2.1.3.404 - WEC Array Power Management and Output Simulation Tool

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July 20, 2022

NREL/PR-5700-83319

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.

Project Overview

Project Summary

The project intends to create a publicly accessible numerical modeling framework to empower the wave energy sector to design projects of various scales (from kilowatts to hundreds of megawatts), which are optimized on a plant performance basis and are compatible with different power systems and wave conditions. The framework will integrate with WEC-Sim and a wave environment model (SWAN-FUNWAVE) as well as with established relevant electrical analysis tools, such as PLEXOS, REopt®, or DER-CAM, to model the grid system and interconnection, forecast short-term power output, and optimize power output and power management for the WEC array.

Intended Outcomes

- Advanced computational design tools and design strategies for WEC array design in combination with grid integration and energy storage at any deployment site.
- WEC developers can characterize and investigate different strategies and design scenarios due to the variation of different sources of electrical output, subsequently improving energy performance and cost reductions.
- Recommendations for industry on scenarios to make fewer power variations on arrays of WEC devices based on array modeling of various device architectures and array layouts.

Project Information

Principal Investigator(s)

- Yi-Hsiang Yu (PI), Thanh Toan Tran (NREL)

Project Partners/Subs

Zhaoqing Yang (PNNL)

Project Status

Completed

Project Duration

- Start Date: August 1, 2018
- End Date: September 30, 2020

Total Costed (FY18–FY20)

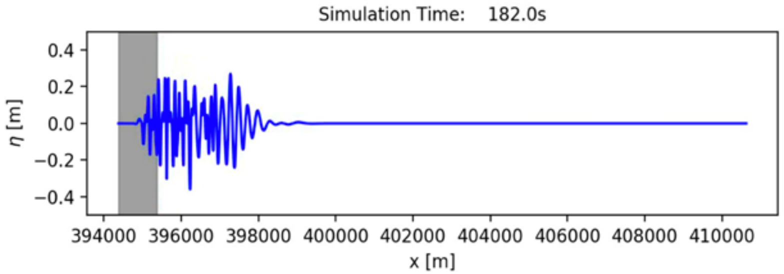
$300k

Project Objectives: Relevance

- This project was developed to contribute to the Marine Energy program's Foundational R&D priorities as well as Technology-Specific System Design and Validation priorities:
  - Foundational R&D:
    - **Develop and validate numerical modeling tools and methodologies for improved understanding of important fluid-structure interactions:**
      - Development tools are used to simulate the resource environment, device dynamics, and utility power system response as well as to create an interface for an array controller to optimize the array performance.
    - **Improve marine energy resource assessments and characterizations needed to optimize devices and arrays and understand extreme conditions:**
      - The project will enable developers to design effective and compatible energy plants with arrays of WEC devices. Tools are needed to model the system from "wave to wire" to control the electrical output from arrays of MHK devices for optimal and compatible output.
  - Reducing Barriers to Testing:
    - **Support additional scientific research on mitigating environmental risks and reducing costs and complexity of environmental monitoring:**
      - The project will evaluate plant-level power control, energy storage, and optimization modeling functionalities for WEC arrays in the power system performance models.

Project Objectives: Approach

- Convene the External Advisory Panel and provide an overview of the overall project; solicit feedback on how to ensure that industry can effectively use the outputs of this project.
- Develop WEC-Sim libraries to improve array modeling capability and interface with wave environment model.
- Identify regions with different classes of sea states; conduct and develop SWAN and FUNWAVE simulation linkage.
- Implement plant-level power control, energy storage, and optimization modeling functionalities for WEC arrays in the power system performance models.
- Host industry forum to review array modeling assumptions, power output, and findings.
- Host webinar to reveal array modeling results; provide a detailed overview of the new WEC-Sim features; and provide more detailed discussion on different technology improvement options, including array control and power smoothing, and conditioning approaches for utility integration.



Project Objectives: Expected Outputs and Intended Outcomes

Outputs:

- Public-domain software modules developed and extended within WEC-Sim to interface and model the WEC array power performance and storage system (https://github.com/yuyihsiang/HESS_Model.git)
- Conference and journal papers documenting the findings of the work:
  - "Analysis on the Influence of an Energy Storage System and its Impact to the Grid for a Wave Energy Converter" (OMAE2019)
  - "Application of a Phase-Resolving Wave Model to Enhance the Capabilities of a Wave Energy Converter Simulation Tool" (Ocean Sciences Meeting 2020)
  - "Influence of Time and Frequency Domain Wave Forcing on the Power Estimation of a Wave Energy Converter Array" (J. Mar. Sci. Eng. 2020)
  - "Analysis of a Hybrid Energy Storage System and Its Cost for a Wave Energy Farm" (In preparation)
- Webinars to solicit feedback and further disseminate the developed model.

Outcomes:

- An add-on library for WEC-Sim that will allow users to model various approaches to control electrical output from WEC arrays using realistic phase-resolving wave resource information at any deployment site and to characterize and investigate the sources of voltage and frequency variation and evaluate different strategies for reducing these variations.
- A case study of effects of the electrical output, power take-off (PTO), controls, and mechanical interaction on array efficiency, and grid impact.
- Recommendation guide for industry on methodologies to reduce power variations on arrays of WEC devices based on array modeling of various device architectures and array layouts.

Project Timeline

FY 2018

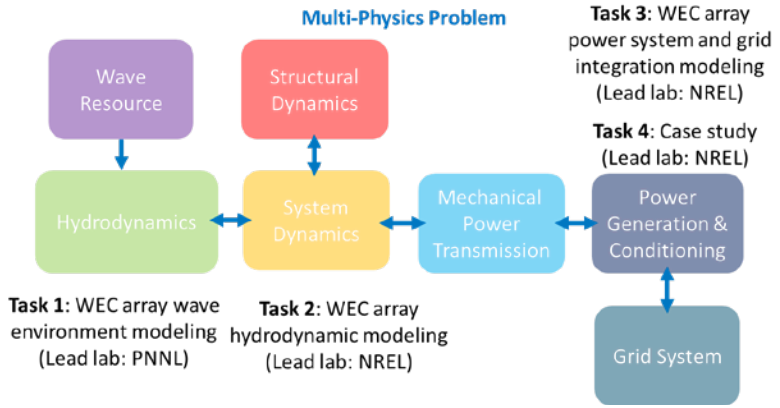
- Aug - AOP initiated

FY 2019

- (**Q1**) Held a meeting with External Advisory Panel
- (**Q2**) Developed virtual WEC array wave environment at PacWave from two wave models - SWAN and FUNWAVE
- (**Q3**) Developed WEC-Sim add-on to model WEC array via developed interface with wave environment model
- (**Q4**) Delivered a year-end project summary report to WPTO.

FY 2020

- (**Q1**) Conducted power system performance models of a plant level power control, energy storage, and WEC arrays
- (**Q2**) Submitted a conference paper on modeling plant-level power control, energy storage, and optimization
- (**Q2**) Hosted industry forum to review array modeling assumptions, power output, and initial finding
- (Q3) Released the interface code for WEC-Sim and power system performance models and documented case studies
- (Q4) Hosted webinar to reveal array modeling results regarding new WEC-Sim features and different technology improvement options, including array control and power smoothing, and conditioning approaches for utility integration.



*The bold text represents key tasks

Project Budget

FY19	FY20	Total Actual Costs FY19–FY20
Costed	**Costed**	**Total Costed**
$200K	$100K	$300K

- The funding was awarded in FY18.
- The project officially started in FY19 Q1 and ended in FY20 Q4.
- The project funding budgeted for both NREL ($216K) and PNNL ($84K)

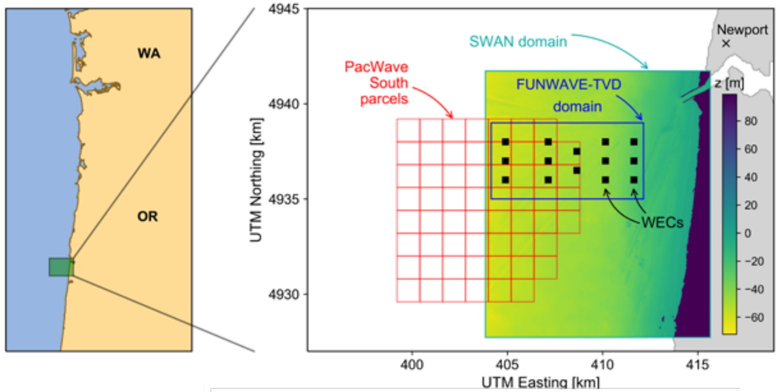
End-User Engagement and Dissemination

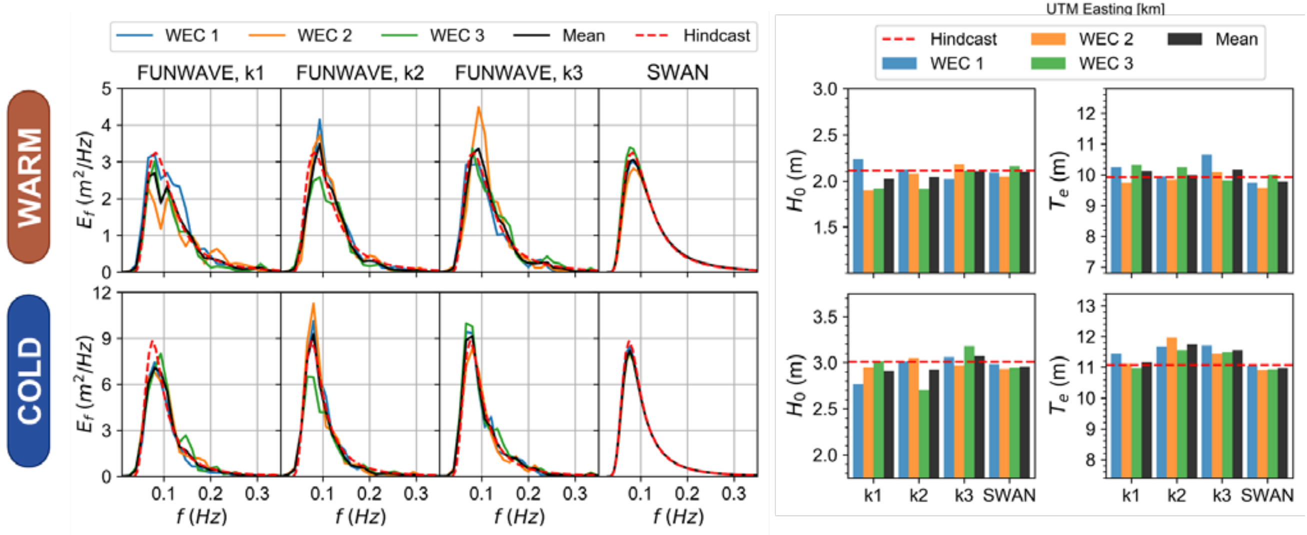
- An External Advisory Panel (EAP) was established to solicit feedback on project outcomes and status
  - The EAP consisted of multiple member organizations representing industry and academia
  - Yearly webinars and an online forum were held to solicit comments and guidance on results from the past year and planned work in the coming year(s).
- Project's dissemination included all maintenance and development of open-source codes, which are publicly available on GitHub, along with the online forum, documentation, applications cases, publications and webinars.
- Further conversions on the usage of project outcomes with internal NREL projects and industry partners during and after the project.

Performance: Accomplishments and Progress

- **Wave Environment Modeling**

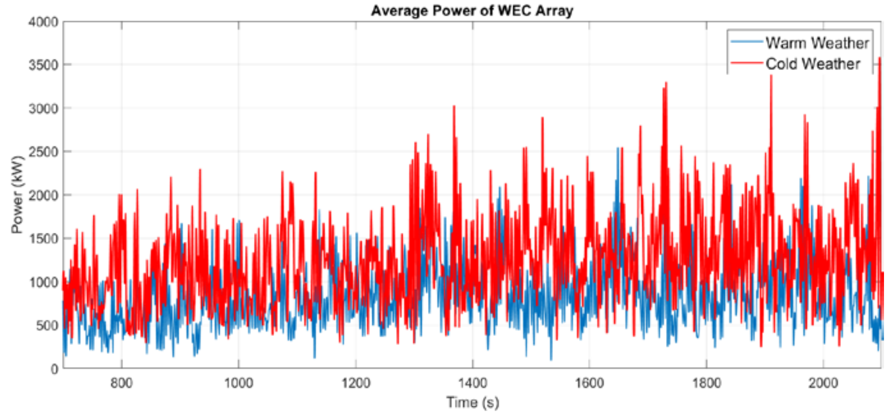
FUNWAVE-TVD	SWAN
Boussinesq equations, fully nonlinear	Wave action balance equation, linear
Phase resolving	Phase averaging
Time domain	Frequency domain
Requires more computer power	Requires less computer power





Ticona Rollano, F., T.T. Tran ,Y.H., Yu, G. García-Medina, and Z. Yang, 2020. Influence of Time and Frequency Domain Wave Forcing on the Power Estimation of a Wave Energy Converter Array, J. Mar. Sci. Eng. 2020, 8(3), 171; https://doi.org/10.3390/jmse8030171

- Virtual WEC array analysis (WEC-Sim) at PacWave is forced with wave data from two wave models – SWAN and FUNWAVE.
- Offshore wave conditions obtained from a regional 32-year hindcast study (Wu et al. 2020).



- Transient power of WEC farm (14 WECs) at PacWave South site in cold-weather season is larger than that in warm-weather season. → Larger power fluctuation as well.
- Cold-weather season is selected to further design an energy storage system for the WEC farm (14 RM3 WEC devices).

Performance: Accomplishments and Progress (cont.)

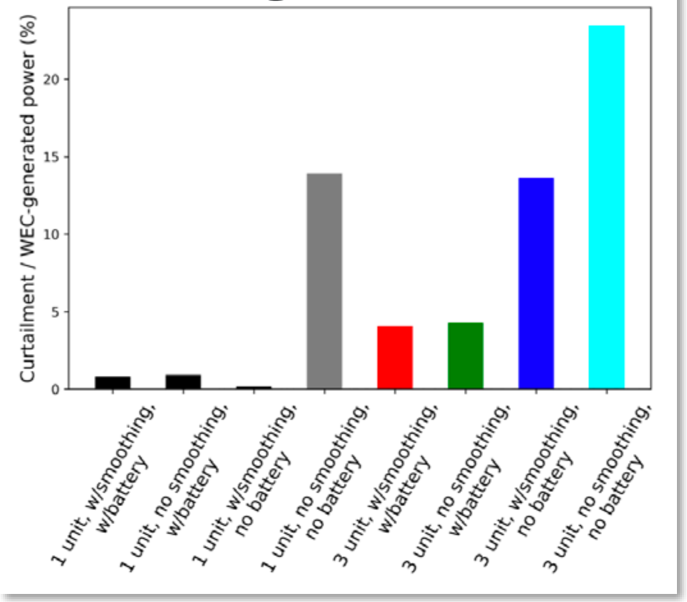
- Power System and Grid Integration Modeling and Case Study

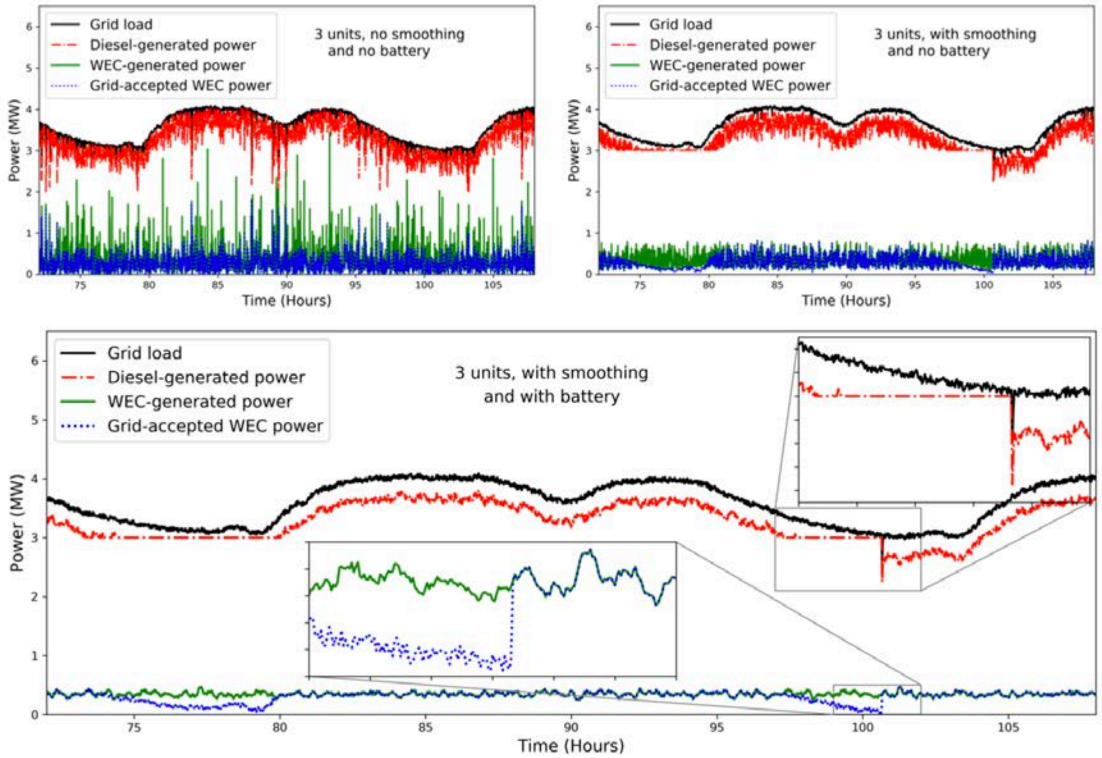
WEC-Sim simulations

RM3 two-body floating point absorber

PLEXOS simulation

- A small island system with a peak of 5 MW and three diesel generators.
- The load used was a down-scaled version of actual 2012 data for an island.
- The case study also includes
  - ➢ Heat rate changes that affect the generator efficiency
  - ➢ Start costs and minimum downtime and start time for the diesel generator.





- 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.
- 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 3–8 a.m.).

Jeremy Stefek, D. Bain, Y.-H. Yu, D. Jenne, G. Stark., Analysis on the Influence of an Energy Storage System and its Impact to the Grid for a Wave Energy Converter. OMAE2019-96466, V010T09A031

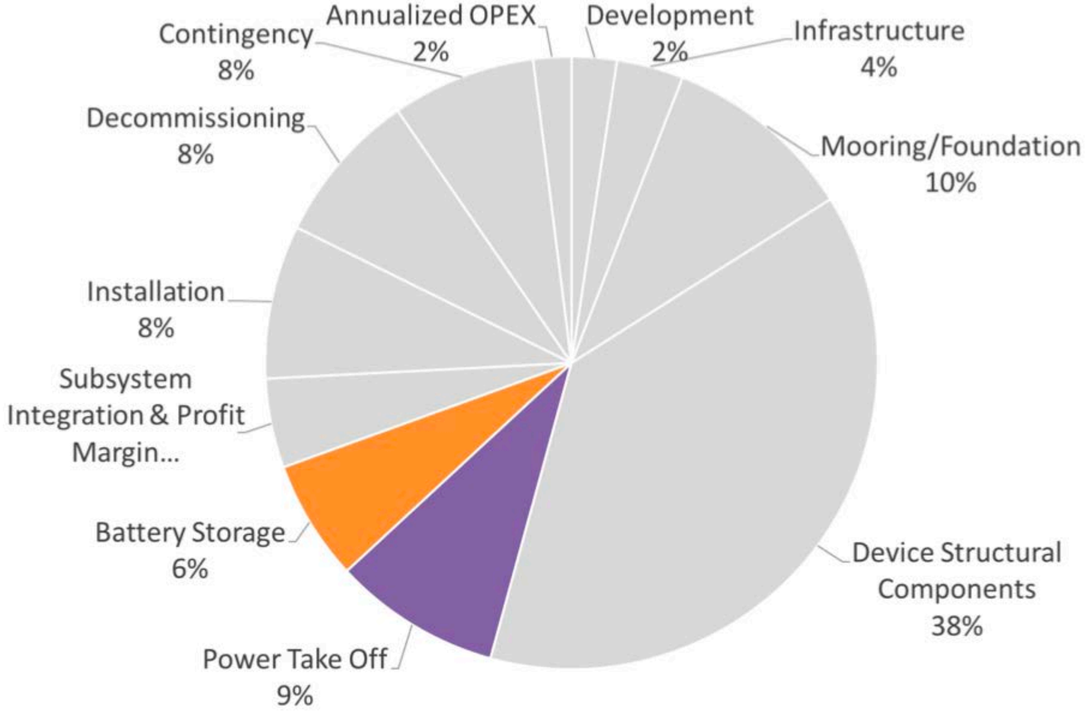
Performance: Accomplishments and Progress (cont.)

- Power System and Grid Integration Modeling and Case Study

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	

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



- Table on the bottom left shows the estimated cost and the levelized cost of energy (LCOE) contribution for battery and PTO based on DOE's reference mode project.
- The cost driver is power capacity, and the cost breakdown for the case is plotted in the figure on the top.

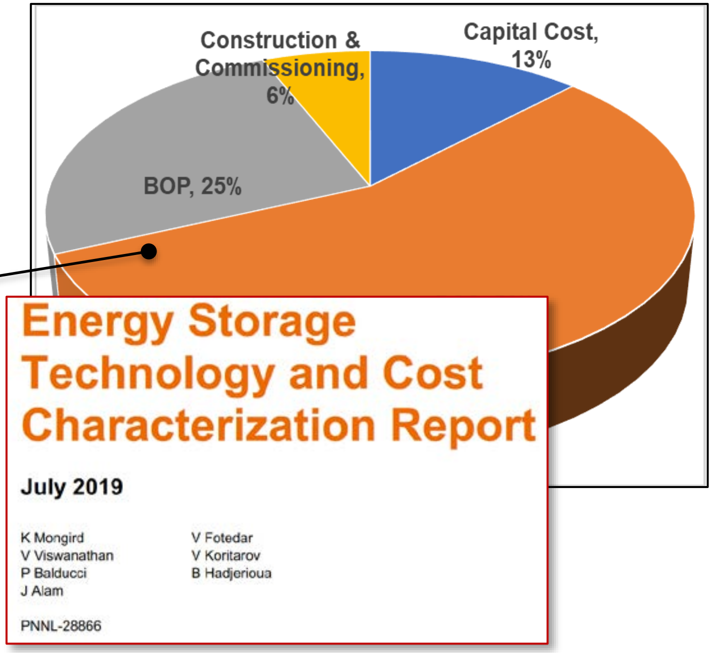
Jeremy Stefek, D. Bain, Y.-H. Yu, D. Jenne, G. Stark., Analysis on the Influence of an Energy Storage System and its Impact to the Grid for a Wave Energy Converter. OMAE2019-96466, V010T09A031

Performance: Accomplishments and Progress (cont.)

- Energy Storage System Cost Analysis

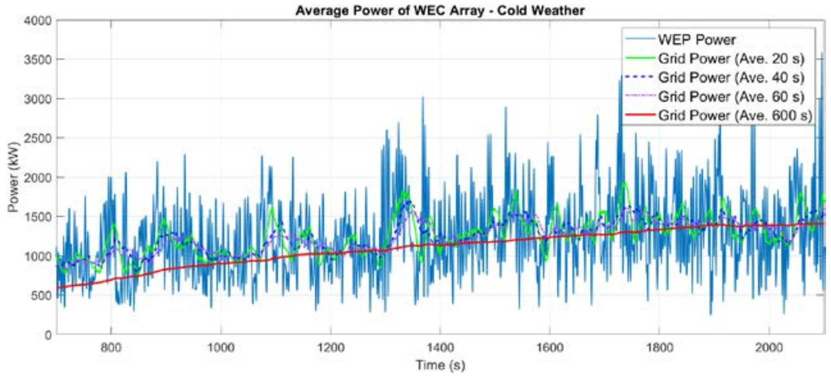
Total project cost (TPC) = Capital cost + PCS + BOP + Construction and Commissioning

- Power control system (PCS) cost = the cost for the inverter + packaging + container + inverter controls.
- Balance of plant (BOP) = site wiring + interconnecting transformers + other additional ancillary equipment.



- With a longer time interval, smoother average power is fed into grid system.
- For power fluctuation mitigation purpose, cost for supercapacitor energy storage system (SESS) is only half of battery energy storage system (BESS) cost.

Data				Total Project Cost Using Li-Ion Battery			Total Project Cost Using Suppercapacitor		
Time Interval	Energy Capacity	Max Power	E/P Ratio	Cost (E/P=4hr)	Cost (Max)	Project Cost	Cost (E/P=0.0125 hr)	Cost (Max)	Project Cost
s	kWh	kW	hr	k$	k$	k$	k$	k$	k$
20	1.21	1903	0.0006	0.57	3570.03	3570.03	89.83	1769.79	1769.79
40	1.68	2089	0.0008	0.79	3918.96	3918.96	124.80	1942.77	1942.77
60	1.89	1994	0.0009	0.89	3740.74	3740.74	140.95	1854.42	1854.42
600	5.17	2174	0.0024	2.42	4078.42	4078.42	384.77	2021.82	2021.82
1400	31.56	2327	0.0136	14.80	4365.45	4365.45	2350.88	2164.11	2350.88



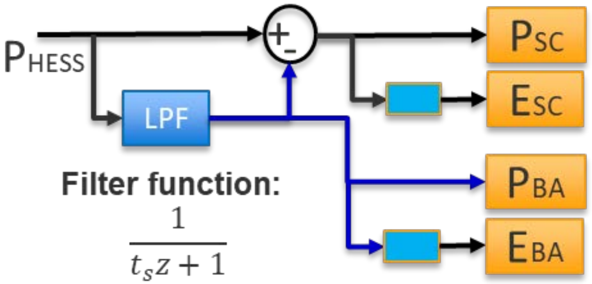
$$E_{HESS}(T_w) - E_{HESS}(0) = \int_0^{T_w} \left(P_{WEP}(t) - P_{grid}(t)\right) dt$$

P_{grid} is an average power over time interval T_w

Thanh Toan Tran and Yi-Hsiang Yu, Analysis of a Hybrid Energy Storage System and Its Cost for a Wave Energy Farm. (Manuscript in preparation)

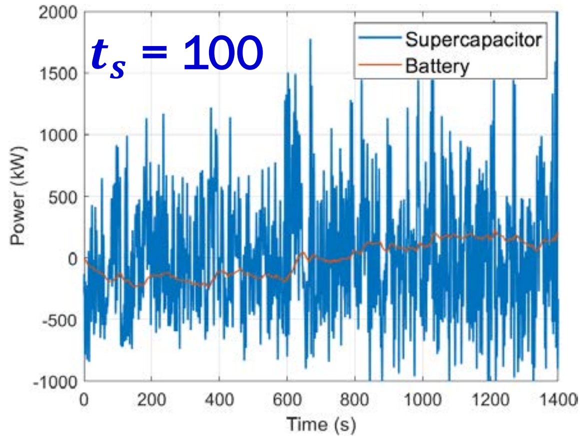
Performance: Accomplishments and Progress (cont.)

- **Energy Storage System Cost Analysis**
  - ➢ Smoother power curve allocated to battery storage element helps increase its life span.
  - ➢ Depending on selected filter function parameters of power allocation system, total project cost of HESS could be significantly reduced.



Filter function:

$$\frac{1}{t_s z + 1}$$



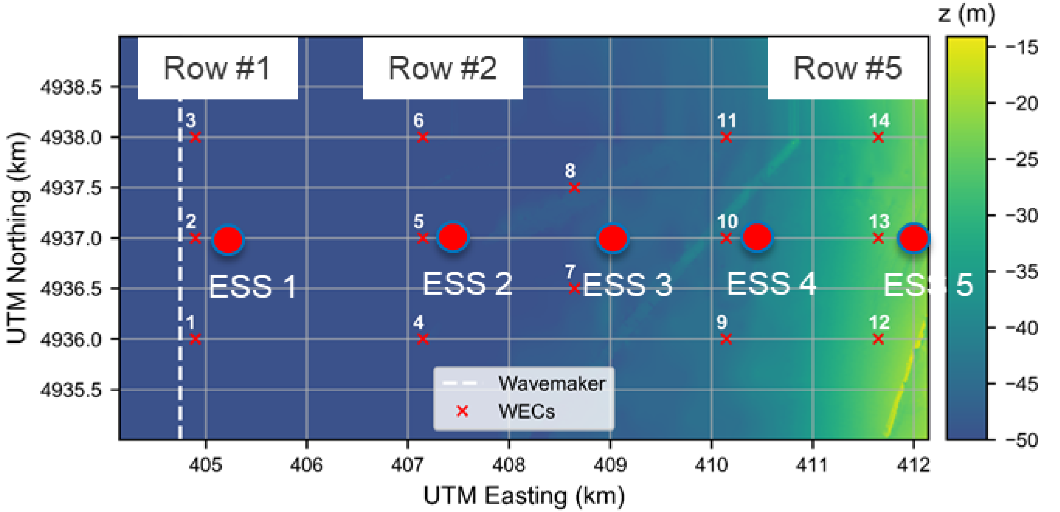
Total Project Cost for HESS (Time Interval = 1400 s)									
Ts	Storage Element	Energy Capacity	Max Power	Energy/Power (E/P) Ratio	Cost (E/P=4hr for BA & E/P=0.0125hr for SC)	Cost (Max)	Project Cost (BA+SC)	Compare to BA Only	Compare to SC Only
s		kWh	kW	h	k$	k$	k$	%	%
BA Only		31.56	2327	0.0136	14.80	4365.45	4365.45		
SC Only					2350.88	2164.11	2350.88		
3	BA	30.95	1192	0.0260	14.52	2236.19	3686.06	-15.56%	56.79%
	SC	1.52	1559	0.0010	113.38	1449.87			
5	BA	30.83	1020	0.0302	14.46	1913.52	3488.01	-20.10%	48.37%
	SC	2.06	1693	0.0012	153.51	1574.49			
20	BA	29.44	523	0.0563	13.81	981.15	2808.60	-35.66%	19.47%
	SC	4.08	1965	0.0021	304.13	1827.45			
100	BA	24.64	238	0.1035	11.56	446.49	2425.53	-44.44%	3.18%
	SC	9.78	2128	0.0046	728.25	1979.04			
200	BA	24.67	196	0.1259	11.57	367.70	2363.48	-45.86%	0.54%
	SC	15.22	2146	0.0071	1133.75	1995.78			

Thanh Toan Tran and Yi-Hsiang Yu, Analysis of a Hybrid Energy Storage System and Its Cost for a Wave Energy Farm. (Manuscript In preparation)

Performance: Accomplishments and Progress (cont.)

- **Energy Storage System Cost Analysis**

  - For ESSs located at individual WEC in the wave farm, cost is substantially increased (~6.5 times).
  - For ESSs located at each row of WEC farm → slightly higher total project cost compared to that at full system → Should we consider cost trade-off between ESSs and power electric cable layout?



Total Project Cost											
				Li-Ion Battery		Sodium-Sulfur Battery		Lead Acid		Supercapacitor	
WEC Row ID	Energy Capacity (ΔE)	Equiv. Energy	Max. Power - ESSs	Energy-Based	Power-Based	Energy-Based	Power-Based	Energy-Based	Power-Based	Energy-Based	Power-Based
-	kJ	kWh	kW	k$	k$	k$	k$	k$	k$	k$	k$
1 (1-2-3)	4,316	1.20	327	0.6	613	1.1	1,185	0.7	717	89	304
2 (4-5-6)	6,710	1.86	440	0.9	826	1.7	1,597	1.0	966	139	410
3 (7-8)	8,257	2.29	455	1.1	853	2.1	1,648	1.3	997	171	423
4 (9-10-11)	19,985	5.55	865	2.6	1,623	5.0	3,137	3.0	1,898	413	804
5 (12-13-14	17,992	5.00	411	2.3	771	4.5	1,491	2.7	902	372	382
Total Cost from each WEC's row				**7**	**4,686**	14	9,057	9	5,480	**1,185**	**2,323**
Total Cost from each WEC				**27**	**26,870**	52	51,935	31	31,425	**4,245**	**13,320**

Total Project Cost				
	Distributed ESS on each WEC row		ESS of WEC farm	
ESS Type	Energy-Based	Power-Based	Energy-Based	Power-Based
-	k$	k$	k$	k$
HESS (BA + SC)	755	**2,468**	1,144.9	**2,363**
Standalone BESS	7.5	**4,686**	14.8	**4,366**
Standalone SESS	1,184.6	**2,323**	2,350.9	**2,164**

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