability, local vessel and crew rates	H
	Insurance and Monitoring OpEx	M/M	Secondary impacts of CapEx or environmental impacts	Presence of listed species	M
Investment Opportunity	Uncertainty in costs and revenues, survivability	H/L	N/A	Sea conditions	N/A
Grid Operations	Forecastability	M/L	N/A	Sea conditions	N/A
	Stable annual energy production	M/M	Different operating timeframes	Sea conditions	M
	Useful to grid	M/H	Different operating timeframes	Sea conditions, electricity demand, grid characteristics	M
Benefit Society	Local job creation	M/M	Secondary impacts stemming from O&M strategies	Preference toward local jobs, local economic priorities	M
	Community benefits	M/M	Various	Various social, political, cultural factors	M
	Global Environmental impacts	H/M	Secondary impacts of O&M strategies	Location of community, potential for fossil fuel replacement	M
	Pollution	M/L	N/A	N/A	N/A
	Tax/ Rate impact	M/L	N/A	N/A	N/A
	Energy security	M/L	N/A	N/A	N/A
Acceptable for permitting and certification	Local environmental impacts	H/M	Different operating timeframes, adaptive monitoring possible	Local species and ecosystem characteristics	M
	Spatial conflict	H/H	Devices can be removed during seasons with high conflict	Local ocean uses	M
	Grid compliance	H/L	N/A	N/A	N/A
Safety	Safety	H/L	N/A	N/A	N/A
Deployability	Local ability to operate and maintain	H/M	Secondary impacts stemming from O&M strategies	Seasonality of local employment, marine infrastructure, available workforce	M

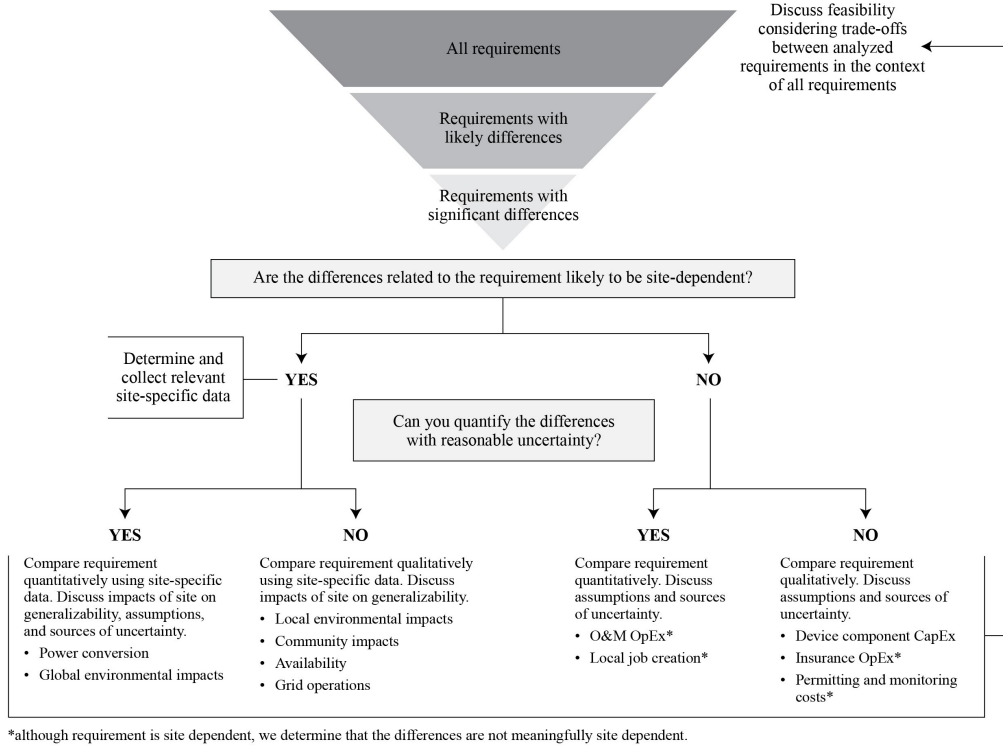


Figure 1: Our holistic approach to comparing seasonal deployments to year-round deployments that account for relevance of requirements, site specificity, and limitations due to uncertainty.

sub-requirement in our analysis is based on both how impactful the potential differences could be as well as our ability to assess them in a meaningful way with available data and techniques.

Once we narrow the requirements, we determine our method of comparison using the questions in the bottom half of Figure 1. We compare seasonal deployments to year-round deployments with respect to the requirement either quantitatively or qualitatively and either with or without site-specific data. The qualitative discussions serve to give a holistic account of potential differences between deployment types while maintaining a reasonable scope for the paper. In the following paragraphs, we define each requirement, briefly introduce our method of comparison, and justify our choice. Details about the method of comparison and the implications of our assumptions are

provided in their respective sections.

We compare power conversion quantitatively using site-specific data. Annual average energy production (AEP, a common metric of power conversion), is dependent on the energy available in the waves and the efficiency of mechanical, electrical, and combined power conversion. To compare power conversion across deployment types, we model a seasonally-optimized WEC in sea conditions local to our case study site. Given that a seasonal deployment would only be in the water for a portion of the year, we know that the difference between seasonal and year-round deployment energy production will be meaningful and require detailed analysis.

Our power conversion analysis, when combined with information about local grid needs, allows us to consider the usefulness of the power produced. The grid operations requirement in Table 4 accounts for the fact that electricity added to the grid should be predictable, stable, and useful. Without meeting these requirements, the value of the electricity produced may be undercut [26; 27; 28], especially in an isolated electric grid. When considering seasonal deployments, we look at electricity production relative to demand and the current generation on the grid. Because a full grid analysis is out of scope of this paper, we compare power conversion results to data about demand and hydropower production in Sitka.

Availability, defined as the percentage of time a device is producing power [29; 30], is another important factor which impacts energy production [31; 27; 29]. Availability depends primarily on reliability—how often and how severely a device fails—and on access—how easy it is to access the device for repair when it does fail [32]. Access can be limited by sea conditions, daylight, vessel availability, and weather [33; 29]. We compare availability qualitatively, considering available local data related to sea conditions and daylight. We discuss potential impacts of our proposed maintenance approach on failure. Due to the lack of empirical baseline data on failure and access rates for wave energy, a qualitative approach is appropriate.

Cost of energy is the most common performance metric used in development [34]. Often measured as levelized cost of energy (LCOE), this requirement accounts for the total costs and the total energy production and measured in kWh . Costs are broken into capital costs (CapEx) and operational costs (OpEx). As shown in Table 1, Babarit et al. further divide those costs into five sub-requirements. CapEx is divided into device component costs; infrastructure, mooring, and installation costs; and design, site assessment, environmental compliance, and contingency costs [35]. OpEx is

divided into O&M costs and insurance and monitoring costs.

Of these five cost sub-requirements, we assume that infrastructure, mooring, and installation CapEx and design, site assessment, etc. CapEx are similar across deployment types. While we will discuss the need for quick-release mooring technology to enable repeated recovery and redeployment, we do not consider this an additional CapEx requirement of seasonal deployments because it is desirable for all deployment types. Additionally, if we were to consider different infrastructure across deployments, we would need to model O&M costs differently and they would contain more uncertainty. As such, the results of this paper, in terms of overall feasibility, are limited by our assumption of comparable infrastructure costs.

Of the remaining three sub-requirements, we look at O&M costs quantitatively and device component costs and insurance and monitoring costs qualitatively. O&M costs have been shown to be highly variable, uncertain, and site specific [36], however they are expected to have a significant impact on the cost of energy, especially in early deployments [37]. We also expect to see a major difference between O&M costs between deployment types due to different O&M strategies. Therefore, we build a comparative cost model for O&M costs.

Although device component costs account for a large percentage of total costs [37], we do not create detailed comparative cost models because we assume the large majority of components will be the same across deployment types. Instead, we describe the main components and the ways in which their costs could differ. Insurance is often assumed to be a constant percentage of CapEx [35], so we treat it alongside component CapEx. Insurance costs might be different across deployment types in ways that are independent of CapEx, but due to uncertainty and situation dependence, we choose to assume insurance as a percentage of CapEx as other studies do. We qualitatively examine the different aspects of permitting and monitoring costs and discuss possible differences across deployment schemes.

Partly due to high uncertainty in LCOE estimates, there are only a few studies that attempt to characterize total costs for wave energy projects. Those studies include the Reference Model Project (RMP) conducted by U.S. Department of Energy National Laboratories [38], studies on the Pelamis and Wavestar devices [39; 40], a policy report from IRENA [41] and a several publications summarized by Astariz and Iglesias [37]. From these studies, device component CapEx ranges 20-40% of total costs; infrastructure, mooring, and installation CapEx 10-30%; design, site assessment, environmental

compliance, and contingency CapEx 10-25%; O&M OpEx 5-30%; and insurance and monitoring OpEx 10-20%. Copping et al. estimate permitting and monitoring could account for almost 19% of total costs [42], considering environmental regulations specific to the United States. For each cost sub-requirement that we consider, we use these percentages to contextualize potential cost savings within the total costs.

We consider global and local environmental impacts. For global environmental impacts, we calculate the greenhouse gas emissions associated with the transportation needs of the different O&M strategies. For local environmental impacts, we take a qualitative approach, discussing the differences in potential local environmental impacts according to the categories suggested by the *OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World* report [43]. Referencing the most current environmental effects literature, we reason potential differences based on our assumptions about device and vessel presence as well as our knowledge of the seasonal variations in the presence of wildlife near Sitka, Alaska.

We take a qualitative and site-specific approach to analyzing differences in community impacts and deployability, bolstered by a calculation of local jobs for each deployment type. When we consider deployability for coastal communities, we think about the ability of the community to operate and maintain a wave energy deployment. We integrate knowledge of local infrastructure and workforce. Investment opportunity, and safety are requirements that we assume will not be meaningfully different under a seasonal deployment.

4. Case Study Sitka, AK, USA

Sitka, AK is an island community with about 8,500 residents [44] served by municipally-owned and isolated water, sewer, and electricity systems. Fishing and its associated industries make up a large portion of the economic activity [45]. Currently, two hydropower dams serve Sitka’s electric grid at Blue Lake (15.9MW nameplate capacity) and Green Lake (18.6MW nameplate capacity). Diesel generators (15MW capacity) serve as back-up power [46; 47]. City leadership in Sitka expects to need additional renewable generation in the next 5-10 years in order to support a new regional hospital and increased electrification without increasing their reliance on imported diesel.

To address the future needs of Sitka’s electrical system, the city government applied to participate in the Energy Transitions Initiative Partnership Program (ETIPP) through the U. S. Department of Energy (DOE). ETIPP provides technical assistance from the national laboratories to remote and island communities interested in increasing their energy resilience [48]. The wave resource data that we use in this paper is from Biorka Island, a site chosen by the city as part of the ETIPP project as a potentially suitable location for wave energy development. The selection of this site was based on a potential opportunity to receive funding to connect Biorka Island to the main electric grid to power the Federal Aviation Administration (FAA) station located on the island. It is notable that without that funding and infrastructure, a transmission line connecting a wave energy farm to Sitka’s grid would require 7-10 kilometers of underwater cabling to reach Sitka, likely making the project financially infeasible.

We consider the seasonal deployment to be from October 1 to April 30. While the models that we present in this paper could be used to make a more informed decision about the ideal length of a seasonal deployment, our priority is to first get a better sense of the general feasibility of seasonal deployments. We chose this time frame using our knowledge of the wave resource (presented in Section 5.1) and the seasonality of ocean uses in Sitka. From April to May is the largest decrease in energy flux, and from September to October is the largest increase, therefore, we chose those bounds for the seasonal deployment. In a different location, we would likely choose a different timeframe.

As many of the studies on wave energy for remote coastal communities emphasize, design decisions and study conclusions are site-specific [2; 14; 13]. In Table 2, we show the site-specific data that we used in investigating each sub-requirement.

5. Power Conversion Comparison

5.1. Seasonal Wave Data

The wave resource data for Sitka is from the U.S. Department of Energy Water Power Technologies Office’s U.S. Wave Dataset, which includes historical wave statistics for Alaska from 1980 to 2009 (missing 1991) in 3-hour temporal resolution and 200m to 10km spatial resolution depending on depth (deeper waters have lower resolution) [49]. We extracted the data using open source code from [50].

Table 2: Site-specific data from Sitka, AK that we use in comparing different sub-requirements.

Sub-requirement	Section	Data
Power conversion	5	Wave hindcast
Grid operations	5	Daily and monthly average load
Grid operations	5	Trends in generation
Availability	5	Wave heights
Availability	5	Daylight hours
Global environmental impacts	7	Geographical coordinates
Local environmental impacts	7	Endangered species
Local environmental impacts	7	Marine mammal presence
Local environmental impacts	7	Marine habitats
Community impacts	8	Fisheries
Community impacts	8	Workforce trends
Community impacts	8	Available infrastructure
Community impacts	8	Tourism trends
Community impacts	8	Subsistence marine uses

The site west of Biorka Island (56.8447, -135.5664), is outside the Sitka Sound and represents one of the largest wave resources available near Sitka. The water depth is about 39m. This site was not selected for this paper through a rigorous site selection process, but instead was chosen by leaders in Sitka, as noted in Section 4.

Figure 2 shows the average annual energy matrix over the 29 years of data. The average annual energy matrix gives the mean normalized annual energy—the portion of the totaled, averaged energy over the given timeframe—according to the wave height and wave period containing that energy. Most of the wave energy near Biorka Island is in 1-4m high waves with 6-10s energy periods and most waves come from the southwest. Variability-related statistics are compared for seasonal and year-round deployments in Table 3. Figure 3 shows the monthly averaged wave energy flux, energy period, and significant wave height.

We used a K-means clustering approach to create representative spectra for each month of the year [51]. K-means clustering has been previously used for wave classification [52] and for establishing conditions for tank testing [53]. This method allows us to represent 95.9% of the energy within the dataset while only using four characteristic spectra for each month of data.

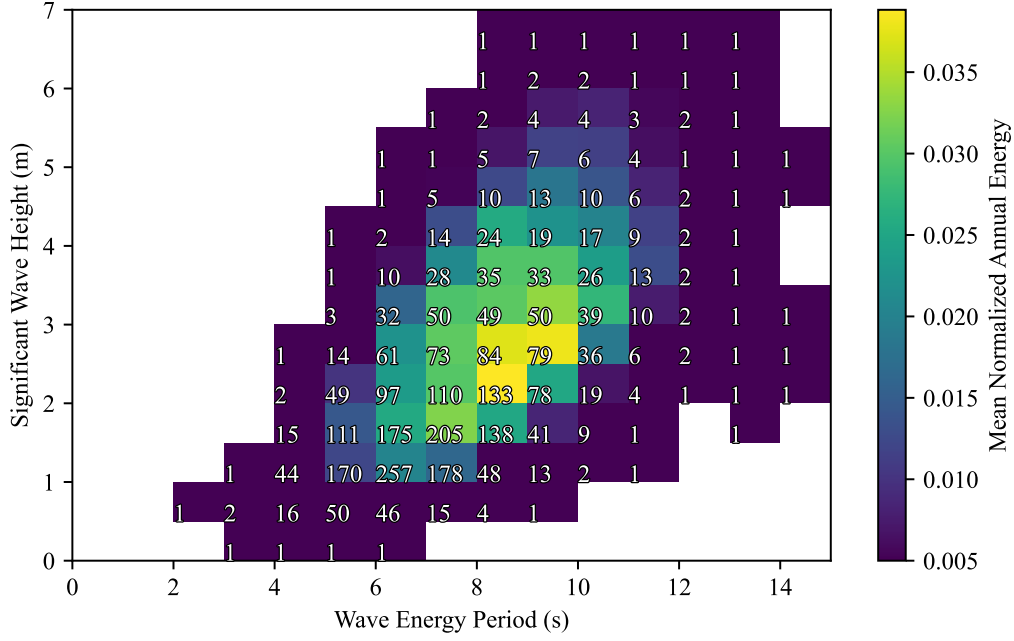


Figure 2: Average annual energy matrix for site near Biorka Island at (56.8447, -135.5664) according to hindcast data from 1980 to 2009 (missing 1991). The number in each box represents the number of datapoints in that bin, while the color bar indicates the amount of energy contained in each bin over the course of the average year, normalized over the 29 years of data.

Figure 4 shows the clustered data for the month of January alongside the 48 cluster centroids, each labeled with their respective month. The colorbar on the right gives the weight of the representative spectra. For every month, the weights of the four representative spectra sum to 1. Table .11 in the appendix gives the significant wave height and energy period of each of the four spectra for each month, as they are plotted in Figure 4.

5.2. WEC

We use a single body, axi-symmetric point absorber with a WaveSpring PTO component that can provide a negative spring stiffness, similar to that designed and tested by CorPower technologies [54]. The model that we propose does not represent the CorPower WEC.

Negative spring stiffness PTO components were initially proposed in 2014

Table 3: Statistics for the modeled wave energy site near Biorka Island.

	year-round	seasonal
Seasonal Variability Index	-	1.54
Spectral Width	0.35	0.32
Directionality Coefficient	0.94	0.94
Monthly Variability Index	1.33	0.67
Annual Variability Index	0.61	0.63

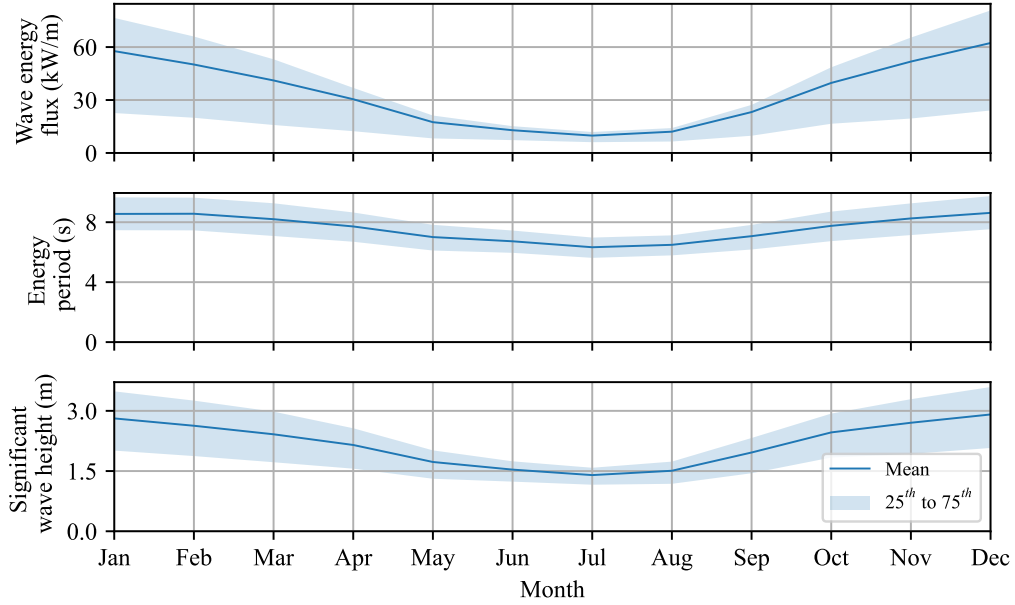


Figure 3: Monthly averaged wave energy flux, energy period, and significant wave height near Biorka Island

[55; 56], and have since been modeled and experimentally tested with a variety of WECs at a variety of scales [57; 58; 59]. The WaveSpring has the benefit of being able to shift the resonance period and increase the response bandwidth for a WEC, achieving high power conversion without the need for large inputs of reactive power from electric components. Providing reactive power requires PTO machinery to facilitate bi-directional power flow in which the peak reactive power can be much larger than the peak active power [60]. Reactive power PTO machinery can be excessively large, expensive, and

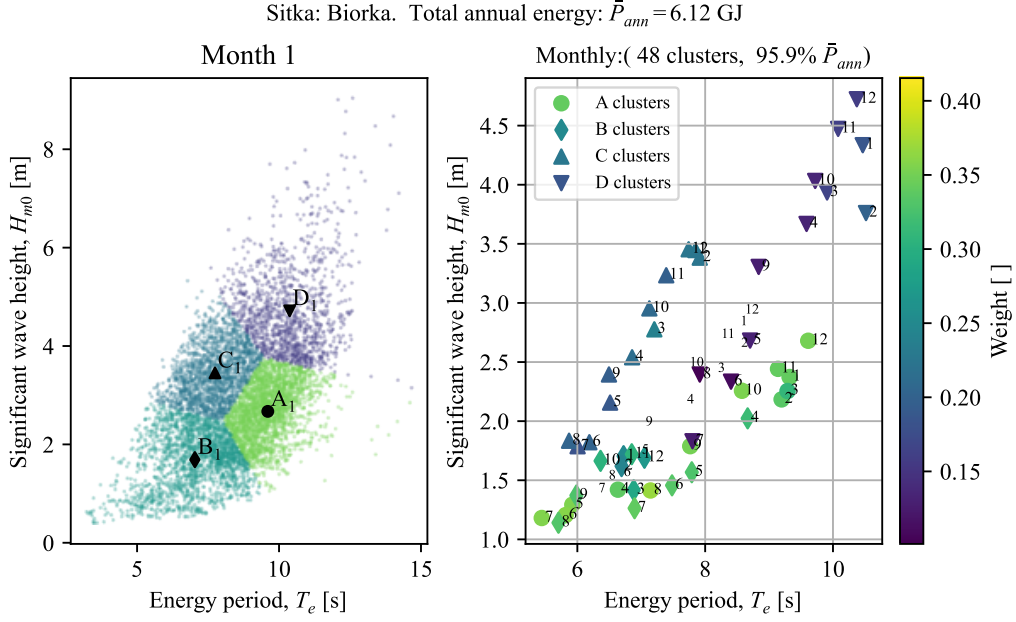


Figure 4: K-means clustering of 29 years of hindcast data at Biorka Island. On the left is the clustered data for the example month of January. Plotted on the right are the 48 cluster centroids, each labeled with their respective month. The color of the plotted centroid indicates the weight of each spectra represented by the centroid.

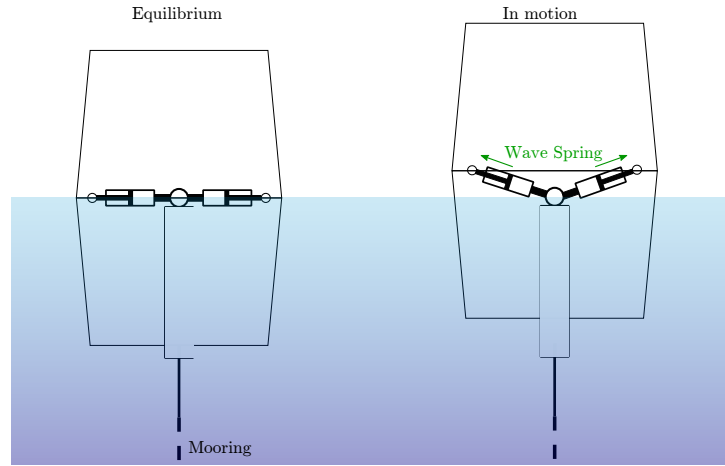


Figure 5: Sketch of a WEC inspired by early iterations of CorPower technologies [54].

subject to high losses [61], which the WaveSpring avoids.

We consider our model WEC to be moored to the sea floor by a single tension mooring with tidal compensation and quick-release technology [62]. The quick-release mechanism would allow rapid and safe connection and disconnection of moorings and electrical cables to marine renewable devices, in a single operation. Mooring mechanisms with similar functionality are essential for seasonal deployments, although they provide the added benefit of ease of recovery to any deployment. We should note that different WECs could have been used in this investigation, however, we do not provide an overview of WEC types. Numerous overviews can be found in the literature i.e. [63; 64]. Optimizing a different device would have given different power conversion outcomes, however, we assume that the comparison between seasonal and year-round would be similar given similar constraints. We recognize a need for more comparative studies that consider multiple WECs, however that is out of scope for this paper.

5.3. Control and PTO Parameter Optimization

Given that sea conditions could have an impact on the optimal WEC parameters, we optimize the WEC parameters for maximum power production using both the seasonal and year-round wave data. We use the Sandia National Laboratories’ open-source control co-design tool, *WecOptTool* [65]. *WecOptTool* is based on the pseudo-spectral method which efficiently deals with linear or nonlinear constraints and nonlinear dynamics by solving the WEC optimal control problem in the time domain using a gradient based optimization algorithm [66]. *WecOptTool* solves the optimal control problem in the inner loop, and supports user-definition of the outer loop of the optimization problem.

On the outer loop, we discretely sweep over four WEC hardware parameters and the overall geometric scale of the WEC, calculating the power with the optimal controller for every combination of parameters so that we can observe trends. The controller and hardware parameters are dynamically coupled, meaning they interact with one another and impact power performance in such a way that for each set of hardware parameters, the optimal controller and the power performance are different. This means that rather than having independent optimal solutions for hardware parameters and a controller, there is instead a single, interdependent, optimal set. This reality of dynamic coupling is the fundamental driver for control co-design of WECs [67].

Figure 6 illustrates the nested loop structure we chose for setting up the optimization problem. We run the simulations with one spectra at a time, summing the power performance over each of the four spectra to get the monthly average power, then summing over the months to get the annual average power. When inputting the spectra into the simulations, we use multiple random phase realizations because average power production can vary between phase realizations. In alignment with IEC standards [68], the simulation length is such that they represent 20 minutes of the sea state. In the following sections, we describe the optimization problem mathematically.

5.3.1. Outer Loop Optimization Problem

The main objective in the optimization study is to find a combination of feasible WEC parameters ψ that maximize the converted electrical energy over the course of the operational year $W_{\text{elec}}^{\text{ssn}}$, or, formulated as an optimization problem:

$$\begin{aligned} \min_{\psi} . \quad & -W_{\text{elec}}^{\text{ssn}}(\psi) \\ \text{s.t.} \quad & \\ & \psi \in \Psi, \end{aligned} \tag{1}$$

where Ψ denotes the parameter search space with dimensions

N Gear ratio between linear motion and PTO shaft rotation,

R_b Ballast ratio of additional ballast relative to WEC mass,

$\mathcal{S}_s$ Scale of the WaveSpring force profile,

R_L Length ratio between hull diameter and the WaveSpring cylinder.

Every possible combination of those coordinates composes a feasible configuration ψ . Table 4 shows the discrete choices for all four parameters— or dimensions— in the search space. Each of the parameters is independent. We run the optimization for each of the three WEC scales.

For the WEC scales, the 1.0 scale is the suggested dimensions (8.4m diameter) and dry body mass (78.0kg) listed for the CorPower device, which was tank tested at 1:16 scale by Todalshaug et al. [54]. For the 1.1 and 1.2 scales, we scale all geometric dimensions linearly and recalculate with new volume and mass assuming the same density as the 1.0 scale device. Scaling the size of the device results in a different required pretension to achieve the same still water position given the new displaced volume. The gear ratio is

Table 4: Possible values for free parameters

Parameter	Discrete Choices
WEC scale	1, 1.1, 1.2
Gear Ratio $[N]$	10-24 in steps of 2 (8 choices)
Ballast Ratio $[R_b]$	0-3.5 in steps of 0.25 (15 choices)
Spring Factor $[\mathcal{S}_s]$	0.0, 0.4, 0.8
Cylinder Length Ratio $[R_L]$	0.5, 0.7, 0.9

the ratio between the linear motion of WEC hull and rotary motion of the generator shaft. We chose the gear ratio inputs initially by best guess, but then altered them according to the trends we saw in test sweeps. The ballast ratio is the additional ballast added to the hull, measured as a portion of the initial mass. This ratio is, therefore, a function of the WEC scale. This is why we do not include WEC scale in the search space, but instead run the three discrete options independently. We sweep from no ballast to a ballast of 3.5 times the initial mass. The ballast ratio has the highest number of discrete choices, which we chose in order to capture the dynamics that we observed in early variable sweeps. The spring factor is a multiplier that we apply to the nonlinear force profile of the wave spring. We chose the inputs such that the spring stiffness near the origin is 80% of the hull's hydrostatic stiffness. Keeping the spring stiffness less than the hydrostatic stiffness ensures that the WEC remains stable. The cylinder length ratio is the length of the WaveSpring cylinder as a function of the hull radius at it largest diameter.

The seasonal energy is the sum of the monthly average electrical power from the start month number N_s to the end month N_e multiplied by the number of hours in the respective month h_m ,

$$W_{\text{elec}}^{\text{ssn}}(\psi) = \sum_{m=N_s}^{N_e} h_m \bar{P}_{\text{elec}}^{\text{mnt}}(m, \psi). \quad (2)$$

The monthly average electrical power is the weighted average over the optimal (indicated with *) average power for each sea state cluster c , during the respective month,

$$\bar{P}_{\text{elec}}^{\text{mnt}}(m, \psi) = \sum_{c=1}^{N_c} w_c \bar{P}_{\text{elec}}^*(x_{\psi mc}^*, S_c, \psi), \quad (3)$$

with $\sum_{c=1}^{N_c} w_c = 1$.

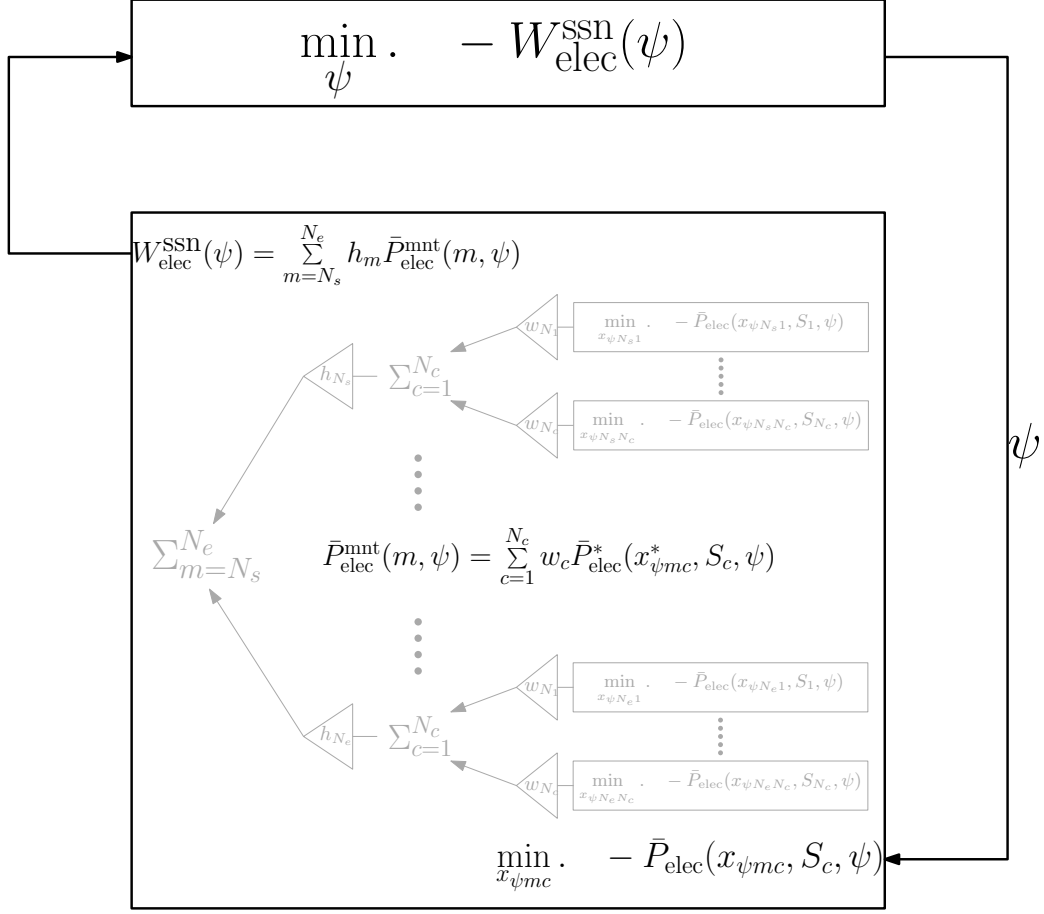


Figure 6: Visualization of the multi-level WEC optimization conducted using **WecOptTool**.

5.3.2. Inner Loop Control Optimization

The inner loop optimizes the control trajectory for the WEC model given the parameters ψ and the irregular wave spectrum S_c , where the subscript c indicates that the spectrum is dependent on the cluster, as described in Section 5.1. That optimization is formulated as:

$$\begin{aligned}
 & \min_{x_{\psi mc}} \quad -\bar{P}_{elec}(x_{\psi mc}, S_c, \psi) \\
 & \text{s.t.} \\
 & r(x_{\psi mc}, S_c, \psi) = 0 \\
 & c_{ineq}(x_{\psi mc}) \geq 0
 \end{aligned} \tag{4}$$

Here, $x_{\psi mc}$ denotes the optimization state vector and the subscripts indicate that there is a distinct optimal vector for each configuration ψ , month m , and cluster c , respectively. The optimal solution for the state vector is denoted $x_{\psi mc}^*$. $x_{\psi mc}$ includes both the WEC dynamic state vector x_{wec} and the control state vector x_{opt} as shown in (5).

$$x_{\psi mc} = \begin{bmatrix} x_{\text{wec}} & x_{\text{opt}} \end{bmatrix} \quad (5)$$

5.3.3. Equality Constraint

In (4) the equality constraint enforces the WEC-PTO dynamics which we express in residual form, in similar fashion to [66],

$$r(t) = (m(1 + R_B))\ddot{z}(t) - f_r(t) - f_{\text{ex}}(t) - f_{\text{hs}}(t) - f_a(t) - f_{\text{reac}}(t) - f_{\text{ten}}(t). \quad (6)$$

Here m denotes the rigid body mass, before adding ballast R_B . **WecOptTool** would be capable of considering additional equality constraints, but we do not need any to accurately model the device dynamics and finite limitations.

The WEC heave position time trajectory $z(t)$ information is contained in the components of its Fourier decomposition in the vector x_{wec} and in the optimization variables for the controller contained in the control state vector x_{opt} [69]. For a numerically optimal controller the PTO force, which is the control state, has the same number of frequency components as the position vector and therefore the PTO trajectory can be chosen freely, as long as it satisfies the dynamics and constraints. This type of controller is referred to as unstructured controller in [69]. In this optimization study we also investigate the performance for a control trajectory with an imposed structure. Specifically, a well-known proportional-integral (PI) controller. For the PI controller the PTO force will be combination of the scaled WEC velocity $\dot{z}(t)$ and $z(t)$ and the optimally tuned PI components K_p and K_i are solved for using **WecOptTool**. Performance was not notably different between controller structures, therefore we show results only from the unstructured controller.

The considered forces f are

f_r : The radiation force which is subject to WEC motion and the radiation damping boundary element method (BEM) coefficient

$f_{\text{ex}} = f_{\text{fk}} + f_{\text{di}}$: The excitation force due to the Froude-Krylov force f_{fk} and its wave diffraction force vector f_{di} , using excitation and diffraction BEM coefficients.

f_{hs} : The hydrostatic restoring force, which is a nonlinear function of the WEC position

f_{a} : The actuation force due to the PTO with generator where $f_{\text{a}} = -f_{\text{pto}}$ is the control input (and thus an optimized trajectory).

f_{reac} : A nonlinear force due to the reactive component in the PTO, namely the WaveSpring

f_{ten} : A linear force due to the tension system, which keeps the mooring line under tension and achieve the desired still water line.

The forces f_{r} and f_{ex} are inherently computed with `WecOptTool` when initializing a WEC with BEM results. `WecOptTool` offers an interface with the BEM solver `capytaine`. We fully utilize this functionality by using a parameterized geometry depending on $\mathcal{S}_{\text{w}}$, meshing it with `pygmsh` and solving for the BEM coefficients with `WecOptTool`'s wrapper function around the `capytaine` solve. The output of `capytaine` also includes a hydrostatic stiffness coefficient, which is the area of the WEC intersection with the still water line. Inherently, `WecOptTool` would also compute a linear hydrostatic restoring force based on this coefficient assuming a cylinder, but we set this force to zero and instead define a custom hydrostatic restoring force to account for the tapered shaped of the hull assumed in this study (Figure 5),

$$f_{\text{hs}} = \left((V_0 - V_{\text{tc}}(z))\rho - m(1 + R_B) \right) g. \quad (7)$$

Here g denotes the gravitational constant, ρ the density of sea water, V_0 the displaced volume at the still water line, which in combination with $V_{\text{tc}}(z)$ gives the instantaneous displaced volume of the truncated cone, and,

$$V_{\text{tc}}(z) = \frac{1}{3}\pi z(r_{\text{w}}^2(z) + r_{\text{w}}(z)r_{\text{b}} + r_{\text{b}}^2), \quad \text{with} \quad (8)$$

$$r_{\text{w}}(z) = r_{\text{b}} \frac{h_{\text{b},0} - |z|}{h_{\text{b},0}}. \quad (9)$$

Here, r_{b} denotes the radius at the largest section of the hull (which is supposed to sit at the still water line), $r_{\text{w}}(z)$ denotes the instantaneously wetted radius (the radius that currently intersects with the free surface), and $h_{\text{b},0}$ denotes the desired buoy draft at equilibrium. The force function from the

WaveSpring is based on assuming linear air compression and using simple trigonometry to determine in the nonlinear expression,

$$f_{\text{reac}} = K_{\text{s,eq}} \frac{\ell_{\text{c},0}^2 z}{\ell_{\text{c},0}^2 + z^2}, \quad (10)$$

where the equivalent stiffness is

$$K_{\text{s,eq}} = \mathcal{S}_s(K_{\text{hs},0} + K_{\text{ten},0}), \quad \text{with} \quad (11)$$

$$K_{\text{hs},0} = \pi \rho g r_b^2, \quad (12)$$

and the stiffness of the pretension system $K_{\text{ten},0}$ is a scalar from [54].

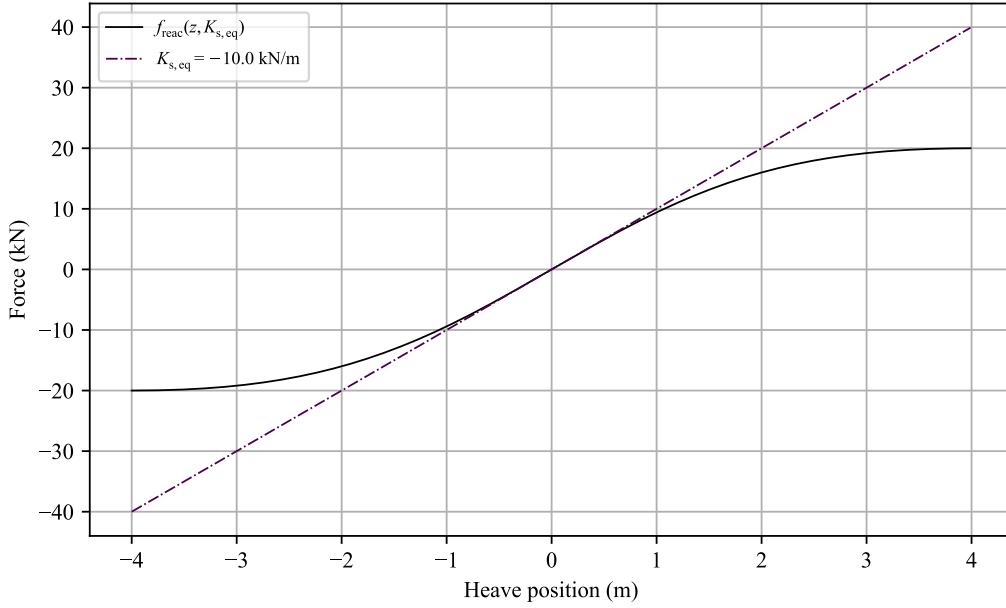


Figure 7: WaveSpring force profile for an arbitrary equivalent stiffness $K_{\text{s,eq}}$.

Figure 7 illustrates the force profile for an arbitrary equivalent stiffness in comparison to the linear implementation with the same stiffness.

The tension force is modeled as

$$f_{\text{ten}} = K_{\text{ten},0} z - f_{\text{hs}}(z = 0). \quad (13)$$

5.3.4. PTO Dynamics and Actuation Force

`WecOptTool`'s `pto`-module offers functions to model PTO dynamics in terms of an impedance matrix, relating the linear PTO force f_{pto} and load voltage V_{out} with the velocity $\dot{z}(t)$ and generator current I . This allows us to model bidirectional power flow. Analog to [69], but with the sign convention followed here, the force and voltage are modeled as:

$$\begin{bmatrix} f_{\text{pto}} \\ V_{\text{out}} \end{bmatrix} = \begin{bmatrix} N^2 Z_d & -\sqrt{\frac{2}{3}} N k_\tau \\ \sqrt{\frac{2}{3}} N k_\tau & Z_w \end{bmatrix} \begin{bmatrix} \dot{z} \\ I \end{bmatrix} \quad (14)$$

Here, k_τ denotes the generator torque constant, and Z_d and Z_w denote the rotational drive-train and the electrical generator winding impedance, respectively, which imply in the time domain

$$Z_d N \dot{z} = (J_g + J_d) \ddot{z} + B_d \dot{z} \quad (15)$$

$$Z_w I = L_w \dot{I} + R_w I. \quad (16)$$

For the generator we consider a commercial-of-the-shelf SIEMENS 1FW3 complete torque motor from the catalog [70], specifically, the model 1FW3287-2□E. The instantaneous electrical power can be computed from the PTO power variables

$$P_{\text{elec}} = I V_{\text{out}}, \quad (17)$$

and the averaged electrical power is part of the objective function in (4).

$$\bar{P}_{\text{elec}} = \frac{1}{t_f} \int_0^{t_f} V_{\text{out}} I dt \approx \frac{1}{N_t} \sum_{n=0}^{N_t-1} V_{\text{out}}(t_n) I(t_n), \quad (18)$$

where t_f denotes the final time and N_t the number of time steps.

5.3.5. Inequality Constraints

Finite limitations of the drivetrain hardware and the WEC's functioning principle are imposed in the numeric model through inequality constraints. Realistic constraints are crucial for optimization studies, else the optimizer might exploit unrealistic physics (which the optimizer is not aware of if not modeled).

`SciPy`, the library that `WecOptTool` uses per default, allows for an effective way to reduce two symmetric constraints into one. A symmetric

constraint with generalized equation $k - |x| \geq 0$, is equivalent to $-k \leq x \leq k$ and we will use this form the present the inequality constraints in this study.

To prevent generator overloading, we introduce constraints that limit peak torque $T_g^{\max}$, maximum speed $\Omega_g^{\max}$, rated power P_g^{ra} , and ensure respect for continuous torque limits. However, we formulate and model them in the linear force frame, to apply them to the **WecOptTool** optimization trajectory f_{pto} directly and fully utilize the built in functions of the **WecOptTool** `pto`-module.

$$\text{Peak force : } c_{\text{ineq},1} = NT_g^{\max} - |f_{\text{pto}}(t)| \geq 0, \quad (19)$$

$$\text{Max. speed : } c_{\text{ineq},2} = \frac{\Omega_g^{\max}}{N} - |\dot{z}(t)| \geq 0, \quad (20)$$

$$\text{Avg. power : } c_{\text{ineq},3} = P_g^{\text{ra}} - |P_{\text{elec}}(t)| \geq 0, \quad (21)$$

$$\text{Conti. force : } c_{\text{ineq},4} = \frac{NP_g^{\text{ra}}}{\Omega_g^{\text{ra}}} - \sqrt{(f_{\text{pto}}^2(t))} \geq 0. \quad (22)$$

The constraints for peak and average limits (19-21) are symmetric constraints, but (22) is not symmetric [66]. A generator's continuous current rating is usually given for steady state operation, but the alternating nature of wave energy and thus the electrical machine operation requires us to limit the root-mean-square (RMS) force (22). The continuous application of the RMS force value results in the same thermal heating as would be calculated in a time-domain simulation. Such a constraint is a unique capability of the pseudo-spectral method because it evaluates the entire time trajectory at once and instead of relying on compromises like a moving average value of the torque signal, as would be required in initial value problems. This enables easy syntheses of the optimal control design.

We introduce a PTO stroke constraint to model a form of physical limitations for the linear pistons that provide the negative spring stiffness. We choose the upper limit to be equal to the full radius. This would imply a maximum angle between the horizontal and the spring cylinders of 45° if the cylinders was fully extended.

$$\text{Stroke constraint : } c_{\text{ineq},5} = r_b s - |z(t)| \geq 0. \quad (23)$$

5.4. Power Conversion Results

As we discuss in the following subsections, our power conversion results give the same optimal PTO parameters for both seasonal and year-round

deployments, along with the same trends in power conversion across those PTO parameters. We show that the modeled WEC has a higher capacity factor in the summer season, and using information from Sitka, we show how the seasonal production aligns with seasonal need in the months of December through April. We discuss the potential consequences seasonal deployments on availability, integrating wave and daylight data.

5.4.1. Optimal Configurations

The optimal configuration for our WEC is the 1.1 scale WEC with a gear ratio of 14, a ballast ratio of 2.25, a spring factor of 0.8, a cylinder length ratio of 0.9, and an unstructured (numerically optimal) controller. This is the optimal configuration for the seasonal deployment and the year-round deployment. As a check, we also optimized for the five summer months, and got the same optimal parameters. We did not expect this result, and we will further discuss it in Section 9.2. For the spring factor and length ratio, there was a clear, mostly linear trend of the optimal value to the highest possible value, shown in Figure 8. However, we found that the gear ratio and ballast ratio impact the power performance and need to be matched well to one another for near-optimum power performance. We show the trends in energy and power conversion with respect to the gear ratio and ballast ratio in Figure 8. Not only is the optimal the same across seasonal and year-round deployments, but the trends are also the same.

5.4.2. Power Conversion

During a seasonal deployment, the optimal configuration produces about 68% of the electricity produced during a year-round deployment near Biorka Island in Sitka, AK. The total energy available in the waves during that seasonal period is 81% of the energy available over the entire year, indicating that the WEC converts a higher percentage of the energy available in the waves— it has a higher capacity factor— in the summertime.

In Figure 9 we show the monthly average power converted by the WEC with optimal parameters. July averages around 18 kW while November, December, and January all average 35 kW or above. The average annual energy production for a single WEC is 172.4 MW h for a seasonal deployment and 253.8 MW h for a year-round deployment. For context, the average annual electricity demand in Sitka is approximately 120 GW h.

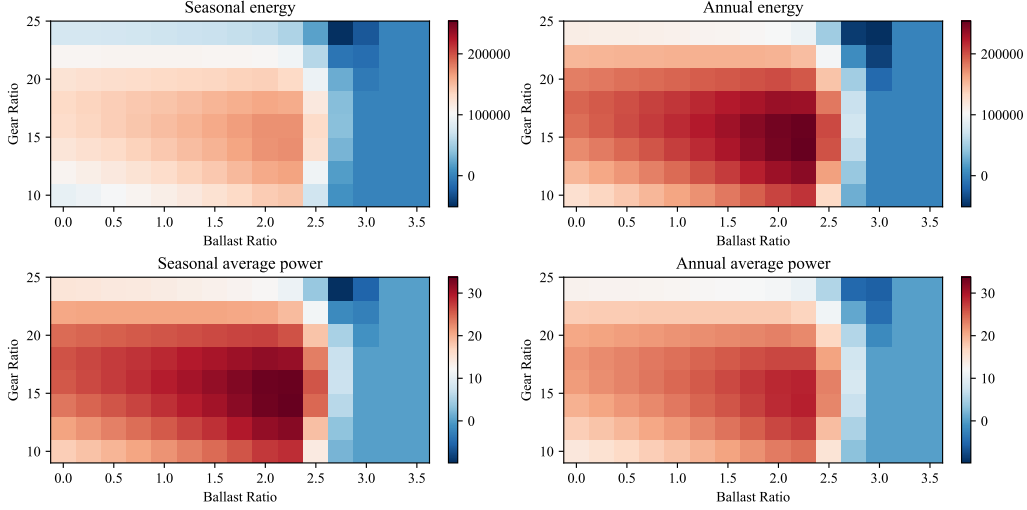


Figure 8: Trends in energy and power conversion over changes in gear ratio and ballast ratio for seasonal and year-round deployments.

5.5. Power Use for the Grid

For an isolated hydropower grid like Sitka’s, additional generation needs to align with unmet (or predicted unmet) demand. As shown in Figure 10, the electricity generation of a WEC trends well with the electricity consumption in Sitka, which is consistent with trends in much of the west coast of North America [49]. The differences between winter and summer generation are greater than the differences between winter and summer demand, however. Figure 11 shows daily average electric loads and predicated loads from [46]. We see that current electric loads tend to stay below 15 MW from mid April through November, with a slight increase during the month of July, likely related to salmon processing activities that align with salmon fishing season shown in Table 10. Considering the predicted future loads with electrification efforts [46], the average daily load nears the combined nameplate capacity of the dams in December, February, and April.

Given that all of Sitka’s current electricity demand is met through hydropower, the times when additional generation might be needed are the times when reservoir water levels are low and demand is high. This depends on rainfall and glacial melt [46]. The gray line in Figure 10 shows the average annual rainfall for Sitka from 1981 to 2010 [71]. Unfortunately, at this time,

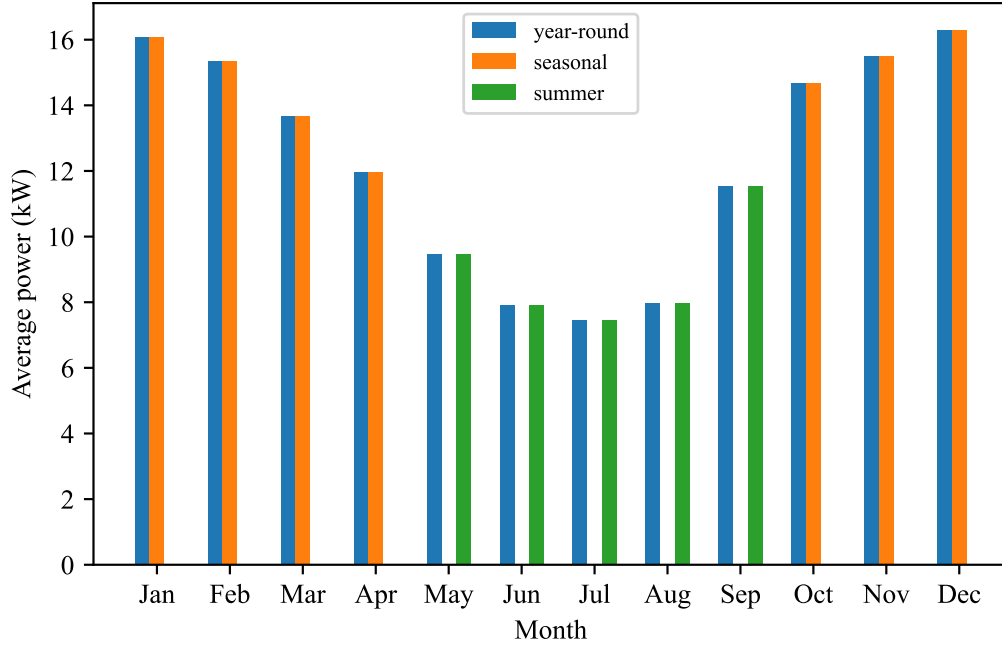


Figure 9: Average monthly power conversion for WEC optimized for seasonal (October-April), year-round, and summer (May-September) wave conditions. Scale=1.1, gear ratio=14, ballast ratio=2.25, spring factor=0.8, cylinder length ratio=0.9.

Sitka does not keep data on dam levels, however we know that the dams in Sitka often spill (meaning there is more water behind the dam than needed to meet electricity demand) during the months of September, October, and sometimes August. Therefore those are months when additional generation might not be as valuable. Early spring has the lowest production, and combined with the relatively higher electricity demand during these month, we can assume that additional generation would provide more value to the grid during March and April.

To fully understand the value added to the grid from a wave energy project in Sitka, a more detailed analysis would include hour-by-hour demand data, future predictions of demand, dam level data, and predictions of future dam levels given changes to rainfall and glacial melt patterns. It might also require a comparison to other renewable energy resources and exploration of storage opportunities. We do not yet have the data necessary for this

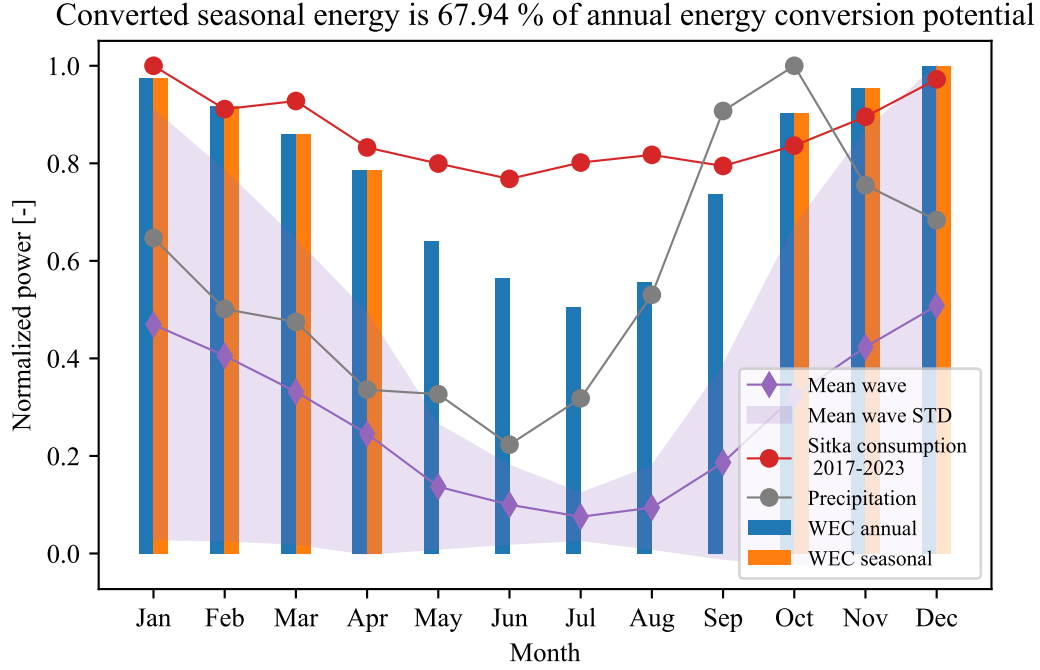


Figure 10: Overlay of WEC normalized power production with available wave power and Sitka electricity demand.

type of analysis in Sitka, and, furthermore, it is outside the scope of this exploratory paper. The data we have indicates a relatively higher value for additional generation in the months of November through April. This means that the 30% decrease in electricity production from a seasonal deployment over the course of the year could correspond to less of a decrease in added value, because the decreased production occurs during months with lower need. That said, without a compelling reason to remove the WECs during the off-season (such as spatial conflict or operational savings), a deployment could just as well stay in the water all year long, even when its generation might be of lesser value.

5.6. Availability

In Figure 12 we show the percentage of time that the significant wave height is under 1.5m and 2m according to hindcast data. These wave heights are typically used as thresholds for accessing an offshore device for maintenance or to address a failure [33; 72; 73]. There is a correlation between

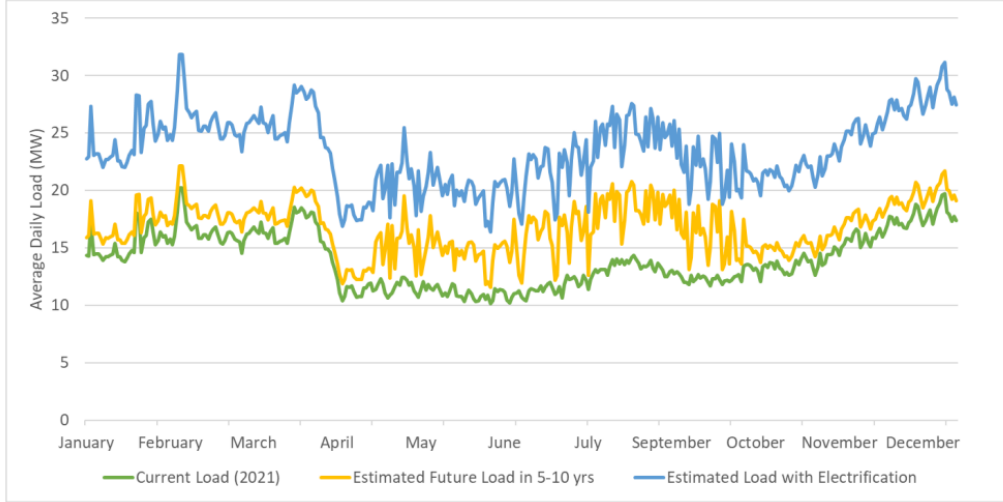


Figure 11: Sitka’s electric load, averaged daily, for the year 2021 along with estimated future loads with and without electrification taken from [46].

the percentage of time that wave heights exceed those thresholds and the availability of the devices [33; 74; 30]. Given that failure rates for WECs are highly uncertain, we do not model availability, however, these data related to access limits can help us make some assumptions. During the seven seasonal deployment months, significant wave heights are under 2m 50% of the time or less and under 1.5m 20% of the time or less. If we only consider November through February, it drops to 30% or less for 2m. In Figure 12, we include the daylight hours at Biorka, taken from the U.S. Naval Observatory’s nautical twilight dataset [75]. In October through February, there is less than 12 hours of daylight, further limiting the potential for offshore maintenance. What this tells us is that a failure during the winter months could result in significant downtime. If seasonal recovery could decrease the chances of winter failures substantially through the prevention of age-dependent failures [74], then this could have meaningful consequences for availability. However, without baseline knowledge of WEC failure rates (age-dependent or otherwise), it is difficult to predict this impact.

We show the percentage of time that the significant wave height is over 4m, a common threshold at which a WEC might enter a non-operational survivability mode. We do not estimate a survivability threshold for this

WEC specifically although they are WEC dependent [76]. From only the wave data, we can assume that any decreased availability due to the WEC entering a survivability mode would only be likely to occur in winter months and would be the same across deployment types.

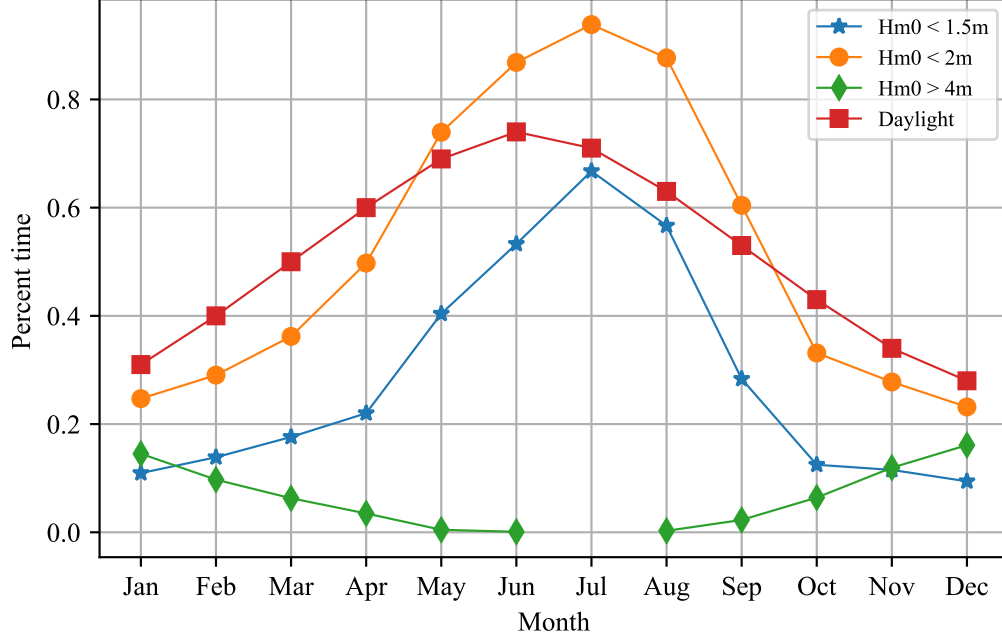


Figure 12: The percent of the time that the significant wave height meets respective thresholds related to accessibility and survivability.

6. Costs Comparison

In this section we consider O&M costs, components costs, insurance costs, and permitting and monitoring costs. All told, we present numerous opportunities for cost savings with seasonal deployments, but when they are contextualized in the overall costs and uncertainty, they range from negligible to 12%. We show that the difference in cost is most sensitive to factors related to the cost and labor needed for shoreside operations and maintenance.

6.1. O&M Costs

O&M costs include both marine and shoreside operations and planned and unplanned maintenance. Some estimates of O&M costs for wave energy

use information from offshore wind as a baseline [72; 30]. Others estimate O&M as a percentage of capital cost [40; 39]. The RMP makes estimates based on labor, vessel, and consumables rates [35].

Operation and maintenance activities include:

- Offshore maintenance
 - Planned onsite maintenance (frequency modeled as f_1): scheduled maintenance which occurs at the deployment site, including on a boat; may include biofouling removal, component maintenance, and routine inspection
 - Planned offsite maintenance (frequency modeled as f_2): scheduled maintenance which requires transporting devices from their deployment site to an shoreside facility; may include device refits or component maintenance
 - Unplanned onsite maintenance (frequency modeled as f_3): examples include removing objects that are entangled in the mooring system, replacing or repairing accessible failed components, and fixing failed cables or moorings
 - Unplanned offsite maintenance (frequency modeled as f_4): may include repair and replacement of components or, in the worst case, the recovery of a totaled device
- Shoreside maintenance: maintenance activities happening onshore associated with either planned or unplanned offsite maintenance
- Shoreside operations: regular monitoring of the devices, data collection and management and dispatch activities

6.1.1. O&M Cost Differences Model

The difference in O&M costs between seasonal and year-round deployments is calculated as the difference between the respective sum of local (C_{loc}) and nonlocal (C_{nonloc}) cost,

$$\Delta C_{\text{OM}} = (C_{\text{loc}}^{\text{year}} + C_{\text{nonloc}}^{\text{year}}) - (C_{\text{loc}}^{\text{seas}} + C_{\text{nonloc}}^{\text{seas}}). \quad (24)$$

We separate the local and nonlocal costs because we use local costs to calculate local economic impact. Local costs are those paid to local workers for labor during offshore maintenance ($_{\text{om}}$), shoreside maintenance ($_{\text{sm}}$), and shoreside operations ($_{\text{so}}$), as well as vessel, fuel, and consumable costs (C_{vfc}).

We assume the only non-local O&M costs are for labor associated with maintenance tasks ($_{\text{om}}$, and $_{\text{sm}}$),

$$C_{\text{loc}} = C_{\text{om}} + C_{\text{sm}} + C_{\text{so}} + C_{\text{vfc}} \quad (25)$$

$$C_{\text{nonloc}} = yP_{\text{nonloc}}(C_{\text{om}} + C_{\text{sm}}). \quad (26)$$

Here, y is the non-local crew factor, a multiplier representing our assumption that crew members who do not come from the local community have higher rates due to transportation costs and potential higher wages owing to their specialized expertise. We define the portion of non-local workers,

$$[ht]P_{\text{nonloc}} = \begin{cases} \frac{1-P^{\text{year}}}{P^{\text{year}}} & \text{if year-round,} \\ \frac{1-P^{\text{seas}}}{P^{\text{seas}}} & \text{if seasonal.} \end{cases} \quad (27)$$

Here, P^{seas} is the percentage of local crew for a seasonal deployment, P^{year} is the percentage of local crew for a year-round deployment. The respective labor associated costs in (25) and (26) are composed out of the respective number of crew (N), their rate (R), and the number of days (d) they work,

$$C_{\text{om}} = N_{\text{om}}R_{\text{om}}d_{\text{om}}, \quad \text{with } d_{\text{om}} = \begin{cases} P^{\text{year}} \sum_{i=1}^4 f_i & \text{if year-round,} \\ P^{\text{seas}}(2 + (f_3 + f_4)p_f) & \text{if seasonal.} \end{cases} \quad (28)$$

$$C_{\text{sm}} = N_{\text{sm}}R_{\text{sm}}d_{\text{sm}}, \quad \text{with } d_{\text{sm}} = \begin{cases} P^{\text{year}}(f_2 + f_4)d_r & \text{if year-round,} \\ P^{\text{seas}}(d_{\text{sm}}^{\text{seas}} + f_4d_r p_f) & \text{if seasonal.} \end{cases} \quad (29)$$

$$C_{\text{so}} = N_{\text{so}}R_{\text{so}}d_{\text{so}}, \quad \text{with } d_{\text{so}} = \begin{cases} 365 & \text{if year-round,} \\ 214 & \text{if seasonal.} \end{cases} \quad (30)$$

$$C_{\text{vfc}} = \begin{cases} \sum_{i=1}^4 f_i V_i & \text{if year-round,} \\ 2V_2 + (f_3 V_3 + f_4 V_4)p_f & \text{if seasonal.} \end{cases} \quad (31)$$

Here, f_i is the frequency of each operation (operations are defined in the following section), i , d_r is the number of shoreside maintenance days per device retrieval, $d_{\text{sm}}^{\text{seas}}$ is the number of shoreside maintenance days during the off-season of the seasonal deployment, and V_i is the vessel, fuel, and consumables rate for each operation. We expect that for seasonal deployments the device

servicing that happens during the non-operational season would decrease the risk of failures during deployment. We account for this expectation through the seasonal failure rate percentage (p_f).

6.1.2. O&M Cost Model Inputs and Sensitivity Analysis

Each model input is presented in Table 5 along with the associated input ranges.

Table 5: Input variables for O&M cost differences model		
	Input Variable	Ranges
1-4	Fulltime offshore operations frequencies $[f_1, f_2, f_3, f_4]$	$[0.5-2, 0.05-0.35, 0.1-0.5, 0.1-0.5]$ Days/year
5	Shoreside maintenance days per retrieval for year-round deployment/ unplanned offsite maintenance $[d_r]$	1-10 days/retrieval
6	Seasonal shoreside maintenance days $[d_{sm}^{seas}]$	20-40 days
7-10	Vessel, Fuel, Consumable Rate $[V_1, V_2, V_3, V_4]$	$[3000-6000, 3000-6000, 3000-6000, 3000-6000]$ \$/day
11-13	Local Crew Rate $[R_{om}, R_{sm}, R_{so}]$	\$240-560/day, \$240-480/day, \$200-400/day
14	Non-local Crew Factor $[y]$	1.1-1.6
15-17	Number of Crew $[N_{om}, N_{sm}, N_{so}]$	4-8 people, 2-4 people, 2-4 people
18	Local Crew Percentage (year-round) $[P_{fulltime}]$	0-0.5
19	Local Crew Percentage (seasonal) $[P_{seasonal}]$	0.5-1
20	Seasonal Failure Rate Percentage $[p_f]$	0.1-1

For a year-round deployment, we assume an O&M strategy similar to those presented in several other operations studies [33; 77; 35; 78]. Once operational, the deployment requires one day of planned onsite maintenance every six months to two years (represented in equations as (f_1)); a device refit, which includes recovery and servicing of all components, every three to ten years (f_2); unplanned maintenance caused by failures, which we assume to occur every one to five years with equal chances for onsite vs offsite

maintenance (f_3 and f_4); shoreside maintenance, which assumes each offsite activity requires one to ten days of associated shoreside maintenance (d_r); and shoreside operations, requiring two to four full-time employees (N_{sm}).

The O&M strategy for a seasonal deployment assumes that the only planned offsite maintenance occurs during the non-operational season, when the devices are inspected and serviced, and any inferior components are replaced. There is no planned onsite maintenance. Unplanned maintenance is still based on failures. We assume the seasonal failure rate percentage ranges from 0.1 to 1.

We expect that shoreside maintenance would take between 20 and 40 days per year. The operational season is 214 days and requires the same number of employees as the year-round deployment.

Our input crew rates are the equivalent of \$30-70 per hour for offshore work, \$30-60 per hour for shoreside maintenance work, and \$25-50 per hour for shoreside operations work. For simplicity, we input all vessel rates as a range between \$3000 and \$6000 per day. Other O&M models (i.e. [35; 33; 78; 79]) have other costs, of which ours are on the lower end. We do not include non-labor costs for shoreside maintenance and operations. We discuss the limitations consequent of these assumptions in Section 9.1.

We hold the number of crew needed for each type of maintenance constant across year-round and seasonal deployments, but vary the percentage of the crew that is local. We expect that the seasonal deployment would warrant the training of a local offshore crew, increasing the ratio of local workers for maintenance activities in seasonal deployments. This assumption follows a similar line of reasoning used to estimate the cost of permanent crews in [35]. For a seasonal deployment, we assume that 50-100% of the workers are local. For a year-round deployment we assume that 10-50% of maintenance workers are local.

There are 20 input variables to the O&M model that each have different levels of uncertainty, as shown in Table 5. We perform a variance based Sobol sensitivity analysis to determine which of those variables have the most significant impact on the O&M cost difference. We use the first 2000 points of the 2×20 dimensional low-discrepancy Sobol sequence to quasi-randomly resample the input parameter space, starting from median between upper and lower end of the input ranges. We produce two sample spaces, A and B , each containing 20 dimensions of the Sobol sequence. The inputs from A represent the varied inputs from the median within the viable ranges. Sample space B is used to radially re-sample the inputs from A , i.e. starting from

A we take a step in each of the (i) input parameters directions, towards B , while keeping the other input parameters fixed in A [80]. We use all the O&M cost difference outputs to quantify the total sensitivity indices, illustrated in Figure 13.

The difference in O&M costs for year-round and seasonal deployment is most sensitive to the input factors related to shoreside O&M. Figure 13 shows the results of the Sobol sensitivity analysis in which the shoreside operations rate and number of crew have the largest impact, followed by the shoreside maintenance rate and number of crew, then seasonal deployments' number of shoreside maintenance days. The higher the shoreside rates and number of crew, the more favorable a seasonal deployment becomes. The more shoreside maintenance days associated with seasonal deployments, the lower the cost savings for seasonal deployments. The cost savings for seasonal deployments range from -6% to 38%: less than 0.5% of samples had a lower O&M cost for year-round deployment. Thus in most cases, the cost savings from not having to pay operators for five months of the year makes up for the extra incurred costs of deployment and recovery. This is unlikely to be true for sites with dozens or hundreds of devices, as shoreside operations costs are unlikely to increase with the number of devices, but the costs of shoreside maintenance, recovery, and redeployment would increase. Shoreside maintenance would require more time and/or more workers as well as more space. Recovery and redeployment would take longer than the one offshore work day each if there are multiple devices.

Other input variables have a relatively small but notable impact on the O&M cost difference. The frequency of planned onsite maintenance (which only occurs for a year-round deployment) has a total sensitivity index of about 0.023. The more planned onsite maintenance a year-round deployment needs, the more savings are possible with a seasonal deployment. The local crew percentage for the seasonal deployment and the seasonal failure rate percentage have sensitivity indices of 0.019 and 0.011 respectively. With more local crew and a lower seasonal fail rate percentage, the seasonal deployments have greater cost savings.

Offshore operations frequencies as well as the seasonal failure rate percentage have little impact on the cost difference, so for estimating costs, we chose not to look further into the impacts of reducing failure rates through seasonal deployments as they pertain to O&M costs. However, failures could have a bigger impact on energy production, as discussed in Section 5.6. Because offshore O&M parameters have little impact on the cost differences, we

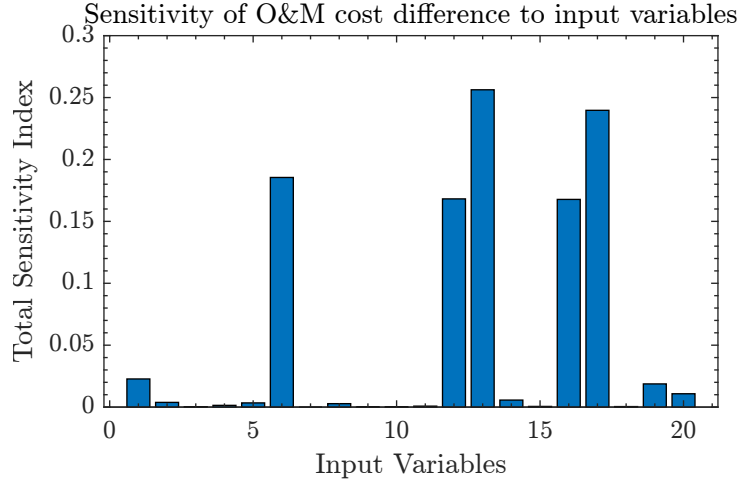


Figure 13: Sensitivity of cost difference to 21 input variables. Variables are numbered according to Table 5

find our assumptions about failure rates and vessel rates to be acceptable. We do not consider the impact of the distance from shore on O&M costs because they would be about the same across seasonal and year-round deployments. The further the deployment is from a grid connection, the higher the cost of transmission infrastructure, making O&M a smaller share of total project costs.

6.1.3. O&M Cost Differences Results

The mean O&M costs for year-round and seasonal deployments are shown in Table 6. The mean cost for seasonal deployments is approximately 30% lower than the mean cost for year-round deployments. This is not unexpected: due to the shorter operational season, seasonal deployments' shore-side operations cost between \$30,200 and \$181,200 less than year-round deployments. The mean difference between seasonal and year-round O&M costs is 28.6%, with a standard deviation of 5.2%. Figure 14 shows a histogram of cost differences from the 42,000 Sobol sampled cases. Estimates from literature say O&M costs likely account for 5-30% of total project costs. A 29% savings in this area could, therefore result in project cost savings of 1.5-8.7%.

Table 6: O&M costs for a year-round and seasonal deployment

Metric	Mean	Standard Deviation	Mean Percent Local
O&M Costs Year-round	\$347,550	\$90,391	97.6%
O&M Costs Seasonal	\$245,360	\$54,438	94.5%

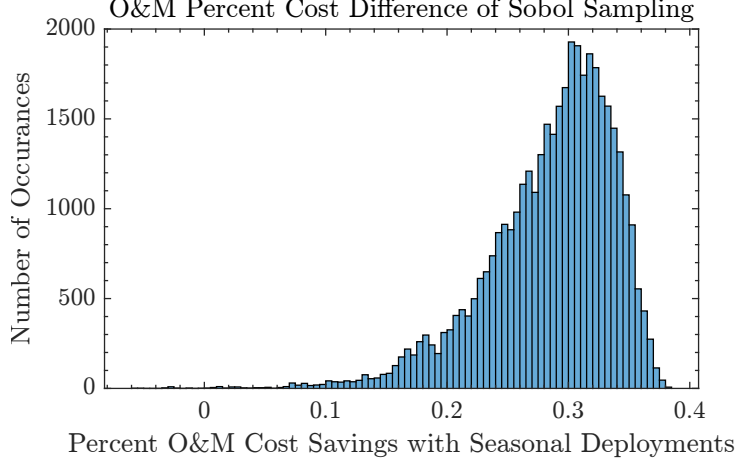


Figure 14: Histogram of cost savings for a seasonal deployment compared to year-round sampled from inputs listed in Table 5

6.2. Component Costs, Technology Learning, and Insurance

Two initial costs that could be impacted by a seasonal deployment are the component costs and the insurance costs. Insurance costs are typically estimated to be 2-10% of the capital cost [35]. The primary avenue for decreased component costs is through the selection of materials and components that need to operate in the ocean for months at a time rather than years. While the trade-off between more durable materials/components with higher up-front costs and lower maintenance costs versus less durable materials/components with lower upfront costs and higher maintenance costs has been acknowledged [30], there is limited research quantifying that trade-off in real design options [81]. Considering these trade-offs might rightfully be left to developers, however, for our purposes, a cursory exploration illustrates possibilities. In Table 7, we list six main components of the device that we model in this study. For each component, we identify common failure/ maintenance types, opportunities that could be unique to seasonal deployments, and the approximate impact those opportunities could have on component

Table 7: Components and related opportunities with seasonal deployment

Component	Custom or off-the shelf?	Common maintenance/ failure mode	Opportunities in case of seasonal deployments	Component cost impact
Hull	Custom	Biofouling, corrosion, damage due to collision	Annual cleaning and resurfacing extends total lifetime of hull, Removal from water during high traffic season reduces risk of collision	(DECREASE) Post-operational savings/ opportunities for lifetime extension
Tension mooring with tidal compensation	Off-the-shelf	Mooring line fatigue	If properly housed during non-operational season, such a mooring could service a seasonal deployment for more years	(DECREASE) Post-operational savings / opportunities for lifetime extension
Wave spring	Custom	Fatigue, degradation, cylinder leakage	Custom, novel components may be updated as lessons are learned in early years, enabling low-cost decisions for initial deployment	(DECREASE) Capital cost savings and possible performance improvement
Drive train	Off-the-shelf	Degradation over time, especially if exposed to ocean water	Regular servicing	(NONE)
Generator	Off-the-shelf	Degradation, overheating, vibrations-induced failures	Regular servicing	(NONE)
Motor Drive	Custom	Degradation	Regular servicing	(NONE)

costs. Overall, the opportunities for initial cost savings are minimal given that one would need to design for the same extreme conditions.

The more time spent in the water without maintenance or recovery, the more susceptible a device is to corrosion, biofouling, and age-induced failure. A WEC hull, being constantly in contact with ocean water, is particularly susceptible to corrosion and biofouling [82]. The seasonal deployment structure provides regular dry dock opportunities for addressing biofouling, however, whether or not that is a sufficient interval or allows for cost savings with respect to antifouling treatments depends on the local marine communities that foul a device. Tension moorings and the wave spring are most susceptible to fatigue failures. With less operational time, they might last for more seasons, but with such novel technology it is difficult to predict. Electri-

cal components, being housed inside the hull and being generally built for very long lifetimes [83], are less susceptible to degradation-related failures. Several papers that assume failure rates for WEC components give electric generators the highest failure rates (i.e. [84; 31; 85]), however, looking to the OREDA Offshore Reliability Data Handbook, we see that failures due to degradation make up for less than 20% of generator failures [86]. For that reason, we do not expect that routine maintenance will open opportunities for lower component costs of the drive train, generator, or motor drive.

For early wave energy deployments and demonstrations especially, some components might become obsolete, inferior, or below regulatory or industry standards prior to the end of their planned lifetime. Obsolescence is a factor of concern even in industries as mature as oil and gas [87; 88]. Seasonal deployments present an opportunity to replace those components and adjust to lessons learned during regular recovery periods. We estimate from Table 7 that a 5% component cost savings for seasonal deployment is reasonable. Component CapEx can account for 20-40% of total cost, meaning that a savings of 5% made possible by a seasonal deployment would be equivalent to an approximately 1-2% decrease in total costs. To reiterate, estimating component costs is an ongoing effort without an established baseline [23], therefore these numerical estimates should be considered illustrative and approximate.

6.3. Permitting and Monitoring Costs

In RMP reporting, cost of permitting and monitoring is divided into four categories, siting and scoping, pre-installation studies, post-installation studies, and National Environmental Policy Act (NEPA) and procedural costs [35]. Table 8 gives a description of each of these categories, our assessment of whether they would be impacted by seasonal deployments, and the costs associated with a pilot deployment according to the RMP. Post-installation studies are the only ones that we expect could be impacted by a seasonal deployment scheme. If a seasonal deployment scheme mitigates the risk of disrupting animal behavior or habitat, it is reasonable to assume that the monitoring costs will decrease, but given the lack of current knowledge of environmental impacts of wave energy, it is unclear how much. Risk is a metric that captures both the likelihood of an event and the severity of consequence of that event, meaning that although the deployment type could have an impact on risk, the vulnerability of the species or habitats in question could have equal or greater impact. Siting and scoping as well as pre-installation costs are not likely to change because the process of identifying concerns and establishing

Table 8: Permitting and monitoring cost breakdown and expected differences for a seasonal deployment

Stage	Description	Seasonal Deployment Impact on Cost?	Pilot Cost Estimates From RM3
Siting and Scoping	Developers identify environmental concerns and conflicting use issues. Studies include a wave resource assessment, environmental scoping, and community and regulatory outreach	No	\$240,000-\$430,000
Pre-Installation Studies	Baseline assessment of the marine mammals, fish, seabirds, turtles, water quality, habitat, cultural resources, navigation and recreation activities that will interact with device deployment.	Unlikely	\$1,218,000-\$2,047,000
Post-Installation Studies	Periodic surveys to monitor environmental risks and ecosystem effects.	Possibly. Post-install monitoring is determined by pre-install environmental risk assessments. Monitoring requirements will be reduced if a seasonal deployment proves lower environmental risks.	\$475,000-\$945,000
NEPA and Process	Post-installation regulatory work and documentation.	No	\$725,000 - \$1,125,000

a baseline is necessary regardless of deployment type. We assume the same is true for the NEPA process.

According to the estimates made for the RM3 device deployment in Humboldt, CA, the post-installation studies account for about 18% of the total pilot-scale environmental siting and permitting costs. The post-installation costs constitute between 3.6% and 4.1% of the total RM3 LCOE [35]. Assuming post-installation costs would decrease a maximum of 25%, we can say that total cost would not decrease by more than 1% due to savings in permitting and monitoring. This is negligible, especially given the “tremendous uncertainty” related to the permitting and monitoring cost estimates [42].

7. Environmental Impacts Comparison

In our comparison of both global and environmental impacts of seasonal deployments, we did not identify any factors that make one deployment type obviously preferable over the other. Instead, we see a range of potential benefits and drawbacks.

7.1. Global Environmental Impacts

Both seasonal and year-round WEC deployments require similar materials for manufacturing and likely employ the same installation and decommissioning schemes. Consequently, any differences in environmental impact will be primarily due to the deployment’s O&M strategy.

The two major transportation activities are piloting a boat to and from the deployment location and flying in a service engineer. Assuming non-local workers arrive in Sitka from Seattle, Washington, and a round-trip distance of approximately 2,800 km, the flight produces approximately 0.555 tonnes of CO₂ per person [89]. Assuming the deployment near Biorka Island with an operational base at the Gary Paxton Industrial Park in Sitka, a boat trip to the deployment site and back would be about 40 miles.

A 85 to 125 foot offshore supply or workboat would be sufficient to deploy and retrieve a WEC [35]. We estimate a fuel consumption of 100 gph and a speed of 22 knots, meaning a 40-mile trip will consume 160 gallons of fuel. Burning one tonne of marine heavy fuel oil (HFO) produces 3.15 tonnes of CO₂ [90]. 160 gallons of HFO weighs around 0.545 metric tonnes [91] (based on a standard HFO density of 900 kg/m³), therefore a 40-mile trip to retrieve or deploy the WEC will produce 1.72 tonnes of CO₂. This is a rough estimate, as exact fuel consumption estimates vary based on the vessel hull size, engine design, speed, ocean conditions, and load weight [90].

Figure 15 compares the yearly emissions for a seasonal and year-round deployment. The assumptions for onsite and offsite maintenance frequency and number of non-local crew member are based on O&M input variable ranges from Table 5. Minimum yearly emission scenarios assume the highest local crew percentage and lowest onsite and offsite maintenance frequency. Maximum yearly emission scenarios assume the lowest local crew percentage and highest onsite and offsite maintenance frequency.

Emissions between seasonal and year-round deployment schemes are generally comparable. Year-round deployments have a wider emission range due to greater variability in the assumed number of non-local crew members and maintenance frequencies. Year-round deployments are associated with potentially higher emissions due to the increased number of flights for non-local crew members, however, if minimizing the number of service engineer flights is made a priority for a year-round deployment, the two deployment types would have similar emission. Further differences would likely be scenario dependent. In a scenario with numerous WECs in a large farm, the vessel emissions would increase for both types of deployments, but to a greater extent for seasonal deployments. In a remote location with extensive air travel for non-local crew, flight emissions would increase for both types of deployments, but to a greater extent for year-round deployments.

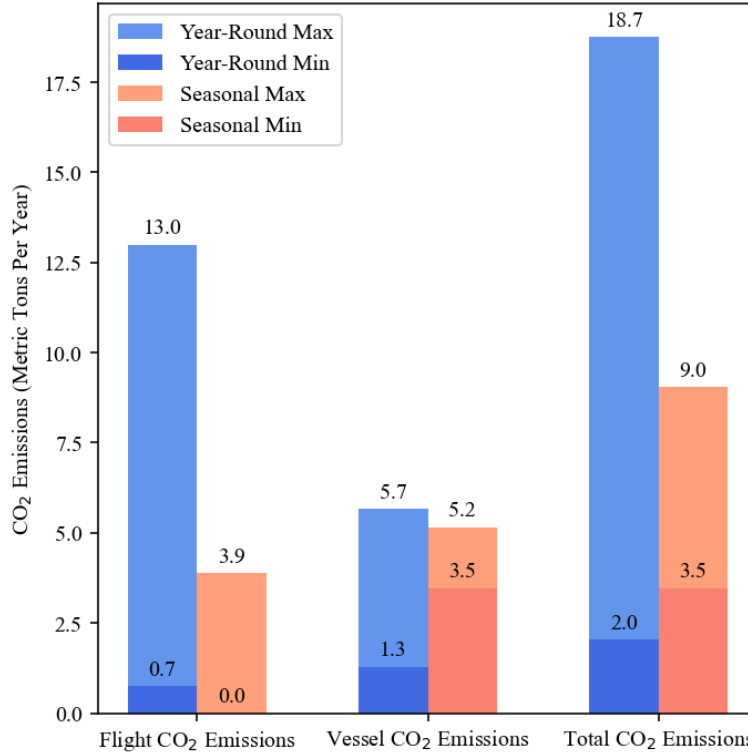


Figure 15: Greenhouse gas emissions comparison between year-round and seasonal deployments shows that the two are generally comparable given our input ranges for O&M activities.

7.2. Local Environmental Impacts

Local environmental impacts associated with wave energy include underwater noise impacts, entanglement, EMF risk, and changes in habitat [43]. These impacts should be considered in the context of the local ecosystem. In the following subsections, we address each aspect of local environmental impacts individually. Overall, we determine that a seasonal deployment in Sitka would increase environmental risk with respect to some aspects and decrease it in others. Given the uncertainty and site-specificity of environmental impacts for wave energy, these results serve less as a generalizable comparison, and more to highlight the important local data and aspects for consideration. We consider a scenario, as we do throughout this publication, with only a single (or a few) deployed WECs. The different types of

environmental effects are hypothesized to scale differently as the number of WECs increases [92]. As far as their comparative differences, we can assume that the impacts related to deployment and recovery (underwater noise and changes in habitat) will increase relatively more for seasonal deployments than year-round deployments in the case of a WEC farm.

The Gulf of Alaska provides habitat for many marine species, including gray whales, humpback whales, fin whales, sei whales, sperm whales, orcas, blue whales, and harbor porpoises [93; 94]. Gray whales have a designated migration biological importance area (BIA) in place along the Gulf of Alaska coast [95; 96]. Biologically important feeding areas for gray, humpback, and sperm whales have been identified near Sitka (Table 9). Although, fin whales have been sighted, no BIAs were designated for them near Sitka [95; 96]. The Steller sea lion and harbor seal generally haul out for breeding during the summer season, and spend most of their time in the water during the winter. The presence of local biologically important species as well as several other seasonal uses are shown in Table 10.

Table 9: Marine Mammal Foraging Grounds near Sitka, AK

Marine Mammal	Type of BIA	Months Present	Location
Humpback Whale	Foraging	March to May and August to December	Sitka Sound
Grey Whale	Foraging Migration	March to June March to June and November to January	Sitka Sound Gulf of Alaska
Sperm Whale	Foraging	April to August	Gulf of Alaska

7.2.1. Underwater Noise

Many marine animals that inhabit or migrate through Alaskan waters near Sitka rely heavily on sound for survival, including both marine mammals and fish. Migrating whales generally respond more strongly to continuous and loud noises than feeding whales do [93]. One of the most commonly sighted whales are humpbacks, which generally migrate near Sitka in the summer months, where they tend to be seen in shallow coastal waters as they forage for food [97]. A seasonal deployment should avoid scheduling deployments or recoveries during peak migratory months.

Table 10: Seasonal marine uses near Sitka, AK. Months outlined in black represent those of a seasonal wave energy deployment.

Mammals	Ja	Fe	Mr	Ap	My	Jn	Jl	Au	Se		Oc	No	De
Humpback Whale													
Gray Whale													
Sperm Whale													
Killer Whale													
Steller Sea Lion													
Harbor Seal													
Commercial Fishing	Ja	Fe	Mr	Ap	My	Jn	Jl	Au	Se		Oc	No	De
Pacific Herring													
King Salmon													
Other Salmon													
Human Dimensions	Ja	Fe	Mr	Ap	My	Jn	Jl	Au	Se		Oc	No	De
Sport fishing													
Tourism season													

The endangered Steller sea lion has critical habitat near Biorka island and the ability to detect sound and communicate is very important for reproduction and predator avoidance. Steller sea lions generally have low numbers in the water over the summer months. In May and June they are hauled out at rookery sites for breeding [98; 93]. During the winter months, Steller sea lions are usually traveling to local haul out sites and following prey species to forage [99]. This may present additional risk if the device is deployed during winter months when higher numbers of sea lions are in the water. This risk could indicate a need for increased monitoring and observation during device deployment and operation.

Fish can also negatively respond to underwater anthropogenic noise. Commercially and ecologically important fish species in Alaska, such as Pacific herring and salmon, have been observed exhibiting predatory response behaviors with increased underwater noise [100], and noise from marine energy devices may mask fish communication [101]. Deployment and retrieval of the device multiple times a year could cause short duration of increases in noise.

7.2.2. Entanglement

Near Sitka, entanglement concerns would likely be highest for large whales such as humpback and gray whales due to migration and foraging behavior in this area. Sperm whales near Sitka have been observed foraging from long lines deployed by commercial fisherman [102]. While this behavior is likely prevalent near fishing operations, sperm whales could be attracted to WEC mooring lines, if secondary entanglement with prey species were to occur. Despite the concerns for large marine mammals, mooring lines are under tension with little slack, and entanglement risk would likely be very low for a single device [103].

7.2.3. EMF Risk

Subsea cables such as those transmitting power from a WEC, emit electromagnetic fields (EMF) that could effect sensitive marine organisms in close vicinity. However, responses to EMF will be species-specific and vary depending on the size of the WEC and cable [104]. A study investigating the impact of EMF on Chinook salmon found limited impact on migration success and movement [105]. The effect of EMF on fish is likely to be more of a concern for electrosensitive species such as elasmobranchii than other less sensitive fish [106; 104]. Impact to invertebrates appears to be species specific as well, as European brown crabs exhibited attraction behavior but had no stress related responses, while European lobsters and a species of polychaete exhibited no attraction behaviors to increased EMF [107; 108; 109]. In this case study, EMF risk would be low with a small deployment and would decrease when the device is not in the water, due to the cable no longer being active.

7.2.4. Changes in Habitat

Changes in habitat could include disturbance of habitat during cable laying and seabed structure installation, scouring of seafloor by device anchor/foundation, and creation of new habitat via biofouling and the artificial reef effect [110]. Cable laying is likely to create the most benthic disturbance in an area but generally show recovery of that area within a short time (days for turbidity, 1-8 years for seabed) [109; 111]. Scouring of the seafloor by the anchor during local turbulence is a concern but was found to quickly dissipate with distance from the disturbance [112]. Habitat change would likely be very small for a WEC with a small seabed footprint. If the mooring system/anchor was kept in the water during the non-operational

season, habitat disturbance would not increase. Not all changes in habitat are negative, however. The installation of a WEC could create new habitat for fouling organisms or provide structure and act as an artificial reef [113]. Seasonal deployments could pose a regular disruption to habitat.

8. Community Impacts Comparison

8.1. Local Economic Impact

We separate the local and nonlocal costs because we use local costs as a metric of local economic impact. Local costs are those paid to local workers as well as vessel, fuel, and consumable costs. We assume the only non-local O&M costs are for labor. We calculate local economic benefit in job years (B), as

$$B = \left[\sum_{i=1}^4 f_i N_{\text{om}} + f_{\text{sm}} N_{\text{sm}} + f_{\text{so}} N_{\text{so}} \right] P_d \times \frac{20 \text{ years}}{260 \text{ days}}. \quad (32)$$

We multiply by 20 years, the lifetime of the project, and divide by 260 days, the number of days in a standard job-year.

Figure 16 shows the difference in local jobs for seasonal versus year-round deployments over the Sobol sampled calculations. The mean difference is 21.5 job years, indicating that a seasonal deployment, despite having a lower percentage of local jobs, could open up more total jobs in a local community. That said, if job creation is a major goal of a coastal community, it could be prioritized in either sort of deployment.

8.2. Community Benefits and Capacity

A coastal community might be drawn to the possibility of a seasonal deployment by either local constraints or the desire to take advantage of unique local opportunities. The most prominent constraints that might encourage consideration of seasonal deployments are those which arise from conflicts about spatial use by humans or wildlife. In Sitka, there are several concerns related to spatial use that would constrain wave energy development, including fisheries access to the area for harvest, recreational access for both subsistence harvest or transit to other areas, disruption of the tourist industry, and impact on marine species. The timing of these spatial uses is shown in Table 10. A seasonal deployment could address the dilemma of resolving environmental and spatial impacts: we cannot fully understand the

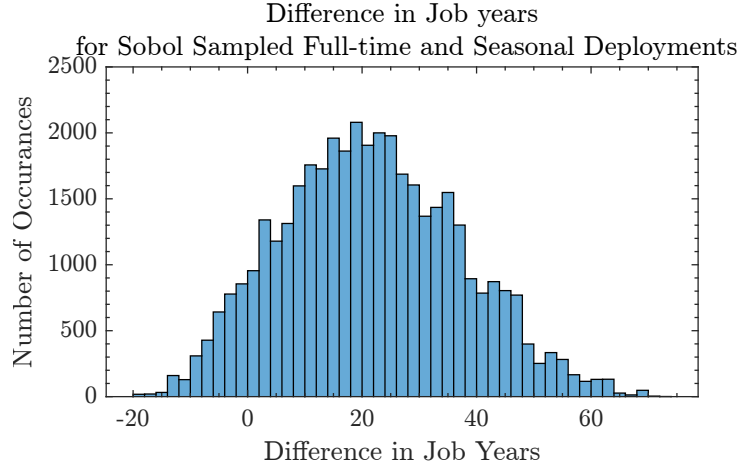


Figure 16: Difference in local job years for a seasonal versus year-round deployment.

impacts until we have data from deployments and we cannot have deployments (at least not deployments which are acceptable to coastal community members) until we understand the impacts. A seasonal deployment provides flexibility for adaptive management and a regular interval for responsiveness to community concerns.

Other preferences that might be able to be addressed by seasonal deployments include preferences toward staged development, which could be reflective of hesitancy about large capital projects, concern over risks of abandonment, or the desire to be active participants in the research and development of wave energy. We saw each of these preferences expressed in Sitka [8]. As coastal communities make energy transitions, there are uncertainties not only about future generation, but about future demand as well. Timing of projects, and the ability of new generation to grow (or not) with demand will be important. A deployment near Biorka Island, seasonal or not and regardless of the device costs, would have a high capital cost simply due to the distance between the island and the electric grid.

To perform seasonal deployments, a coastal community needs the shore-side infrastructure to store and maintain the WECs in the offseason, a seasonally available workforce, and a vessel available for offshore operations. We discuss each of these points in the context of Sitka’s capacity, exemplifying the kind of knowledge or data to collect in collaboration with the community to establish the feasibility of a seasonal deployment.

For shoreside infrastructure, Sitka has a public, board-run industrial park called Gray Paxton Industrial Park (GPIP) in which a boat haul-out and boat storage lots are currently under construction [114]. The shoreside infrastructure associated with GPIP could meet many of the needs of a wave energy projects, including means of getting WECs in and out of the water, dockage for a work vessel, available experts in marine maintenance, and a place to store WECs during the offseason. In Sitka there are several fishing tender vessels that would have the capacity to service a wave energy deployment. For a deployment season opposite the fishing season, these vessels are more likely to be available.

Sitka has a high population of non-resident workers, most of whom work in the fishing or tourism industries during the summer months. For a place with an already seasonal workforce opposite to the proposed deployment season, a seasonal deployment could present a unique opportunity for year-round employment. While local job creation is generally considered a good thing, a community needs to be able to fill the positions created by a new project. If a community is unable to staff positions, the potential local economic benefits of a seasonal deployment that we discuss may not be accessible. Sitka, like many municipal and cooperative utilities in rural areas, is currently experiencing staffing difficulties. Therefore, while the seasonal aspect does create a unique opportunity, that opportunity is limited by this broader context.

9. Discussion and Impacts of Assumptions

9.1. Feasibility of Seasonal Deployments

Overall, our results show that seasonal deployments are unlikely to lower the cost of energy from a wave energy deployment. In the case of a point absorber WEC deployment near Biorka Island in Sitka, the decreases in costs (still less than 10% if we are generously considering 6% savings in O&M, 2% component CapEx, 1% permitting) are smaller than the expected decreases in energy production (around 30%). Only in the case where failures have an outsized impact on production for the year-round deployment (which is possible given the winter access rates) could these two percentages become more comparable. This would be due to the impact of failures on availability, not, as we show in Section 6.1.1, on the increased O&M costs. As described in Sections 7 and 8, there are not overwhelming environmental or community benefits of seasonal deployments, although there could be some depending

on the site. Given these results, our main suggestion is that there are several scenarios in which considering a seasonal deployment for a specific location might be warranted, and it should not be ruled out as an approach to early development. Seasonal deployments are unlikely to be feasible for large WEC farms.

A seasonal deployment could be preferable in a community with a seasonal need for additional generation. For instance, in Sitka, having a wave energy project deployed in August, September and October may theoretically decrease the levelized cost of energy when considered out of the context of Sitka’s grid, but in Sitka, there might not be a buyer for that electricity during those months. As it is, the dams are often spilling then, meaning potential electricity would have limited value. Since the total cost of a seasonal deployment is likely less than that of a year-round deployment, a seasonal deployment might be a better choice if a seasonal need for additional generation is combined with a tight operational budget or workforce. Finally, if a community has a hard constraint related to seasonal spatial use or environmental concerns, this research shows that choosing a seasonal deployment could be a way to respect that constraint. Again, this depends on the alignment of the constraint, the wave resource, the community’s energy demand, and infrastructure and workforce availability. Ultimately, one is looking for the alignment of times of year when electricity production and job creation have high value, but environmental and spatial conflict is low. To make a holistic comparison for a specific site, one needs to collect monthly/ seasonal data on sea conditions, electricity demand, local species and ecosystem characteristics, local ocean uses, and available infrastructure, vessels, and workforce.

There are numerous assumptions that we made throughout this paper that impact our results, but a few deserve to be called out here as particularly impactful on our final discussion of feasibility. Firstly, our assumption that there are no additional infrastructure CapEx costs for a seasonal deployment means that we only account for increases in the LCOE caused by the deployment scheme related to losses in energy production. Should there be significant differences in infrastructure costs, be it for advanced anchor and mooring systems or otherwise unnecessary shoreside infrastructure, than seasonal deployments would become less desirable.

Secondly, we assume that seasonal deployments relate to a more local workforce. Although our sensitivity analysis in Section 6.1.1 shows that this assumption does not have a significant impact on O&M costs, it does have an

impact on our discussions of global environmental impacts and community benefits. If a seasonal deployment does not create job opportunities that warrant training local workers any more than a year-round deployment, the resulting benefits would be lost.

Thirdly, we assume that wave energy deployments need full time operators. Our calculations of O&M cost differences are most sensitive to the shoreside operations crew number and rate, meaning our assumption about full time operators is largely responsible for the favorable O&M cost results for seasonal deployments. Should wave energy deployments not require additional operational staff, much of the potential cost savings of seasonal deployments would be lost.

Fourthly, we assume a range of potential failure rates in calculating the O&M costs, but we do not calculate availability base on those same rates due to the uncertainty associated with those calculations. This means that our comparison of power production assumes no failures, while our comparison of O&M costs assumes failure. This difference prevents us from using the cost comparisons and power comparisons together to compare cost of energy quantitatively.

Fifthly, our assumptions about the comparability or negligibility of difference between design costs, site assessment costs, grid connection costs, forecastability, pollution, tax impact, energy security, grid compliance, and safety were all made through our own reasoning presented in Section 3. It is possible that these categories warrant further consideration that could not be addressed while maintaining a reasonable scope for this paper.

There is a high amount of uncertainty around failure rates for wave energy (Teillant et al. estimate component failure rates that are all less than 0.007 [33], whereas Rinaldi et al. have estimates that range from 0.001 to 1.59, depending on the component [31]). In the future, when we have more data, if failures become a major hindrance for wave energy, seasonal deployments might become more appealing. On the other hand, seasonal deployments could be a promising cautionary approach for early deployments. Instead of waiting to see if failure rates become an issue (a process that would inevitably be costly), demonstration campaigns might consider beginning with seasonal deployments. Further discussion about these industry-scale development approaches, however, is outside the scope of this paper.

For each cost comparison, we contextualize the differences in the cost of a specific aspect within the overall percentage of costs that that aspect might account for, according to other top-down cost modeling studies. It

is relevant, therefore, to acknowledge the huge range of cost percentages, and how the factors that impacts those ranges would, in turn, impact the feasibility of seasonal deployments. To reiterate, top-down cost studies give the following ranges for cost breakdowns: device component CapEx ranges 20-40% of total costs; infrastructure, mooring, and installation CapEx 10-30%; design, site assessment, environmental compliance, and contingency CapEx 10-25%; O&M OpEx 5-30%; and insurance and monitoring OpEx 10-20%. If, as wave energy cost data is collected, we see CapEx percentages land on the higher side of these ranges, and OpEx on the lower, this makes seasonal deployments less appealing. This could be the case for deployments that are far from a grid connection and require long lengths of underwater cabling or for deployments of WECs with durable, high cost components.

9.2. Impact of Sea Conditions on Optimal WEC Configuration

From the WEC optimization, we note two results: that the optimal parameters for the WEC were the same for seasonal and year-round deployments and that the WEC had a higher capacity factor in the summer (low energy) months than in the winter (high energy) months. These findings expose the challenge of understanding site-specific WEC design. In a place where the winter and summer wave resource is as different as Sitka's, one might expect a WEC to have different optimal parameters.

There could be a few explanations for these results, however to know for sure more research is needed. It could be that we did not sweep a large enough parameter space. In theory, a larger WEC might have better winter efficiency, given that the winter months have lower frequency (higher period) waves. Optimal WEC size is related to wave period [115], but as Tan et al. (2021) show, the relationship between optimal buoy size and wave resource is not necessarily proportional to mean power density [116]. It could also be that the difference in wave energy period between summer and winter is just not large enough to make a difference regarding the efficiency of energy conversion. In that case, we ask, what variability does result in different optima? How does it differ between types of WECs? The answers to these questions have important implications for WEC design approaches, most notably, our knowledge of which WEC parameters need to be altered based on the deployment site.

Our research suggests that the optimal control and PTO parameters are more influenced by how well those parameters match the hull shape and size than how well they match the sea conditions. Modeling this WEC at

a broader range of sizes and sea conditions would allow us to test this hypothesis. Again, understanding these interactions has consequences for WEC design, especially for specific sites.

The higher capacity factor of our WEC during the summer months adds to the scholarly conversation about whether designing WECs for higher or lower energy seas is preferable. It was once generally accepted in WEC design that larger WECs in larger seas are better for wave energy conversion to the extent that survivability conditions can be met. This assumption comes mostly from knowledge about WEC power absorption, or, how much wave energy a WEC can convert to mechanical energy (movement of the hull). It has become apparent in recent years, however, that considering both the conversions to mechanical energy and then to electrical is important for optimizing performance [117]. Recent work has argued that smaller wave energy resources could also be important to consider given the variability of ocean wave resources and the positive correlation between a WEC's ability to capture shorter period waves and its capacity factor [26; 118]. Our work adds to evidence that even in places with lower wave energy resource in summer, wave energy could provide year-round value [26].

9.3. Strengths and Limitations of Comparative Approach

In this paper, we introduce a holistic approach to comparing design, development, or deployment decisions for wave energy that begins with a full set of stakeholder requirements for wave energy. Instead of assessing based on all those requirements (something that a technology performance level assessment enables [119]), we only consider requirements that are likely to be different across our area of comparison. Then we choose our method of comparison based on site-specificity and uncertainty. In the end, as in Section 9.1, we consider our resulting differences in the context of all costs and requirements.

The way that this approach separates aspects of comparison is both a benefit and a drawback. It is a benefit in the sense that, by separating aspects, it allows stakeholders to assign importance to those aspects as they see fit. It also allows us to consider different aspects with different levels of detail, which can be especially important when the goal is to inform a generalized feasibility. Finally, treating aspects separately allows for some aspects to be explored generally while others have to be investigated using site-specific data. Each of these benefits, however, has a companion drawback: they make it more difficult to bring the aspects together to draw broader conclusions.

As such, we find that this comparative approach is appropriate for high-level feasibility studies and for comparisons in which some relevant aspects are site-dependent and others are not.

Throughout this paper, we are constrained by the need to limit the scope based on our own opinions about what is important and by the many areas of uncertainty in wave energy development due to the lack of empirical data from deployments.

10. Conclusions

In this paper we investigate the feasibility of seasonal wave energy deployments, comparing them to standard year-round deployments in terms of electricity production, O&M costs, and local economic benefit. We also consider the impacts seasonal deployments could have on components costs and insurance, global and local environmental impacts, permitting and monitoring costs, and community benefits.

We find that seasonal deployments would likely be related to small cost savings. For the WEC we modeled, a seasonal deployment operating in months that represent 58% of the year, where there is approximately 81% of the total available energy in the waves, produces about 68% of the amount of electricity as the comparable year-round deployment. This higher capacity factor in the summer months, when the waves are a higher frequency, is consistent with research on smaller WECs in low energy seas [26; 118; 39]. Further investigation of the relationship between sea conditions, WEC parameters, and electricity production will be able to tell us more about the conditions in which seasonal deployments could be preferable. More importantly, they will be able to guide future approaches to WEC design by helping us to understand the extent to which a WEC and its components need to be designed for and tuned to a specific site.

Despite the need for further site-specific investigation, we conclude that in places where there is a seasonal energy need, a limited budget, or seasonal constraints on ocean spatial use, a seasonal deployment could be a feasible development approach and should not be ruled out. This paper contributes a comparative approach to feasibility that can be replicated to investigate the impacts of other design, development, or deployment decisions across the range of wave energy design requirements.

Table .11: The significant wave height [H_{m0}] and energy period [T_e] for each of the four clusters which represent the associated month of wave data.

Month	H_{m0}	T_e
January	(2.39, 1.17, 3.44, 4.35)	(9.35, 6.75, 7.84, 10.47)
February	(2.18, 1.62, 3.38, 3.76)	(9.20, 6.69, 7.91, 10.52)
March	(2.26, 1.43, 2.79, 3.95)	(9.30, 6.89, 7.22, 9.93)
April	(1.45, 2.03, 2.60, 3.71)	(6.64, 8.68, 6.93, 9.69)
May	(1.29, 1.57, 2.16, 2.68)	(5.92, 7.79, 6.51, 8.70)
June	(1.22, 1.45, 1.85, 2.32)	(5.79, 7.45, 6.23, 8.47)
July	(1.31, 1.08, 1.55, 1.97)	(7.05, 5.60, 5.62, 7.30)
August	(1.41, 1.14, 1.83, 2.39)	(7.14, 5.71, 5.87, 7.92)
September	(1.79, 1.35, 2.36, 3.30)	(7.77, 5.99, 6.44, 8.82)
October	(2.25, 1.68, 2.99, 4.02)	(8.56, 6.36, 7.16, 9.74)
November	(2.44, 1.72, 3.24, 4.47)	(9.14, 6.85, 7.40, 10.08)
December	(2.71, 1.69, 3.45, 4.74)	(9.64, 7.09, 7.73, 10.37)

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