Analysis on the Influence of an Energy Storage System and Its Impact to the Grid for a Wave Energy Converter

Preprint

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National Renewable Energy Laboratory

Presented at the ASME 2019 38th International Conference on Ocean, Offshore and Arctic Engineering
Glasgow, Scotland
July 9–14, 2019

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5000-73332
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Suggested Citation
Stefek, Jeremy, Dominique Bain, Yi-Hsiang Yu, Dale Jenne, and Greg Stark. 2019. *Analysis on the Influence of an Energy Storage System and Its Impact to the Grid for a Wave Energy Converter: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5000-73332. https://www.nrel.gov/docs/fy19osti/73332.pdf.

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ANALYSIS ON THE INFLUENCE OF AN ENERGY STORAGE SYSTEM AND ITS IMPACT TO THE GRID FOR A WAVE ENERGY CONVERTER

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ABSTRACT

This paper presents an analysis on the cost of and how a battery storage system can be used to further reduce the variation of power generated from the wave energy converter (WEC) due to the fluctuating nature of waves and its impact to the grid. The electrical power output from WEC-Sim simulations for the six sea states used in the Wave Energy Prize was analyzed to compute the peak power and power time history. The results were used to evaluate the battery storage capacity that is needed for a WEC system to provide reasonable power flow to the grid and estimate its cost based on the latest cost information for battery technologies published by the U.S. Energy Information Administration. Finally, a preliminary grid integration analysis was performed to demonstrate how WEC-generated power would contribute to a small island electricity system. As shown in the study, the instantaneous peak power is the primary cost driver for the battery storage and the power take-off system, and reducing the power fluctuations is essential for reducing the overall levelized cost of energy (LCOE). The power flow variation from WECs can be significantly reduced using battery storage without adding significant overall system costs, and the implementation of battery storage is essential for grid integration applications. There may also be additional opportunities to further investigate energy storage technologies that are specific to WEC applications to reduce these costs even further.

Keywords: Wave energy converter; battery storage; power take-off (PTO); grid system analysis

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NOMENCLATURE

A_∞	Added mass matrix at infinite frequency
X	Translational and rotational displacement vector
M	Mass matrix
K	Matrix of impulse response function
F_{ext}	Wave-excitation force vector
F_{PTO}	Power take-off force vector
F_{mo}	Mooring force vector
F_{vis}	Quadratic viscous force vector
F_{res}	Net buoyancy restoring force
LCOE	Levelized cost of energy
CapEx	Capital expenditures
OpEx	Annual operating expenditures
AEP	Annual energy production provided to the grid
FCR	Fixed charge rate
P	Instantaneous power output in kilowatts (kW)
P_{avg}	Averaged power over the duration of the simulation
P_{10mins}	10-minute averaged power output
R_{PF}	Power fluctuation ratio
E	Measure of energy in kilowatt-hours (kWh)
ΔE	Energy capacity in kilowatt-hours (kWh)

INTRODUCTION

Conventional and well-established renewable energy power plants, such as wind and solar energy, are better understood electrically, with clear power signatures that are now easily modeled and controlled, as compared to wave energy technologies. Through the development of isolated and weak grid deployment for variable renewable technologies, specifically wind and solar photovoltaics, it has been demonstrated that the variations of the power output (e.g., voltage, frequency, rate of change in power output) can be a problem that must be well understood as it drives additional design considerations for the wider power system.

For wave energy technologies, even for ideal monochromatic waves, the sinusoidal shape of the incoming wave causes a sinusoidal reaction of the power-take-off (PTO) system, and does not allow the PTO to run constantly at rated speed. Moreover, from a resource perspective, waves are a fundamentally fluctuating source of energy, where the behavior of ocean waves is generally random in terms of amplitude, phase, and directionality. In addition, waves often group into wave trains that consist of a series of waves with similar amplitude, which adds subharmonic fluctuations with respect to the incoming wave period [1]. Like other renewable energy resources, such as wind, wave energy is also subject to seasonal variation, where the wave energy is greater in winter than the summer in the Northern Hemisphere [2, 3]. Finally, to a lesser extent and beyond the scope of this work, yearly changes of wave energy have been observed. Studies on ocean climate have suggested a general trend of increasing values of wave height with a greater rate of change for extreme scenarios as compared to the normal (averaged) condition based on the data from the last two decades [4]. Without the ability to accurately understand and model the potential variations of power output in target time scale for single devices in various conditions or arrays of devices, it will be challenging to integrate wave energy technologies to the grid system.

Reducing power fluctuations is essential for reducing the integration impacts of wave energy converter (WEC) plants in both distribution and transmission grids, and in stand-alone isolated power systems. Reduced variability of wave-energy-generated power in combination with energy storage will help increase hosting capacity of distribution feeders for this type of variable renewable generation and minimize electric losses. Studies have shown that power fluctuation from WECs can be reduced by implementing PTO controls, and various mechanical power smoothing methods [5, 6], such as pressure accumulator, fly wheel, and pressure bypass valves, depending on the types of the PTO system, as well as the aggregation of WECs in an array or a farm [7, 8]. In particular, Blavette et al. [8] looked into the impact of a wave farm on a local grid system, including the influence on voltage fluctuation, peak-to-average power ratio, and flicker level. The study demonstrated that the power fluctuation impact of a wave farm could be reduced for a sufficiently large wave farm or when storage was introduced. However, using storage and actively controlling the WEC PTO also come with a cost, and the effectiveness of these methods depends on the size of the storage and how the control method is implemented. Aggregation of WECs in an array could reduce the overall impact to the grid system under design wave conditions but still require a suitable size of generator and undersea cables and transmission lines to handle the power fluctuation between WECs and the interconnection station. Therefore, these power fluctuation mitigation strategies need to be better understood, including the cost and effectiveness of the methods.

The energy storage market is growing exponentially, as reported by the U.S. Energy Information Administration (EIA) in their U.S. battery storage market trends report [9]. The increase of demand for energy storage made mass production and cost reduction possible because of economy of scale. Therefore, evaluating the cost of battery storage for WEC applications will help understand the WEC system and component designs and will be useful for grid impact and system integration analyses.

Following the analysis of hydraulic PTOs and the influence of power smoothing methods for a point absorber WEC system [6], the objective of this work is to evaluate the battery storage needed and estimate its cost using the information from this EIA report. The paper first describes the hydrodynamic and PTO models, which were developed based on the study of Yu et al. [6]. Next, we summarize the methodologies for LCOE analysis and estimate the cost of battery storage. The results from the simulation were used to estimate the battery storage size, the cost for the WEC application, and the influence on the LCOE for the WEC. Finally, a preliminary grid integration case study on the impact of how WEC-generated power would contribute to a small island electricity system is presented.

NUMERICAL MODEL

The hydrodynamics of the WEC were simulated using WEC-Sim. A summary of the numerical methods, mass properties, and PTO parameters are described in this section.

Hydrodynamics and PTO Simulations

WEC-Sim is a radiation-and-diffraction-method-based numerical model that has been developed to solve the system dynamics of WECs comprising multiple bodies, PTO systems, and mooring systems [10]. The dynamic response in WEC-Sim is calculated by solving the equation of motion in the time domain for each body about its center of gravity, based on Cummins' equation [11],

$$\begin{aligned}(\mathrm{M}+\mathrm{A}_\infty)\ddot{\mathrm{X}} = &-\int_0^t \mathrm{K}(t-\tau)\dot{\mathrm{X}}(\tau)d\tau \\ &+\mathrm{F}_{\mathrm{ext}}+\mathrm{F}_{\mathrm{vis}}+\mathrm{F}_{\mathrm{res}}+\mathrm{F}_{\mathrm{PTO}}+\mathrm{F}_{\mathrm{mo}}\end{aligned} \tag{1}$$

In this study, we used WAMIT [12], which is a boundary-element-method-based frequency-domain potential flow solver, to obtain the added mass, wave excitation, impulse response function, and restoring stiffness terms. The PTO force was calculated from the hydraulic PTO model, which was developed using SimScape Fluids, a MATLAB toolbox that provides prebuilt libraries for modeling hydraulic systems.

Model Setup and Properties

Following the PTO modeling and power smoothing study carried out by Yu et al. [6], we used the same two-body floating-point absorber (FPA) to perform the study on the influence of

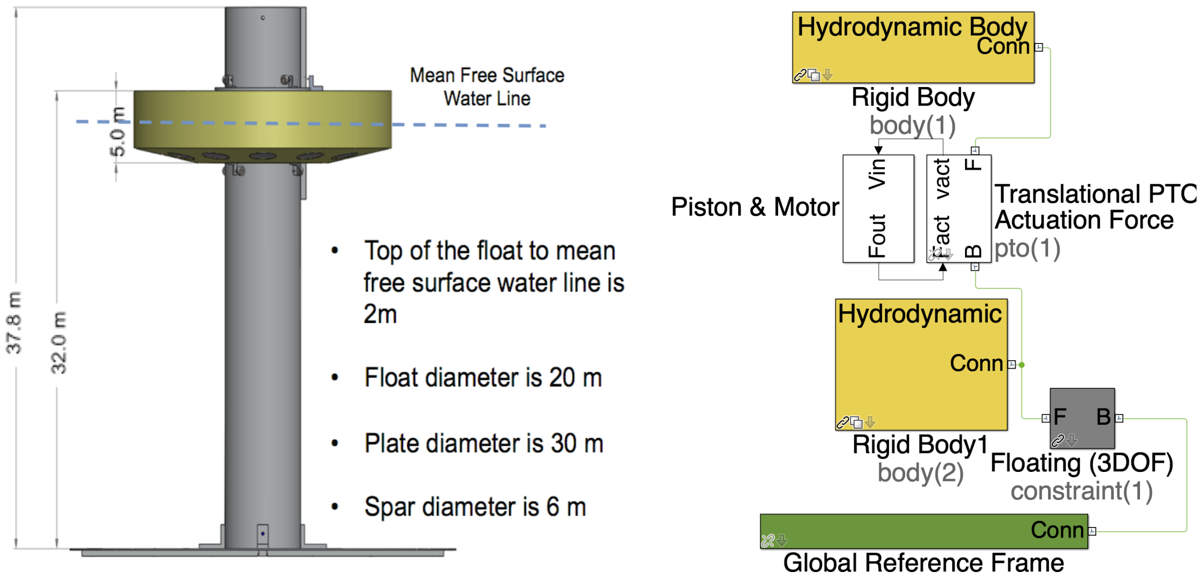

FIGURE 1. THE SCHEMATIC REPRESENTATION OF THE WEC (LEFT) AND WEC-SIM MODEL (RIGHT).

TABLE 1. TWO-BODY FLOATING-POINT ABSORBER WEC MODEL SPECIFICATIONS

	Center of Gravity (m)	Mass (10^3kg)	Moment of Inertia (10^3kg-m^2)		
Float	[0, 0, -0.72]	727.01	20,900	0	0
			0	21,300	4.30
			0	4.30	31,700
Spar/ Plate	[0, 0, -21.29]	878.30	137,000	0	0
			0	137,000	218
			0	218	28,500

battery storage and impact to the grid system. The two-body FPA, as shown in Fig. 1, contains a float and a spar/plate that are connected to a central column, and developed as part of the U.S. Department of Energys Reference Model (RM) project [13]. It converts energy from the relative motion between the float and the spar/plate induced by ocean waves, and the relative motion is in the axial direction of the device. The dimensions and mass properties for the WEC are presented in Fig. 1 and Table 1. The mass for each body was equal to its displaced mass, and both the float and spar/plate were located at their equilibrium positions.

Based on the WAMIT potential flow solution, the viscous damping coefficient, given mooring stiffness, and the PTO mechanism, the time-varying forces were calculated and applied in WEC-Sim, where the equation of motion (Eq. 1) was solved. Figure 1 shows the two-body FPA in the WEC-Sim model and blocks that contain the modules for calculating the wave radiation, excitation, net buoyancy restoring, viscous damping, and mooring forces. The PTO model parameters are listed in Table 2. The model also included a pressure accumulator for energy storage, a pressure-reducing three-way valve to remove the pressure and power generation spikes in the system, and a power-based set-point controller. More details on the model development and settings are described in [6].

TABLE 2. HYDRAULIC POWER-TAKE-OFF PARAMETERS

Parameter	Value
Hydraulic Piston & Direction Valve	
Hydraulic cylinder piston area	0.06 m^2
Valve passage maximum area	0.01 m^2
Pressure-Reducing Valve	
Pressure-reducing valve threshold range	2.8×10^4 – 4.1×10^4 kPa
Regulation/transition pressure	500 kPa/200 kPa
Valve maximum area	10^{-3} m^2
Pressure Accumulator	
Accumulator volume	1 m^3
Precharge pressure	3.5×10^3 kPa
Hydraulic Motor & Generator	
Hydraulic motor displacement	3.5×10^{-5}m^3/rad
Volumetric efficiency	92%
Friction torque vs. pressure drop	0.6×10^{-6}
Proportional gain for control	0.4
Generator efficiency	95%

COST OF ENERGY ESTIMATE

This section describes the methods used to evaluate the cost of energy, the required battery storage, and impact to the grid.

Levelized Cost of Energy

Following the methodology used in the RM project [13], LCOE is adopted in this study to determine the “break-even” cost for a WEC system assuming a minimum rate of return. For comparison purposes, the LCOE is calculated for 100-unit array sizes, which allows for a detailed breakdown of initial capital expenditures (CapEx) and operating expenditures (OpEx). The simplified LCOE can be represented using these inputs [14]

$$\mathrm{LCOE} = \frac{(\mathrm{FCR} \times \mathrm{CapEx}) + \mathrm{OpEx}}{\mathrm{AEP}} \tag{2}$$

where the fixed charge rate (FCR) includes the real discount rate, inflation, tax rates, depreciation, and project life. CapEx and OpEx costs are further broken down into a cost breakdown structure that was developed in the RM project [13]. CapEx costs are broken down even further depending on the specific design, where the battery costs are included in the CapEx cost.

Annual energy production (AEP) is estimated based on the WEC power output from the WEC-Sim simulations (assuming power smoothing and no power smoothing for the sea states) and the reference site resource used in the Wave Energy Prize with specified weighting. The six sea states in Wave Energy Prize are listed in Table 3, where the adjusted weighting function is given based on the wave environment for Newport, Oregon, which has an estimated annual averaged energy flux of 37.9 kW/m [15].

TABLE 3. SELECTED WAVE ENVIRONMENT

Sea States #	Tp (s)	Hs (m)	Weighting
SS1	7.31	2.34	0.175
SS2	9.86	2.64	0.268
SS3	11.52	5.36	0.058
SS4	12.71	2.05	0.295
SS5	15.23	5.84	0.034
SS6	16.50	3.25	0.054

Battery Size Estimate and Cost

In this study, battery storage is used for additional electric power smoothing. Costs for battery storage technologies depend on the power capacity (peak power) and energy capacity of the system, which is highly influenced by the power quality. To evaluate the variation of system power output, we calculate the power fluctuation ratio as

$$\mathrm{R_{PF}} = \frac{\mathrm{Max(P)} - \mathrm{Min(P)}}{\mathrm{P_{avg}}} \tag{3}$$

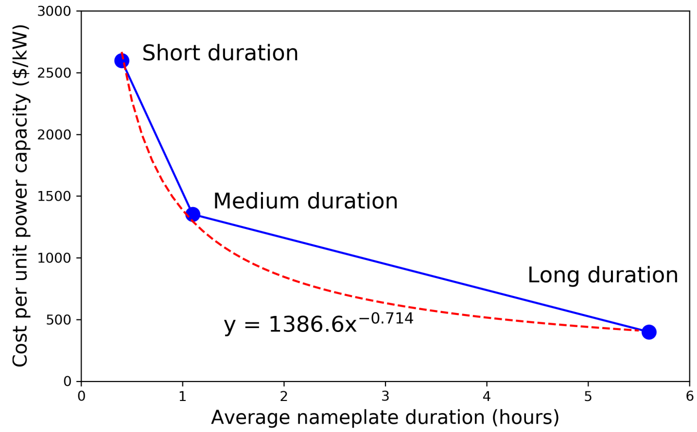

FIGURE 2. CAPITAL COST ESTIMATES FOR LARGE-SCALE BATTERY STORAGE BY DURATION

where the maximum and minimum values are calculated using 99.9 and 0.1 percentiles of identified peaks from the simulated time history. In this study, power capacity or energy capacity were calculated based on the power output from the WEC-Sim simulation, assuming the power output from the battery was controlled based on the 10-minute-averaged input power. The measure of energy and energy capacity can be obtained based on the following equations

$$\begin{aligned} \mathrm{E} &= \int_0^t (\mathrm{P} - \mathrm{P_{10mins}})\, dt \\ \Delta\mathrm{E} &= \mathrm{Max(E)} - \mathrm{Min(E)} \end{aligned} \tag{4}$$

Based on the EIA report, the cost per-unit power capacity for short-duration batteries is $944/kWh [9]. The EIA-reported battery costs are based on large-scale battery storage systems installed across the United States between 2013 and 2016. These systems include several battery chemistries and projects with varying battery storage duration. Because of the fluctuating nature of ocean waves, the battery for a WEC is expected to require an even shorter nameplate duration. However, the cost per energy capacity for a unique battery, capable of a nameplate duration over a much shorter period, is expected to increase. Battery costs based on energy capacity are calculated using an equation derived from the curve-fitting average of nameplate duration versus capacity-weighted cost per-unit power capacity as shown in Fig. 2. The equation is derived from short-, medium-, and long-duration battery storage systems and the estimated energy capacity costs associated with each duration from the EIA report. Using a curve fit of EIA data over multiple durations, we calculated the required nameplate duration for the WEC as follows

$$\mathrm{hours} = \frac{\Delta\mathrm{E}}{\mathrm{Max(P)}} \tag{5}$$

Methods for Grid Integration

In order to better understand how the wave generation interacts with the power grid, this study set up a small island system with a peak of 5 MW and three diesel generators [16]. The load used for the model was a down-scaled version of actual 2012 data for an island. Each diesel generator had a maximum capacity of 2.5 MW, a minimum stable level of 1 MW, a ramping rate of 0.125 MW/minute, and a minimum down time of 5 minutes. The cost of the diesel generator varied between \$138.25/MWh and \$141.25/MWh, due to a variable operations and maintenance charge of \$12/MWh, a fuel price of \$15.03/GJ, and a heat rate which varied between 8.3 GJ/MWh and 8.6 GJ/MWh. Capital costs were not included because we are most interested in operational impacts for this study.

The analysis was carried out using PLEXOS [17]. PLEXOS is a production cost model that uses mixed-linear programming to solve optimization problems. It optimizes operation of the generators (i.e., diesel and wave energy in this study) to minimize overall production cost while observing various constraints, such as the generator, reserve requirements, and transmission limits. The case study also includes the heat rate changes that affect the generator efficiency, start costs and minimum downtime, and start time for the diesel generator. Because only the variable costs were included, \$0.08/kWh for wave energy (a variable OpEx based on the RM project report [13]), the system chose to run as much of the wave energy as possible without violating the constraints on the diesel generators.

COST ANALYSIS AND INFLUENCE OF BATTERY SIZE

This section presents the simulation results, the process of estimating battery storage size and cost, and the overall influence on the WEC power output and LCOE.

Overall Efficiency

Following the modeling work described in [6], the WEC-Sim simulation was carried out for all six sea states (Table 3) with and without applying the power smoothing methods (i.e., pressure accumulator, pressure-reducing three-way valve, and set-point control). The simulation time for each run is 4600 s long with 1000 s of ramp time. The results from the simulation are presented in Fig. 3. The figures on the top and bottom show the overall power quality before charging to the battery and after discharging from the battery, respectively. Note that we did not consider energy losses for battery storage, and the averaged power outputs from both cases are identical.

As mentioned in [6], the PTO system can be practically designed by using the abovementioned power smoothing methods to reduce the maximum power fluctuation. The time history for the power output and energy variation from the simulations for two critical sea states (SS2 and SS5) are plotted in Figs. 4 and 5, where SS2 is the design-operational wave condition and SS5 is the off design but most energetic wave condition. Note the y-axis of the plots is scaled with the peak power and, therefore, varies depending on the cases with and without power smoothing. For

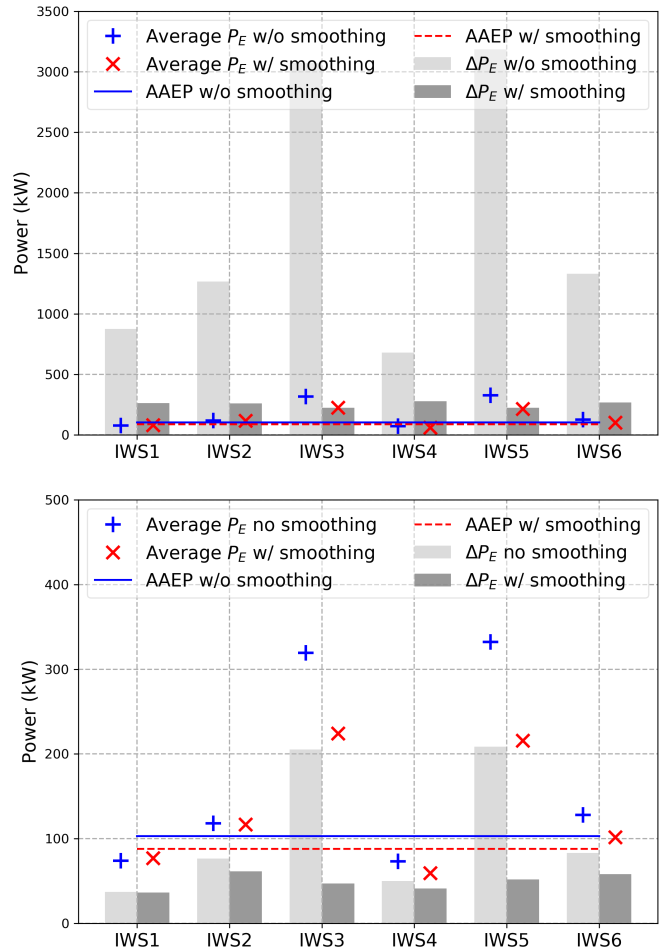

FIGURE 3. POWER QUALITY OF THE WEC WITH AND WITHOUT APPLYING THE POWER SMOOTHING METHODS: (TOP) BEFORE THE BATTERY STORAGE; (BOTTOM) AFTER THE BATTERY STORAGE.

TABLE 4. REQUIRED BATTERY STORAGE ENERGY CAPACITY FOR THE ANALYZED SEA STATES WITH AND WITHOUT APPLYING THE POWER SMOOTHING (PS) METHODS

	Sea States#	Without PS	With PS
	SS 1	3.77	3.80
Required	SS 2	7.41	5.93
Battery Storage	SS 3	20.31	4.50
Capacity	SS 4	4.98	4.34
ΔE (kWh)	SS 5	22.61	5.15
	SS 6	8.03	5.23
P_{max} (kW)		3185	286

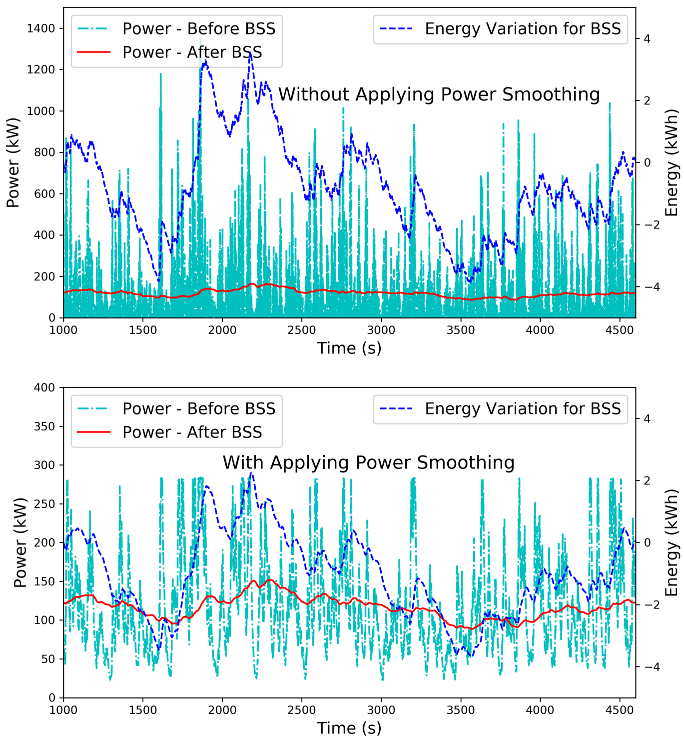

FIGURE 4. POWER OUTPUT AND ENERGY VARIATION FOR THE BATTERY STORAGE (SS2).

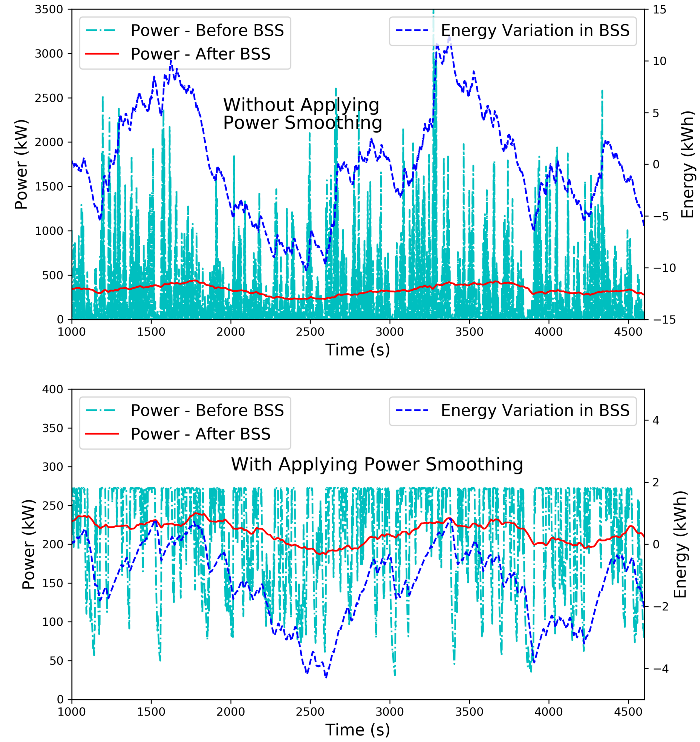

FIGURE 5. POWER OUTPUT AND ENERGY VARIATION FOR THE BATTERY STORAGE (SS5).

the WEC with power smoothing, the peak power was limited to 286 kW, and the maximum ΔE was 5.93 kWh, which occurred in SS2. For the WEC without power smoothing, the peak power was 3185 kW, and the maximum ΔE was 22.6 kWh, which occurred in SS5. The use of battery storage helped mitigate the system power fluctuation. Table 4 shows the required battery energy capacity for all six sea states with and without applying the power smoothing methods.

The WEC-Sim simulations were performed to estimate both the power capacity and energy capacity, which are the main drivers for the required battery storage and its cost. The results suggest that the use of WEC power smoothing methods mitigates the power fluctuation, which minimizes the peak power and required battery storage capacity.

Cost of Battery Storage and Influence on LCOE

The cost of the battery was calculated for both power capacity and energy capacity scenarios for the WEC with and without power smoothing. For power capacity, the cost of the battery is calculated by multiplying the peak power and $944/kW with an added operating contingency of 10%. For energy capacity, the cost of the battery is obtained by multiplying the energy capacity cost and the energy capacity with an added operating contingency of 10%.

Based on the required battery power capacity and energy capacity (Table 4), the cases with power smoothing and without power smoothing have an average nameplate duration of 0.02 and 0.007 hours, respectively, following Eq. 5. Using the curve-fitting equation (Fig. 2) and the calculated average nameplate duration, the estimated energy capacity cost is equal to $22,072/kWh and $47,446/kWh for power smoothing and no power smoothing, respectively.

TABLE 5. BATTERY STORAGE CAPITAL COST PER WEC

Estimated Method	Size with 10% Contingency	Cost of Battery	Cost of PTO
With Power Smoothing			
Power Capacity	315 kW	$297 k	$413 k
Energy Capacity	5.8 Wh	$144k	
Without Power Smoothing			
Power Capacity	3604 kW	$3.4 M	$599 k
Energy Capacity	24.9 kWh	$1.2 M	

The results are summarized in Tables 5 and 6. Note that the average nameplate duration is different for the WEC with and without power smoothing. The PTO cost for a WEC without power smoothing does not include the accumulator cost, but it does include the cost for a larger generator. The baseline LCOE for the FPA model is $0.73/kWh. A WEC with power smoothing, supported by an accumulator and battery storage, would in-

TABLE 6. LCOE CONTRIBUTION FOR BATTERY AND PTO

Estimated Method	PTO ($/kWh)	Battery ($/kWh)	Other ($/kWh)	LCOE ($/kWh)
With Power Smoothing				
Power	0.06	0.05	0.67	0.78
Energy Capacity	0.06	0.02	0.67	0.76
Without Power Smoothing				
Power	0.09	0.52	0.68	1.30
Energy Capacity	0.09	0.19	0.68	0.96

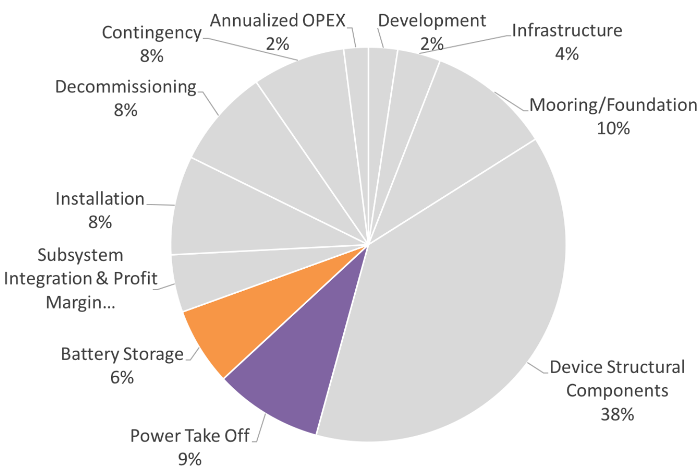

FIGURE 6. ESTIMATED COST BREAKDOWN FOR THE FPA WITH POWER SMOOTHING METHODS APPLIED AND THE USE OF BATTERY STORAGE

crease the LCOE by $0.05/kWh and $0.03/kWh for power capacity and energy capacity scenarios, respectively. Ultimately, the cost driver is power capacity, as the system will need to be designed to store the maximum power generated, and the cost breakdown for the case is plotted in Fig. 6. The cost breakdown includes the baseline LCOE from the RM project and the added battery cost calculated in this study. For a WEC without power smoothing, the WEC design will require a larger generator and no accumulator, increasing the required size of the battery for more storage or discharge capacity. This increases the LCOE by $0.57/kWh and $0.23/kWh for the power capacity and energy capacity scenarios, respectively.

GRID IMPACT ANALYSIS

PLEXOS was used to analyze the potential grid integration impact of WEC-generated power. A preliminary case study is presented in this section. Note that this is a highly simplified version of a grid; however, it allows for some insight into how WEC-generated power could contribute to a small island electricity system. For the WEC, four cases were considered: no smoothing, no battery; no smoothing with battery; smoothing, no battery; and smoothing with battery. The power output for the wave generators was sampled each minute for a day based on the simulation results from WEC-Sim in SS2, which is the design-operational wave condition. We analyzed both a single-WEC unit and three WEC-unit scenarios, where three units were created from each single-WEC unit case and offset from each other by 4 s, and 8 total cases were run as listed in Table 7.

TABLE 7. ANALYZED GRID INTEGRATION CASES

Number of WECs	Smoothing /Battery	WEC Production Range (MW)
1	Yes/Yes	0.08–0.16
1	No/Yes	0.08- 0.18
1	Yes/No	0.016–0.27
1	No/No	0.0–1.4
3	Yes/Yes	0.24–0.48
3	No/Yes	0.24–0.54
3	Yes/No	0.048–0.81
3	No/No	0.0–5.0

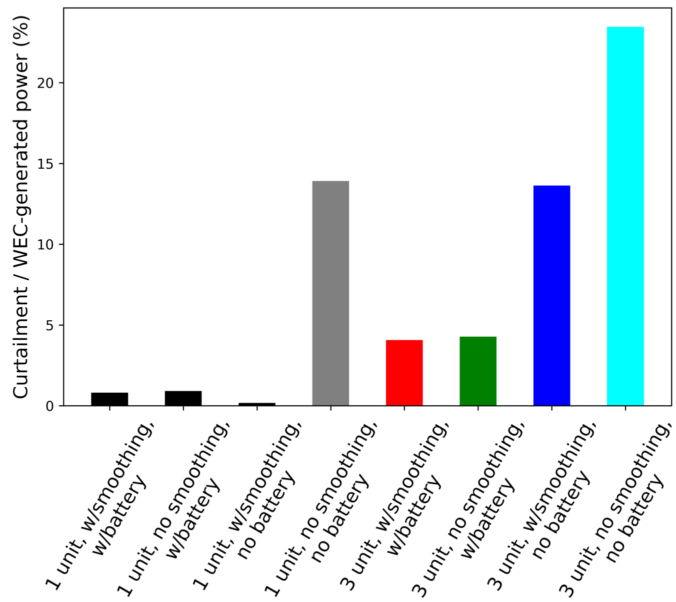

FIGURE 7. PLEXOS ESTIMATED AMOUNT OF CURTAILMENTS FOR EACH SCENARIO

In the system we created, power spikes or low loads can be a challenge. The system wants to keep the generators on, whereas use the lowest price generation at the same time. The system was set up to allow for curtailment of the wave generation if it would cause a violation of the diesel generator flexibility constraints. In this study, the wave energy had a lower variable OpEx cost than

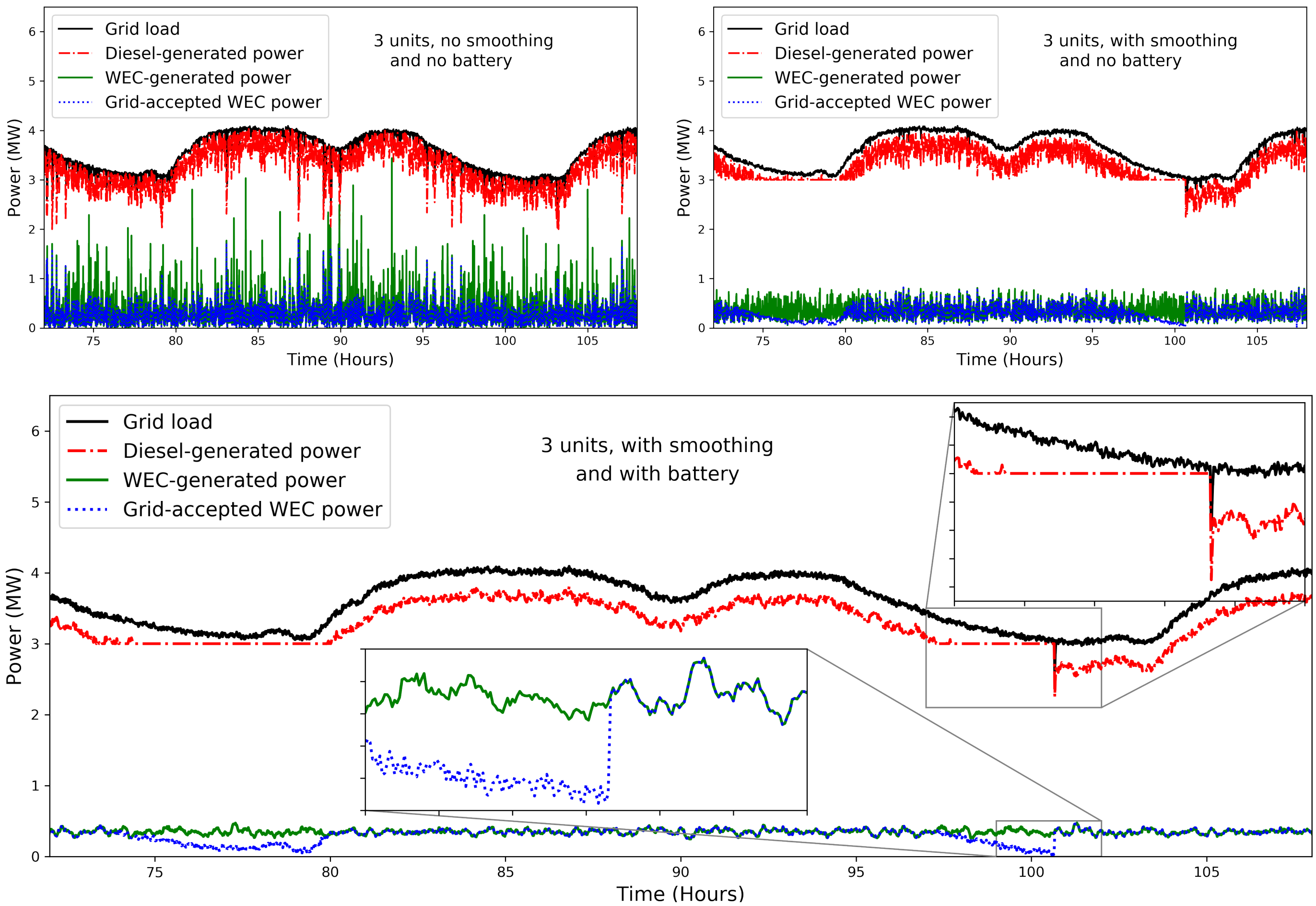

FIGURE 8. TIME HISTORY OF THE LOAD AND THE POWER GENERATION FROM THE DIESEL GENERATORS AND THE WECS

the diesel generation, and production cost is inversely correlated with the amount of usable wave energy. We also assumed, when the wave energy is curtailed, that the WEC-generated power is only partially accepted by the grid, depending on the demand. The range of power production from WECs for WEC-generated power for each scenario is also listed in Table 7, and the amount of curtailment is shown in Figure 7. The single-WEC-unit scenarios have a very low penetration for wave energy (3%). As a result, there is very little curtailment needed in those cases.

For the three-WEC-unit scenarios, the penetration of wave energy is about 9%, and the curtailment of the wave generation occurs more often than the single-WEC-unit scenarios. Figure 8 shows the time history of the load and the electricity generation from the diesel generators and the WECs for three 3-unit cases. For no smoothing and no battery case, the steep power fluctuation drives the curtailment of the wave energy. In some periods, the system is turning the generators on and off far more frequently than other scenarios in response to the fast changes in wave power. For the case with both power smoothing and the battery, the two periods where we see curtailment are periods of low load, which is happening in the early hours of the morning (approximately 3 a.m. to 8 a.m.). For the period between hours 75 and 80, the load never goes below 3 MW and so all three of the diesel generators are put to their minimum generation (1 MW), and the wave generation that exceeds the amount needed to meet load is curtailed. For the section at 101 hours, the load dips below 3 MW, thereby necessitating turning one of the diesel generators off and ramping up the other two; then wave generation is used to meet the load demand.

This is a preliminary WEC-integrated grid analysis. We also included the heat rate changes, start costs, and minimum downtime and start-up time for the diesel generator. This would avoid the system unrealistically turning the generator on and off several times in response to changes in load. For a more detailed analysis, it is essential to consider a suitable size of diesel generator, depending on the production of power from WECs when integrating WEC-generated power into a grid system. For the model, we only simulated the grid system for 5 days with each day using the same wave energy generation. This means that sea state variability is not included. In future work, it would be useful to have a full year of wave production data to include that seasonal variability and gain a better understanding of how it interacts with the load over the year.

CONCLUSIONS

In this study, we analyzed the power output from WEC-Sim simulations for six sea states in Wave Energy Prize to compute the peak power and power time history to estimate the required battery storage capacity. The results were then used to evaluate the battery storage cost based on the cost information from the EIA report with and without the consideration of additional power smoothing (i.e., pressure accumulator, pressure-reducing three-way valve, and power-based set-point control). Finally, a preliminary grid integration analysis on WEC-generated power was performed using PLEXOS based on the results from WEC-Sim simulations to demonstrate how WEC-generated power could contribute to a small island electricity system.

The study shows that the cost of the battery storage for WEC application is primarily driven by the instantaneous peak power, resulting from the relatively short storage requirement needed. Therefore, reducing the power fluctuations is essential for reducing the overall LCOE of the WEC. The use of those power smoothing methods has been effective at reducing both the power fluctuation and size and cost of the battery storage system. When power smoothing methods were applied, the cost of battery storage was about 6% of the total LCOE, wherein the power fluctuation ratio was less than 0.7 (peak-to-average ratio of 1.4), which is significantly reduced as compared to the cases without applying the power smoothing methods and battery. There is also potential to further reduce the power fluctuation by adjusting the size of the parameters for the power smoothing methods to minimize the required battery storage cost. The grid integration analysis shows that implementing battery storage can be a viable solution for WEC applications. The study also suggests that multiple stages of an energy storage system may be more suitable for minimizing the LCOE.

This study is the first step of looking into the power fluctuation impact from WECs to the grid system. Future work includes more detailed cost estimation of undersea cables and subsea stations, detailed analysis on the impact to the grid system, larger wave energy penetration, and the potential and cost of using other energy storage technologies. Deeper analysis in these areas will enable system-level cost optimization.

ACKNOWLEDGEMENTS

This work was authored [in part] by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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