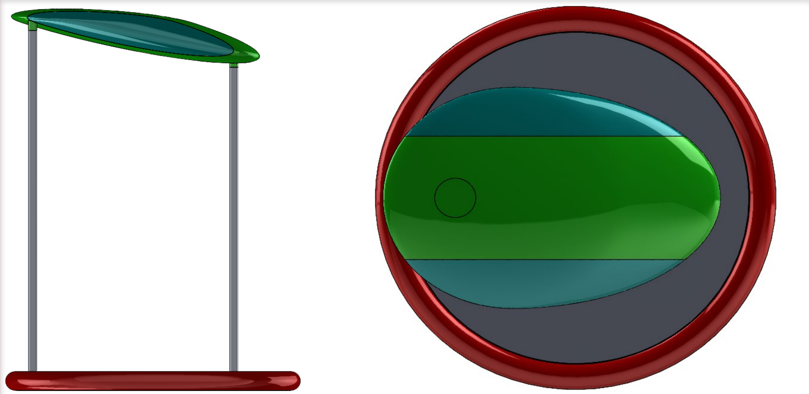
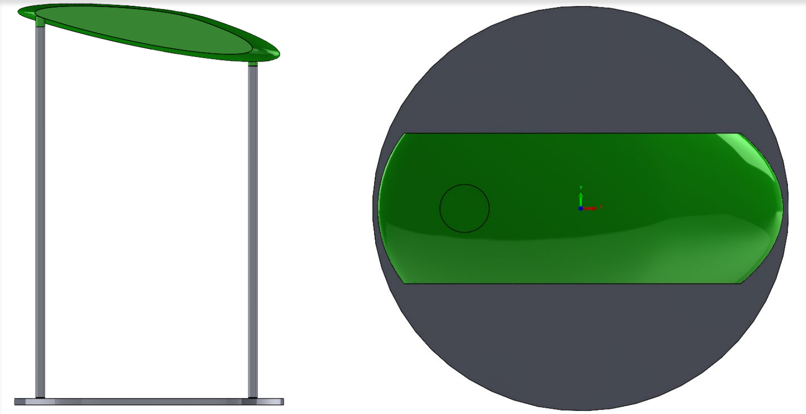
2.1.2.403 – Fatigue and Structural Load Analysis and Control for Variable-Geometry Wave Energy Converters (VGWECs)



Geometry Configuration 1



Geometry Configuration 2

Two-body Point Absorber Variable VGWEC Concept

Presenter: Nathan Tom

Organization: National Renewable Energy Laboratory

Email: nathan.tom@nrel.gov

Presentation Date: July 20, 2022

NREL/PR-5700-83333

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.

Project Overview

Project Summary

- The VGWEC project will generate and disseminate foundational knowledge to enable a paradigm shift in the design of wave energy converters (WECs) by adding a geometry control option on top of power take-off (PTO) load control. The variable-geometry modules (VGMs) provide control over a WEC's hydrodynamics that can emphasize power absorption or load shedding. Additional load shedding provided by the VGMs is expected to reduce the device structural mass and extend the sea state operating envelope by limiting peak loading, contributing to reduced levelized cost of energy (LCOE) estimates.

Intended Outcomes

- VGWECs aim to lower LCOE through a structural optimization that reduces the required WEC steel thickness, which is directly coupled with capital costs. The reduction is possible only if greater control over peak loads is enabled by the hydrodynamic load control provided by VGMs. Although there are clear benefits to VGMs, there will be additional costs associated with the additional actuators and sensors needed to manipulate and control any active VGMs. Therefore, the VGWEC project aims to demonstrate that the variable-geometry concept is viable technology that does not add significant cost to a WEC's system design.

Project Information

Principal Investigator(s)

- Nathan Tom (NREL)

Project Partners/Subs

- Dr. Raju Datla (Stevens Institute of Technology)
  - Model build and tank test subcontractor

STEVENS INSTITUTE of TECHNOLOGY THE INNOVATION UNIVERSITY®

Project Status

Ongoing

Project Duration

- August 2018 – FY18 Q4
- September 2025 – End of FY25

Total Costed (FY19–FY21)

$597,803.00

Project Objectives: Relevance

Alignment with Program Goals:

The VGWEC project is focused on contributing to the marine energy program's R&D priority on Foundational R&D:

- Under Foundational R&D, the main activities relevant to this project include:
  - **Drive innovation in components, controls, materials, manufacturing, and systems:**
    - The design of wave energy converters that can modify their geometry in water by up to 40% has a significant effect on system design and variable geometry component selection in order to complete the shape change economically.
    - Rather than optimizing the WEC geometry across a range of wave frequencies, one could optimize geometry for each wave frequency while designing the morphing technology to transition between states.
  - **Develop numerical and experimental tools and methodologies to understand the fluid-structure interactions:**
    - Variable-geometry WECs open a new range of geometries that push the limits of linear hydrodynamic theory, with mismatches between experiment and theory already observed.
    - Depending on the actuation mechanism, the potential for hydrodynamic changes on the wave-to-wave time scale is not well understood and it is unclear how best to capture those dynamics.
- The VGWEC project aims to meet WPTOs long-term goal of **significant deployment of grid-scale cost competitive marine hydrokinetic (MHK) projects, driven by dramatic MHK technology LCOE reductions**:
  - The load shedding capability provided by variable-geometry components is expected to reduce device structural mass and extend the sea state operating envelope, both of which contribute to lower LCOE.

Project Objectives: Approach

This VGWEC study was proposed as an initial 4-year, two-phase project:

- Previous experience designing a variable-geometry oscillating surge WEC but wanted to design variable-geometry modules for other WEC architectures:
  - Phase 1 (FY19–FY20) consisted of a design case study for three new VGWEC concepts: 1) submerged pressure differential plate, 2) two-body attenuator, 3) two-body point absorber.
  - Development of the three VGWEC concepts would follow the Wave Energy Prize methodology and use average climate capture width to capital expenditure (ACE) as the final evaluation metric to compare across concepts.
- Top-performing VGWEC from case study would be moved to the wave tank
  - Phase 2a (FY21–present) is focused on building confidence in the numerical tools used throughout the design case study with validation against an experimental dataset.
  - Verify the target load shedding magnitudes are achieved in a representative proof-of-concept WEC model.
  - Wave tank results can highlight deficiencies in current modeling approaches that may need further development in order to fully understand VGWECs.

Project Objectives: Expected Outputs and Intended Outcomes

Outputs:

The VGWEC project will develop:

- Novel numerical models, developed within WEC-Sim, to model the performance of VGWECs
  - Including three VGWEC designs.
- A wave tank experimental dataset of a two-body variable-geometry point absorber WEC.
- A hardware-in-the-loop experimental dataset incorporating hydrodynamic numerical models and physical hardware.

Outcomes:

- Development, distribution, and publication on VGWEC numerical models lays the groundwork for new researchers to explore this domain, magnifying the number of VG concepts.
- Demonstrate capability of VGWECs to provide a clear LCOE reduction pathway.
- Comparison of experimental and numerical results may highlight shortcomings in traditional WEC modeling, leading to novel hydrodynamic approaches.

Project Timeline

FY 2019

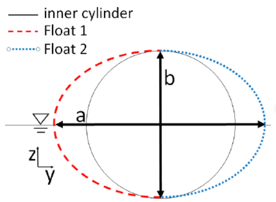
- VGWEC Project Phase I Kick-Off
- Begin first VGWEC design to include the following:
  - VGM design and operation
    - Hydrodynamic analysis
    - Power performance estimate
    - Preliminary structural design
    - Complete ACE estimate
    - Iterate on design based as needed.
- Begin second VGWEC design following design process above.

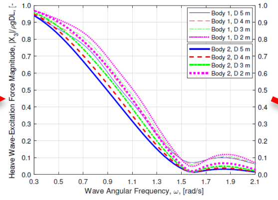
FY 2020

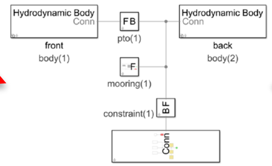
- Finalize first VGWEC concept and draft design report for WPTO.
- Finalize second VGWEC concept and draft design report for WPTO.
- Begin and finalize third VGWEC design following same design process.
- Summary report contrasting the three VGWEC concepts and lessons learned from design case study.

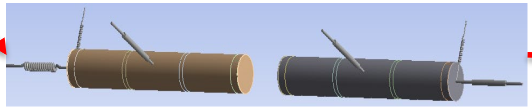
FY 2021

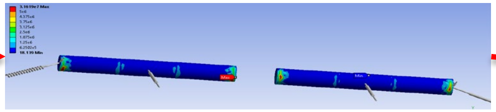
- Phase 1 **Go/No Go** incorporated into 2021 Merit Review Proposal.
- Down-select VGWEC from design case study completed.
- Select model fabricator to agree on build details.
- Select wave tank facility to complete experimental testing campaign.
- Iterate on VGWEC model details.







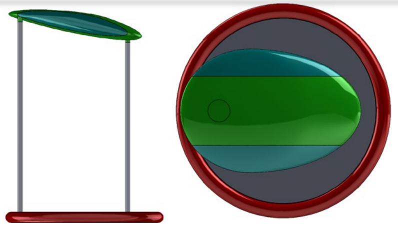




Average Climate Capture Width

Charac. Capital Expenditure

ACE



Down-selected concept

Project Budget

FY19	FY20	FY21	Total Actual Costs FY19–FY21
Costed	**Costed**	**Costed**	**Total Costed**
$216K	$266K	$115K	$597K

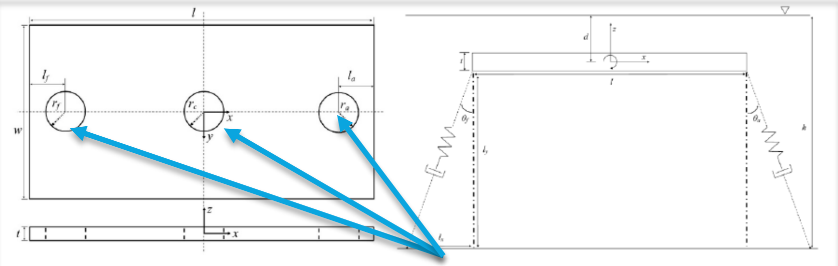
- **Phase I** had an overall budget of $500k ($250k for FY19 and FY20)
- **Phase 2a** has an overall budget of $300k (FY21–present) but delays in subcontracting prevented completion of the wave tank test in FY21.
  - As of 1/25/22, subcontract in place between NREL and Stevens Institute of Technology for $150k.
  - Subcontract includes model fabrication and 3 weeks of wave tank testing of the VGWEC concept.
  - Wave tank testing was scheduled to begin in late June.
- In **Phase 2b** (FY22) the budget is $375k to use the validated hydrodynamic model (from wave tank testing) to complete hardware-in-the-loop (HIL) testing at NREL's Flatirons Campus.
  - Focus on using larger and a more representative electrical machine to represent the PTO.
- The VGWEC project has requested a no-cost time extension because of delays in subcontracting and wave tank schedule but has not required any increases in project funding.

End-User Engagement and Dissemination

- The VGWEC project external advisory panel (EAP) was established to collect feedback on results and status of the project
  - EAP consists of 6 member organizations representing industry and academia
  - Yearly webinars to receive comments and guidance on past year results and planned work
  - Desire for project results to be relevant to industry who can adopt the VGM technology.
- The PI Nathan Tom has taken every opportunity to engage with industry
  - Poster presentation at the **National Hydropower Association's Water Power Week** in 2019
  - Webinar presentation as part of the **Marine Energy Council Transparency Series,** July 2019
  - Oral presentation at the **International Conference on Ocean Energy (ICOE2020),** April 2021.
- Submission and presentation of results in peer-reviewed conference:
  - To date, three conference papers submitted and presented (one on each VGWEC concept).
- Dissemination of wave tank experimental datasets and model build details
  - This information provides researchers and developers a foundation to explore other VGWECs.
- General public dissemination highlighted through NREL news articles
  - "Shoring up wave energy's bottom line through variable-geometry WEC designs"
  - "A window into the future of wave energy" includes animations and video.

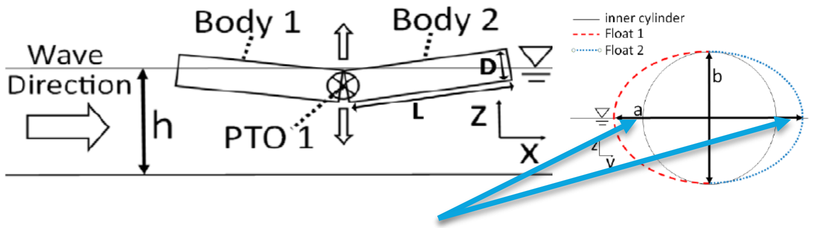
Performance: Accomplishments and Progress

- Major technical accomplishment to date is completion of the state-of-the-art design case study that generated three new variable-geometry WEC concepts:
  - Design case study highlighted how there is no one VGM concept that would support all WEC designs; optimum size, placement, and operation dependent on number of bodies and coupling oscillatory motion to drive PTO(s).
  - Inclusion of VGMs improved ACE score across all WEC designs; however, only two designs met or exceeded the 8 m/$M target ACE value set by the winner of the Wave Energy Prize.
  - A major takeaway from the cost analysis was the potential use of inflatables instead of mechanical actuators to achieve desired shape change.
  - Large-scale shape changes can significantly alter device buoyancy and mass properties, adding design complexity.
- Preliminary results from the design case study are promising and **demonstrate that the variable-geometry concept remains a worthwhile technology to continue development** through this project.



VGMs are rigid actuated openings

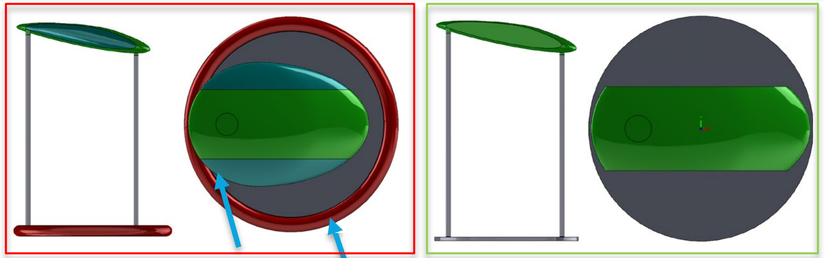
Submerged Pressure Differential WEC



VGMs are air-inflatable side bags

Two-Body Attenuator WEC

Concept selected for wave tank testing



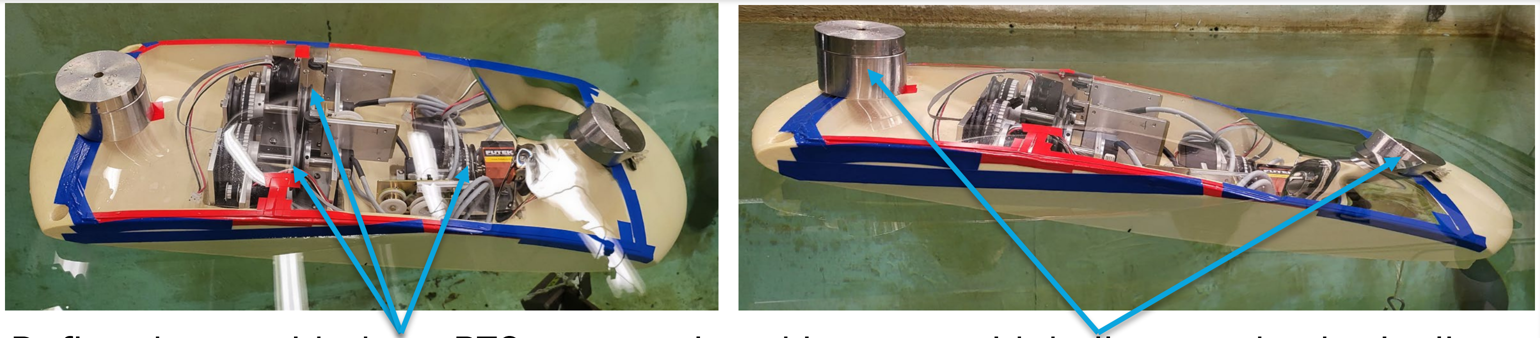
Inflated State (Air+Water) *Deflated State*

Two-Body Point Absorber WEC

Performance: Accomplishments and Progress (cont.)

- Through frequent iterations and discussions with the Stevens Institute of Technology (SIT) engineers, significant progress has been made on the VGWEC model fabrication:
  - The surface and subsurface floats will be machined from rigid foam with VGMs made as rigid foam attachments
    - NREL, along with SIT, decided that designing a VGWEC model that could adjust shape in the water at this model scale would be too complex and would not guarantee that the team could validate load shedding capabilities; a simplified model was pursued.
  - Wave tank testing at SIT is planned for three weeks between June 27 and July 15, 2022
    - Key measurements captured during wave tank testing are: 1) surface body motion, 2) subsurface body motion, 3) tension in each PTO cable, 4) rotational velocity of PTO simulators, and 5) tension in stationkeeping lines.

Deflated core made of rigid foam



Deflated core with three PTO system placed in water, with ballast, to check trim lines

Photos from Raju Datla, SIT

- After completing the design case study, a record of invention was submitted for VGWEC design moving to the wave tank.
  - NREL's Technology Transfer Office reviewed existing patent pool, decide to file U.S. provisional patent application, *Two-body variable geometry wave energy converter*, Application No. 63/239,070.

Future Work

- The VGWEC project will be completing wave tank testing of a VGWEC model in FY22.
  - The experimental results will be compared against the predictions from the design case study and presented to WPTO to pass a **Go/No Go** prior to entering Phase 3.
- The other main milestone for FY22 includes hardware-in-the-loop (HIL) testing completed at NREL's Flatirons Campus using the WEC dynamic models verified from wave tank testing.
  - PTO simulators used in wave tank testing are not representative of electrical machines that would be used at scale.
  - Numerical models can be coupled with larger electrical machines to better account for efficiency and power electronics so the impact of VGMs on the PTO (and vice versa) can be characterized at relevant scales.
- The VGWEC project was Merit Reviewed in 2021 and requested a 3-year extension to the project to achieve the following objectives:
  - Phase 3A, FY23 $250k, further explore mechanical or inflatable actuation trade-offs
  - Phase 3B, FY24 $250k, further explore control strategies for both PTO and geometry
  - Phase 3C, FY25 $400k, to support a second round of advanced wave tank testing
- The project has remained on budget; recent timeline delays started during the pandemic, with supply chain issues remaining for all parties. Project projected to be caught up in FY22.

Q&A