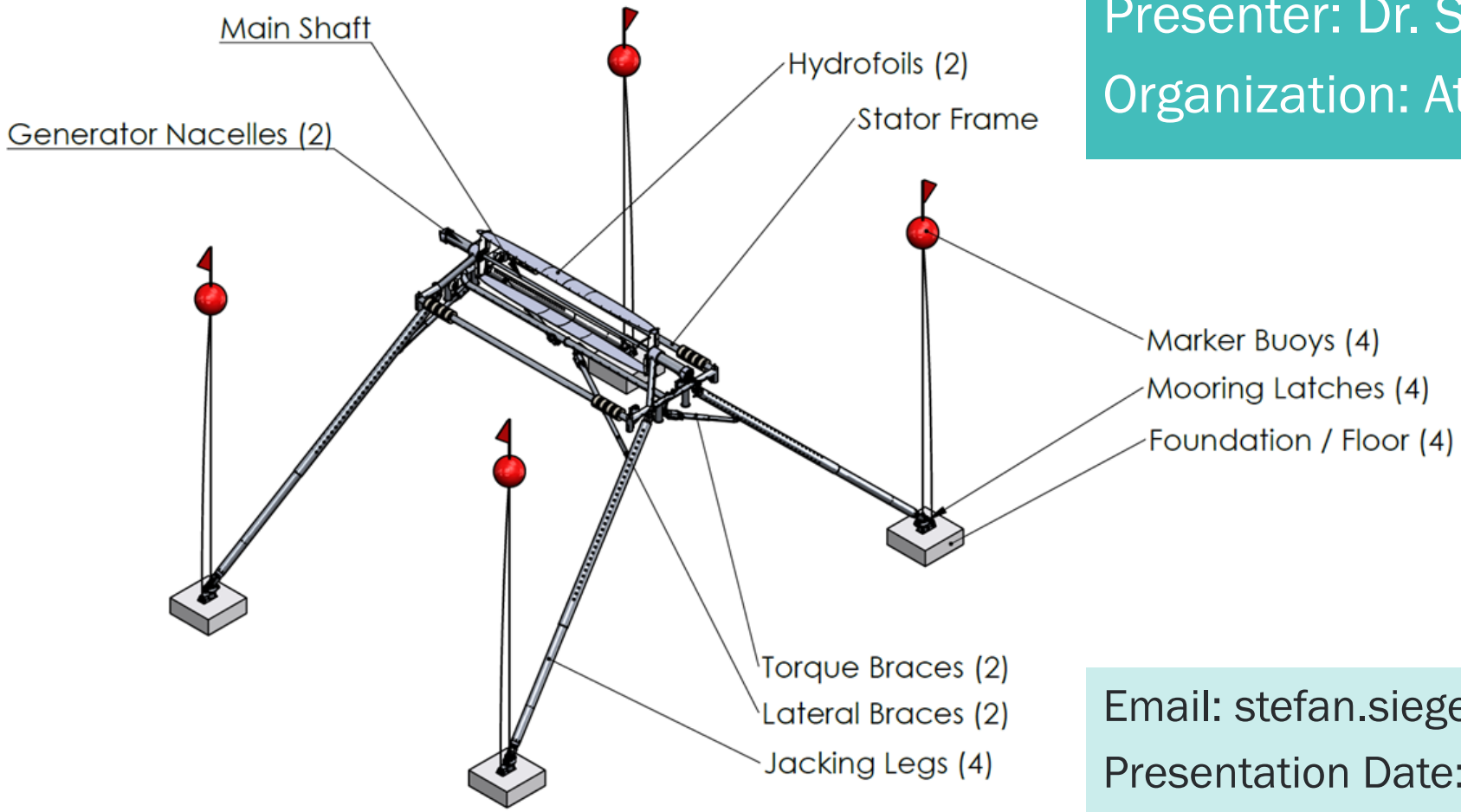
DE-EE0008626 Cycloidal Wave Energy Converter



Presenter: Dr. Stefan G. Siegel
Organization: Atargis Energy Corporation

Email: stefan.siegel@atargis.com
Presentation Date: 2022-07-19

Project Overview

Project Summary

The Cycloidal Wave Energy Converter (CycWEC) enables cost efficient wave energy conversion by means of utilizing hydrofoil lift and operating as a wave termination device that utilizes economies of scale.

- *As a wave termination device, scales to utility power production (>2.5MW)*
- *Uses hydrofoils to efficiently extract energy from deep ocean waves*
- *A wave energy converter that operates fully submerged*

Intended Outcomes

- *Design and wave tank testing of a 1:15 scale model*
- *Advance the TRL level from 4 to 6*
- *The device will be ready for ocean testing at the end of the program*
- *Experimentally validate the TPL level estimate of 7, which is presently based on numerical simulations*

Project Information

Principal Investigator(s)

- Dr. Stefan G. Siegel

Project Partners/Subs

- US Navy MASK Basin for wave tank testing

Project Status

Ongoing

Project Duration

- 2019-09-01
- 2023-03-31

Total Costed (FY19–FY21)

$1,896K

Project Objectives: Relevance

Relevance to Program Goals:

- Some aspects of this project falls into the *Foundational R&D category:*

The next-generation CycWEC improves "*Energy Affordability*" by means of "*Dramatic MHK technology LCoE Reduction*":

  - We estimated a LCoE of 13.5 US Cents/ kWh in the proposal based on the NREL/Sandia spreadsheet model and previous control algorithm performance
  - This has been improved to 10.5 US Cents / kWh due to feedback controller optimization performed in Budget Period 1 of this project
  - At 1GW deployed, LCoE is estimated to be reduced to 6.1 US Cents / kWh

- "Technology-specific system design" was performed in order to:
  - Improve "Energy Security" by optimizing the mooring system design of the CycWEC to survive storms
  - Development of "cost-efficient installation", commissioning and decommissioning procedures by means of a novel mooring latch was performed

Project Objectives: Approach

The CycWEC implements 12 major improvements over 1st generation WEC designs:

- The CycWEC is a wave terminator than scales to large per device power levels (MW)
- Direct conversion of wave power to continuous rotation shaft power / direct drive generator (no mechanical components in between foils and generator)
- Hydrofoils for hydrodynamically efficient interaction with ocean waves
- The hydrofoils rotate faster than the wave particle velocity, reducing PTO size and cost
- Feedback control to achieve efficient operation in all sea states
- Fully submerged to enable storm survival without excessive structural loads
- Mooring system enables lifting device out of water for on site maintenance
- Mooring system orients CycWEC to align with incoming waves
- Mooring system optimizes submergence for sea state and tidal changes
- Direct attachment to mooring points by means of legs, no fatigue in mooring lines
- Deployment without special equipment, floats and can be towed to installation site
- Intermediate water depth to minimize scour at mooring points

Project Objectives: Expected Outputs and Intended Outcomes

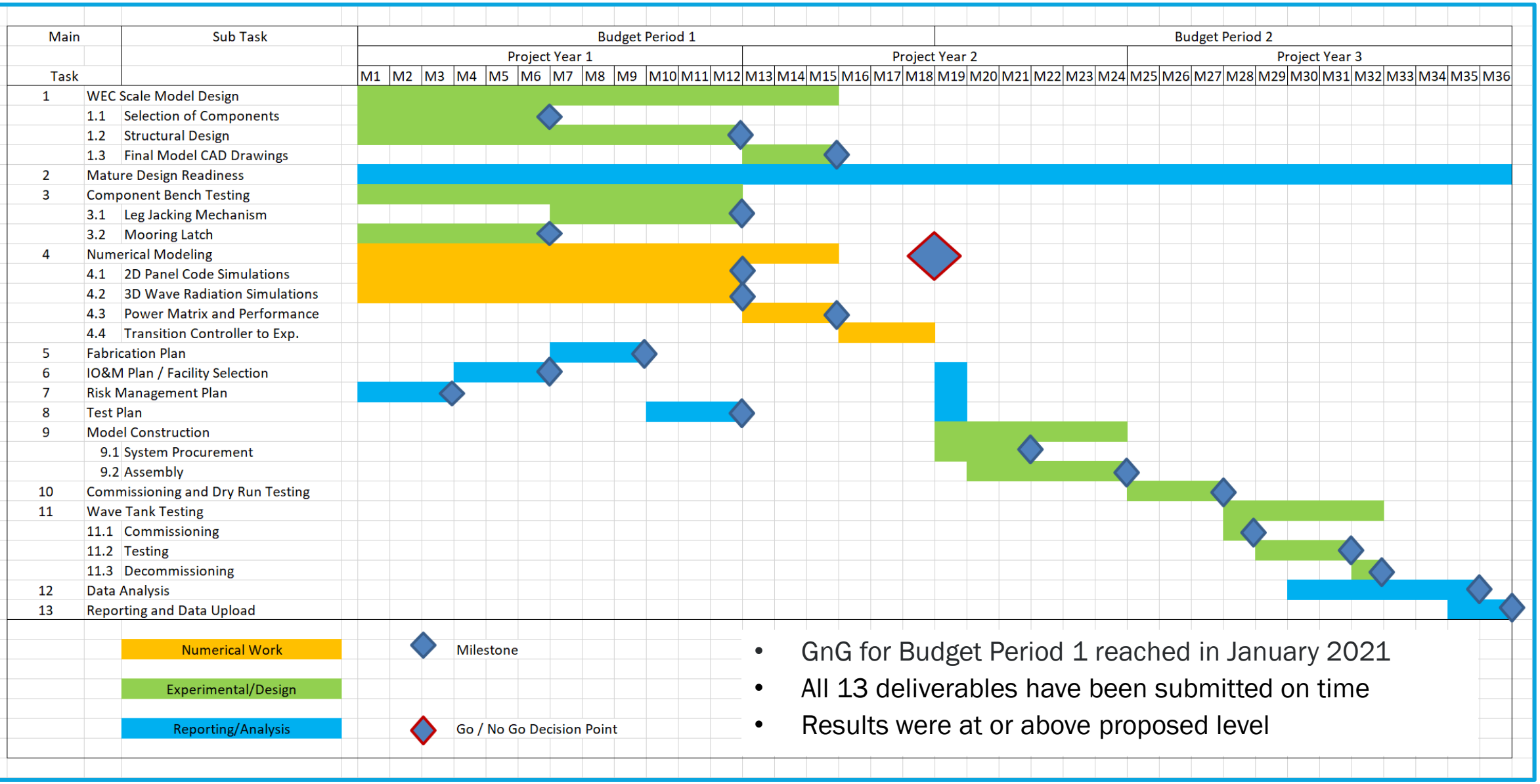
Outputs:

- Bench testing model and results for the CycWEC leg jacking mechanism (BP1)
- Bench testing 1:15 model and results for the mooring latch (BP1)
- 1:100 scale mooring system mockup and testing results (BP1)
- Control system bench test (BP1)
- Design of wave tank model (BP1)
- Construction of a 1:15 scale wave tank model (BP2)

Outcomes:

- Feedback control design is validated in numerical simulations (BP1)
- Power matrix at wave tank and ocean scale for irregular waves established (BP1)
- Advancement of the CycWEC TRL from 4 to 6 by means of wave tank testing (BP2)
- CycWEC ready for ocean testing at the end of BP2

Project Timeline



- GnG for Budget Period 1 reached in January 2021
- All 13 deliverables have been submitted on time
- Results were at or above proposed level

Project Budget

Total Project Budget – Award Information		
DOE	Cost-share	Total
$3496K (BP:1 - $1,496K)	$900k (BP1 - $400K)	$4396K (BP1 - $1,896K)

FY19	FY20	FY21	Total Actual Costs FY19–FY21
Costed	Costed	Costed	Total Costed
$178K	$1,108K	$610K	$1,896K

- The project was under budget for the 18 months of BP1 until the Go-No Go Decision point
- This was due to some staff members being hired after the starting date of BP1
- The remaining BP1 funds were spent during the no cost extension to perform independent external review with NREL and Sandia staff.
- The project is currently on hold to raise matching funding for BP2.

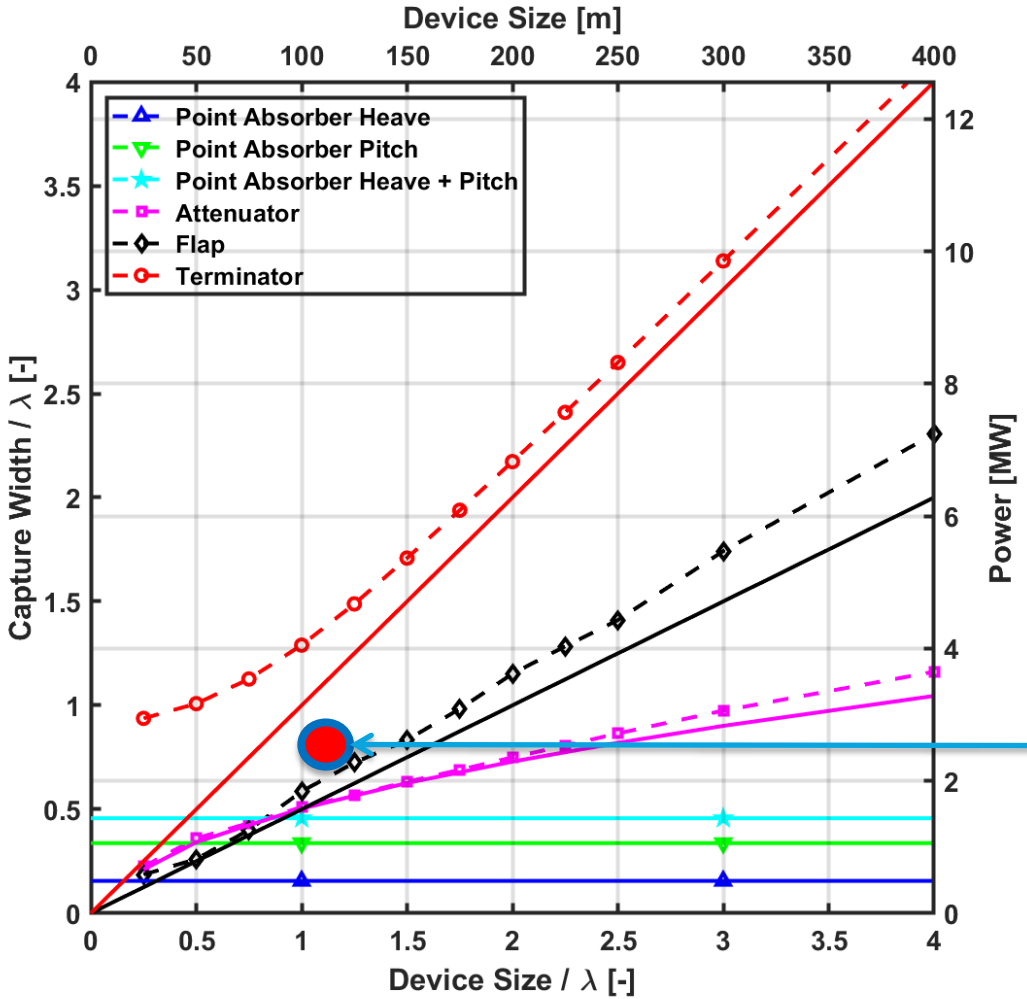
End-User Engagement and Dissemination

- Atargis has published all BP1 results in open literature, resulting in 4 conference papers:
  - S.G. Siegel, Scalability Limits of Ocean Wave Energy Converters, ICOE - International Conference on Ocean Energy, 2021
  - Chitale, K. C.; Fagley, C.; Mohtat, A. & Siegel, S. G., Numerical Evaluation of Climate Scatter Performance of a Cycloidal Wave Energy Converter, 14th European Wave and Tidal Energy Conference, Plymouth, UK, 2021
  - Mohtat, A.; Fagley, C.; Chitale, K. C. & Siegel, S. G., Efficiency analysis of the cycloidal wave energy convertor under real-time dynamic control using a 3D radiation model, 14th European Wave and Tidal Energy Conference, Plymouth, UK, 2021
  - Casey Fagley Ali Mohtat, K. C. & Siegel, S. G., Dynamic Estimation and Control of a Cycloidal Wave Energy Converter in Three-Dimensional Sea States, 14th European Wave and Tidal Energy Conference, Plymouth, UK, 2021
- All of the above conference papers are under peer review for journal publication
- Three US Patent Applications have been filed with the USPTO and are under review:
  - Siegel, S. G. Floating Cycloidal Wave Energy Converter, U. S. Patent Application 17/216,828, 2021
  - Siegel, S. G. Mooring Latch for Marine Structures, U. S. Patent Application 17/149,272, 2021
  - Siegel, S. G. Mooring Structure for Ocean Wave Energy Converters, U. S. Patent Application 17/149,388, 2021
- One Bachelor Thesis: “Programming, Calibration and Commissioning of a 5-Hole Probe”, Freia Siegel, Technische Universität Berlin, School of Electrical Engineering and Computer Science, Germany, February 25th, 2022. Supervisor Prof. Dr.-Ing. C. Gühmann.

Performance: Accomplishments and Progress

Scalability of WECs

Maximum possible energy absorption with no viscous or power train losses
This is a hard upper limit similar to the Betz limit (59%) for wind turbines



- Atargis 3D Wave Radiation Simulation and Theory for:
  - Wave Period 8s
  - Wave Height 2m
  - Power 30kW/m
  - Wave Length 100m
  - Airy Wave
- Theory is shown as solid lines
- Atargis Numerical Wave Tank Results are shown as symbols

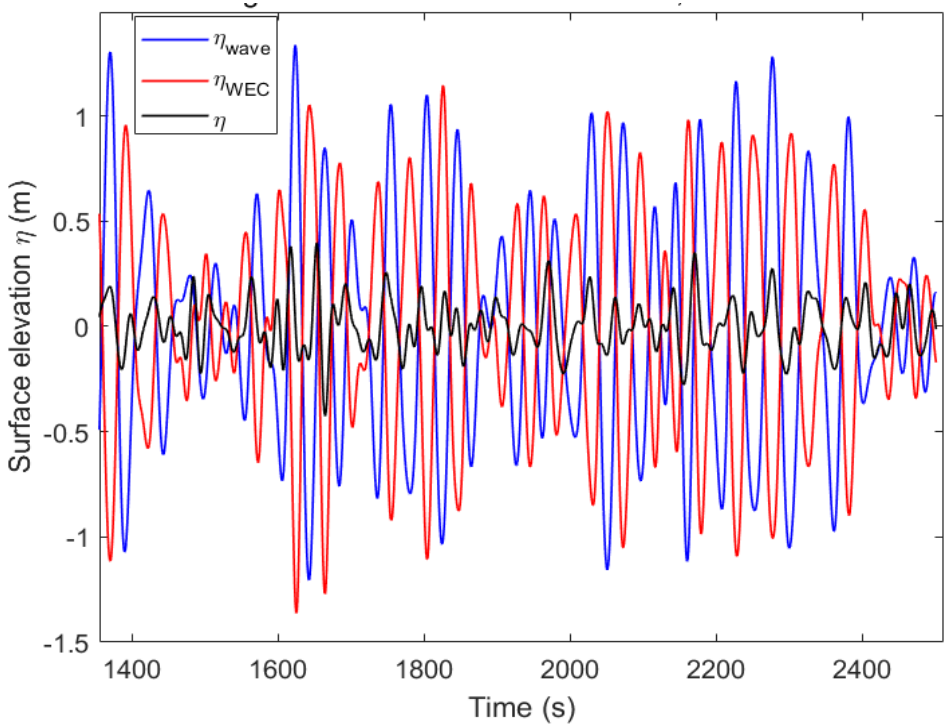
2.5MW Wind Turbine with 105m Rotor Diameter

Source: Siegel 2021

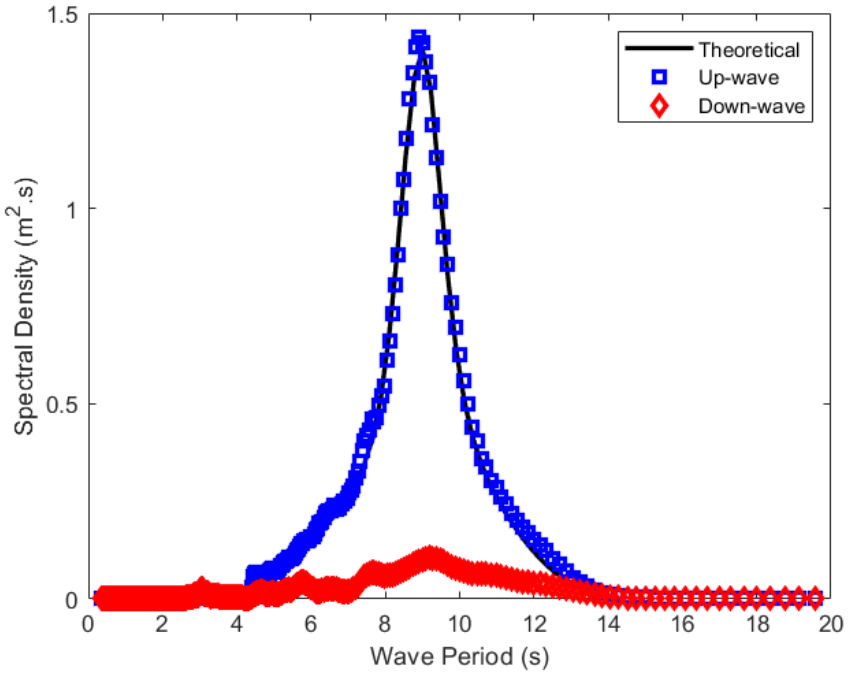
Performance: Accomplishments and Progress

Power Matrix

- JONSWAP spectrum used to approximate irregular waves.
- Wave power calculated based on individual wave components.



Surface elevation at downwave location for a significant wave period of 9s.



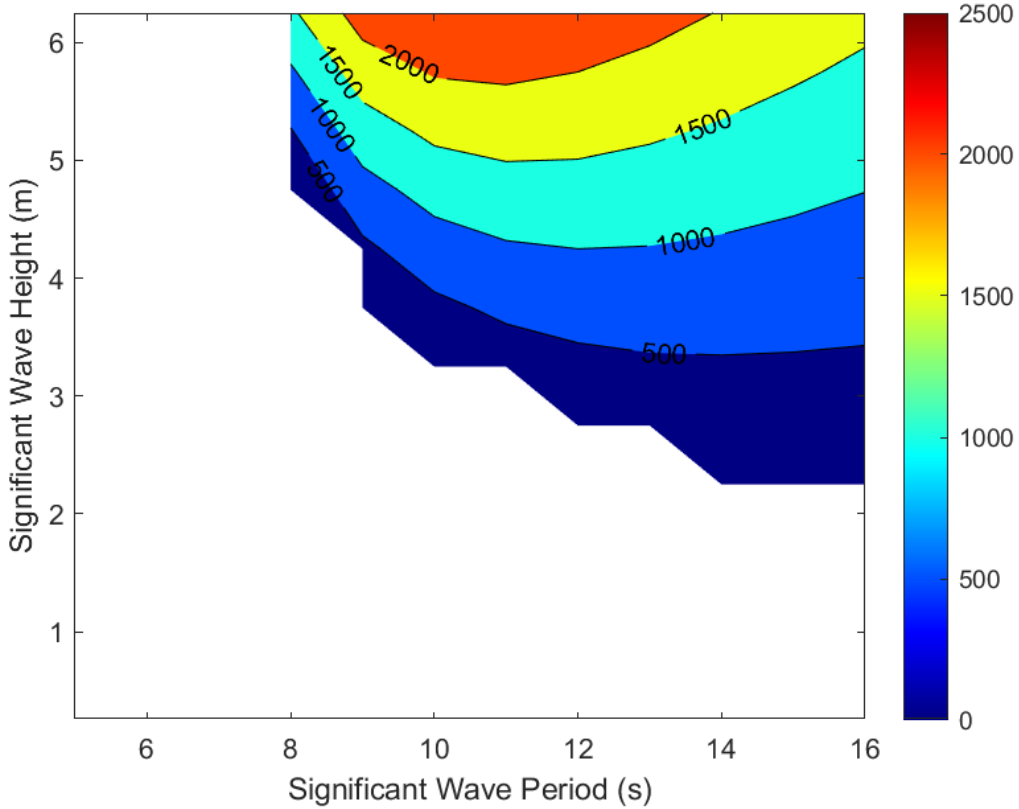
Wave spectra at upwave and downwave locations

Source: Chitale et. Al. 2021

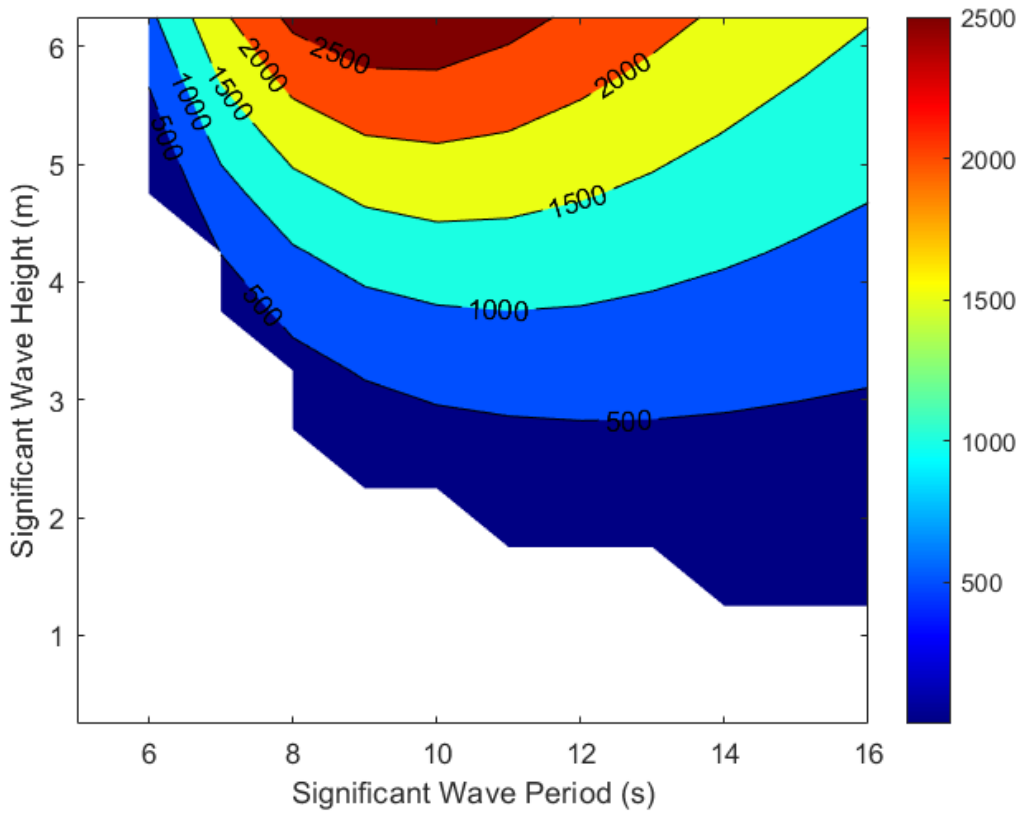
Performance: Accomplishments and Progress

Power Matrix

Shaft power calculated from simulations in kW – Irregular Wave Cancellation
These are the first irregular wave power matrix results for the CycWEC



Controller 1



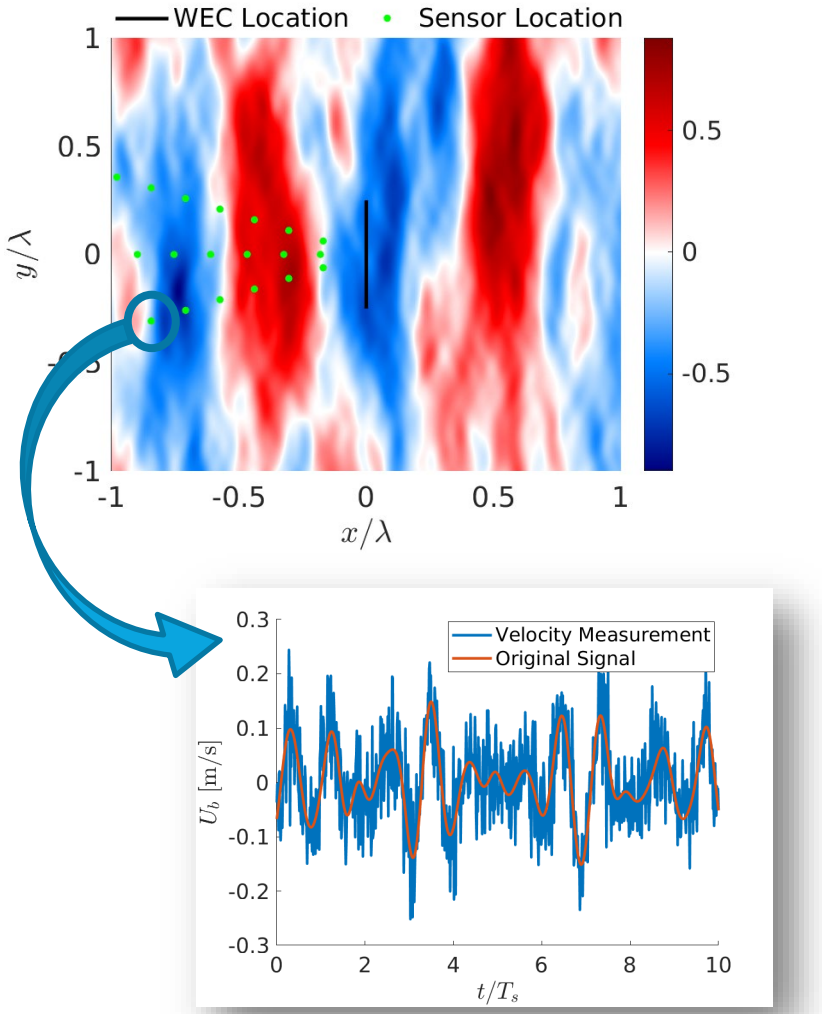
Controller 2

Source: Chitale et. Al. 2021

Performance: Accomplishments and Progress

HADCP Estimation

- Goal: Accurately estimate wave state given beam velocities from a Horizontal Acoustic Doppler Current Profiler (HADCP) with addition of typical sensor noise
- Approach: Use both temporal AND spatial POD based estimation (novel approach developed in this program)
- Determined required parameters
  - ARX order
  - POD basis order
  - Cut off frequency
- Demonstrated estimation limitation
- Simulated impact on CycWEC energy extraction efficiency



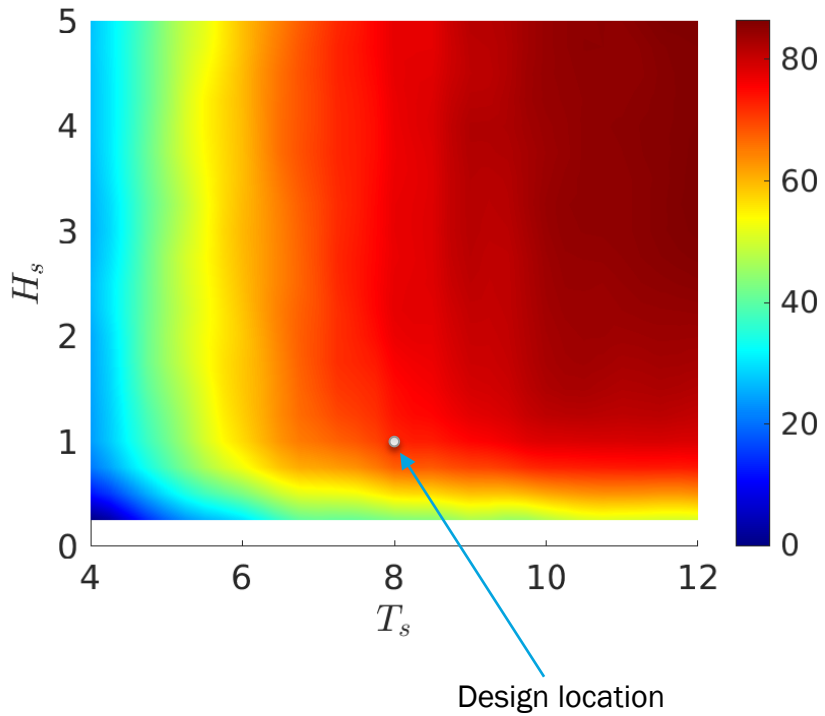
Source: Fagley et. Al. 2021

Performance: Accomplishments and Progress

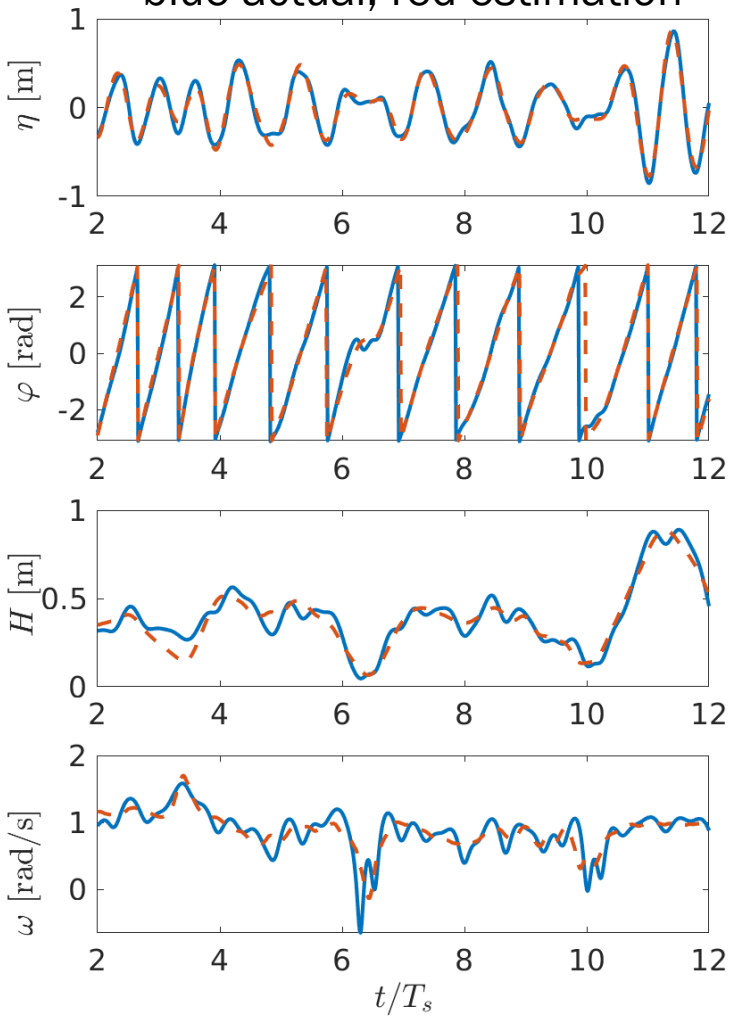
HADCP Estimation Results

- Standard wave conditions
  - T_s = 8 seconds
  - H_s = 1 meters
  - S_I = 10
- Estimation order
  - [na nb nk] = [24, 2, 4]
  - Nsensors = 16 bins/beam
  - Nmodes = 16
- 1542 coefficients in ARMAX
- Prediction performance of validation case
  - 19% reconstruction error
- Error has minimal impact on CycWEC efficiency

Reconstruction Accuracy [%]



Time Signals:
– blue actual, red estimation

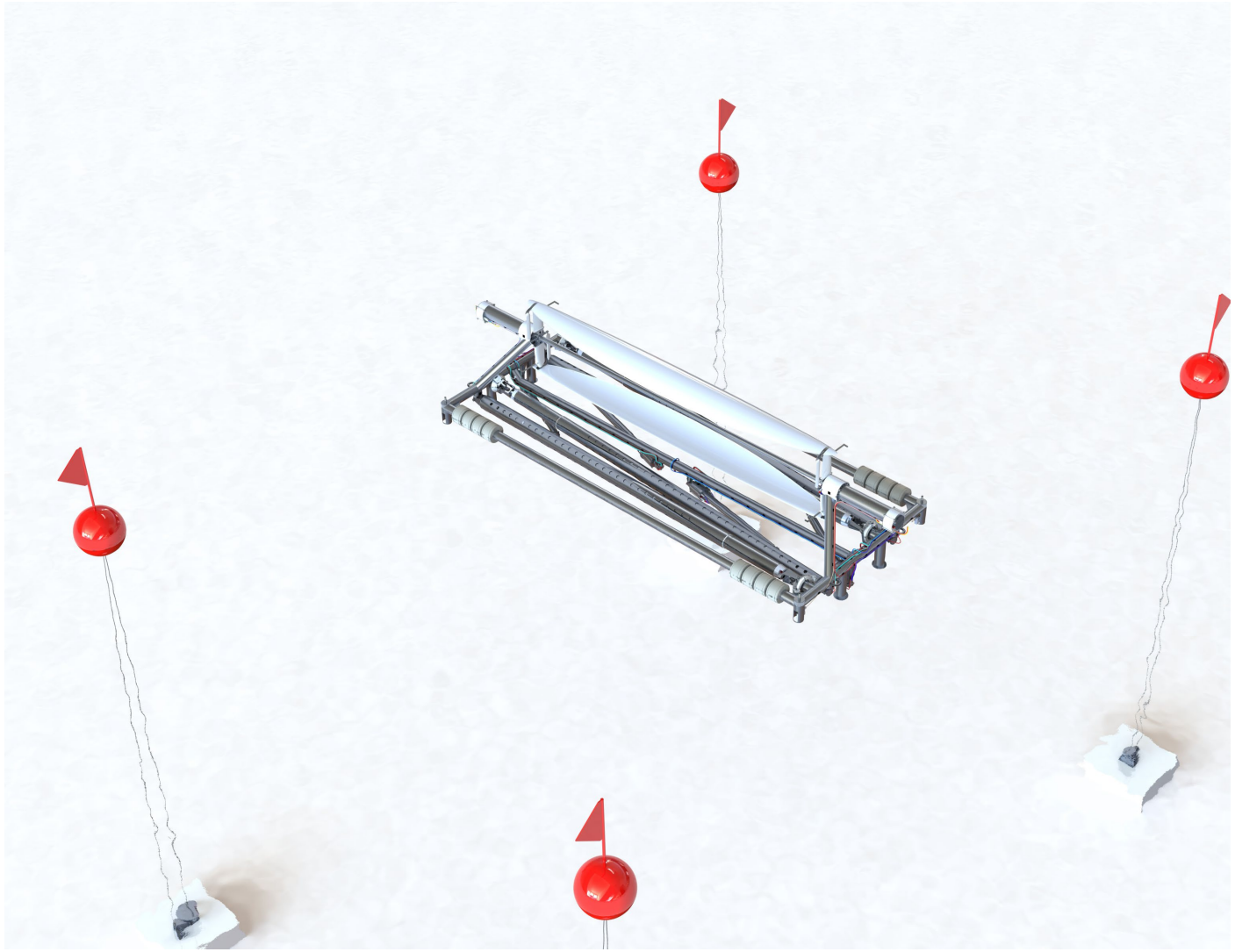


Source: Fagley et. Al. 2021

Performance: Accomplishments and Progress

1:15 Scale Model Design

- Defined Model Geometry and scale of 1:15:
  - Span 4m
  - Hydrofoil Chord Length 400mm
  - Radius 400mm
- Selected components and instrumentation
- Performed structural analysis
- Detailed CAD design
- Developed Test Plan
- Commissioning and Decommissioning procedures
- Designed, programmed, built and bench tested CANOpen based DAQ / Control system:
  - 200 measurement parameters
  - Pressure Distribution on Foils
  - 5 Hole Probes on Rotor
  - Structural loads at Struts and Legs
  - Leg jacking pins and spindles
  - Main Shaft Generator and Blade Pitch Actuators



CycWEC in floating (commissioning/decommissioning) configuration

Performance: Accomplishments and Progress

Mooring Latch Bench Test

Mooring Mockup

Maintenance Position

Storm Survival Position

Jacking Leg Bench Test

Future Work

Proposed work for Budget Period 2:

- Build the 1:15 scale model that was designed in BP1
- Test the model at the Navy MASK basin:
  - Validate performance matrix
  - Test deployment/commissioning and decommissioning process
  - Demonstrate storm survival
  - Harmonic, irregular and spread spectrum waves
- Post process testing data and compare to simulation results
- Publish results in open literature

Q&A