Power at Sea Prize
CArbon Sequestration Harnessing Energy from Waves (CASHEW) Concept

SEAquestration Team
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July 26, 2024

Summary Page

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Mission: The SEAquestration Team from the SEA Lab at Cornell University is committed to the larger mission of the lab to develop interdisciplinary symbiotic solutions to advance sustainable offshore technologies vital to the growth of the Blue Economy and the mitigation of climate change. This specific team investigates how Wave Energy Converters (WECs) can be used to power a carbon sequestration system, CArbon Sequestration Harnessing Energy from Waves (CASHEW). The CASHEW system address all components of the larger SEA Lab mission, since it investigates a new Blue Economy application for WEC technologies that would help mitigate climate change. In addition, the CASHEW project takes an interdisciplinary approach, recognizing the need to account for the system dynamics, economics, and seabed geology when designing such a system.

Challenge area and blue economy application

- Challenge area: suitability of power (direct-drive application for higher efficiency)
- Blue economy application: marine carbon dioxide removal (mCDR)

Short Description

We have developed CASHEW, a system that uses wave energy to directly pump liquid CO_2 deep into the ocean for long-term carbon sequestration. We demonstrate that an individual wave energy converter (WEC) can sequester 0.32 Mt/yr of carbon in a wave with 1m height and 0.7 rad/s frequency, such that a global fleet of 31 arrays of 100 WECs can achieve 1 Gt/yr sequestration, a scale with significant climate impact. We analyze how the energy requirement depends on key technical parameters including injection depth, water depth, pipe diameter, and CO_2 massflow, and outline a WEC system definition that meets requirements. We perform economic analysis to demonstrate that even with a significantly higher levelized cost of energy, wave energy leverages the efficiency gain of direct-drive pumping to achieve significantly lower levelized cost of carbon sequestration compared to other renewables.

We outline a plan for the DEVELOP stage to solidify our system specifications, refine our analysis model, incorporate more detailed wave dynamics, partner with other organizations, and potentially prototype the system. Prize funding would allow us to hire 4 student researchers to assist in the execution of these tasks.

Video pitch

Our video is available at https://youtu.be/GPyi_EUzb6E.

Contents

1 Technical Narrative:

1.1 Identification of Application and Challenge Area

CASHEW (CArbon Sequestration Harnessing Energy from Waves) aims to address the blue economy application of marine carbon sequestration, and the selected challenge area is the suitability of power. To sequester CO_2 into the ground, a high power pump is needed to drive the fracking process. When powering such a pump with a renewable energy source such as solar panels, an energy conversion from electricity into mechanical energy is required. For wave energy, where the energy is already mechanical, the energy just need to be directed, with no conversion required. This creates an opportunity for WECs to excel in an area that solar and wind might be less suited for.

The scope for CASHEW covers only the sequestration process, this fits with the mission analysis on Deep Ocean Storage put together by NREL [1]. It does not include the capture of CO_2 (which may be done through carbon capture at a fossil fuel plant or perhaps a separate marine energy powered carbon capture system). It also does not include the transport of the CO_2 from the capture point to the CASHEW system. Although in the work done so far the incoming CO_2 is assumed to be liquid, it is worth noting that it would be possible to use the CASHEW device to also compress gaseous CO_2 into the liquid state.

Though this Power at Sea Prize submission is the SEA Lab's first investigation of the CASHEW system, the concept builds on previous work investigating offshore energy as a power source for carbon sequestration. References [2, 3] consider techno-economic optimization and location analysis of offshore wind powered carbon sequestration; [1] presents a mission analysis comparing carbon sequestration techniques, scale, and feasibility for marine energy; and several marine carbon startups are conducting pilots with a long-term vision of "platforms powered by offshore renewable energy" [4].

The concept also builds on "CO_2 enhanced oil recovery," a practice in the oil and gas industry where CO_2 is injected into oil wells to allow additional oil extraction. While the SEAquestration team does not condone oil extraction, the industry expertise and modeling methods are useful for CO_2 sequestration. An initial concept of CASHEW involved using existing offshore oil rig infrastructure to lower capital cost and depleted oil reservoirs to store carbon, the salinity of the Gulf of Mexico (the location of most offshore oil activity in the continental US) was incompatible with system requirements [5].

The CASHEW concept also extends research that looks into non-electrical energy conversion strategies for WECs. One that has a particular level of similarity is wave-driven desalination [6, 7, 8]. Wave-driven desalination uses the motion of wave energy to directly drive a piston to push seawater through a reverse osmosis membrane, converting the energy from the waves into desalinated water rather than electricity. A similar approach is used in this concept: the motion of the wave energy directly drives a piston that pushes liquid CO_2 down a pipe to the ocean floor and into the ground, therefore converting the energy from the waves into sequestered CO_2.

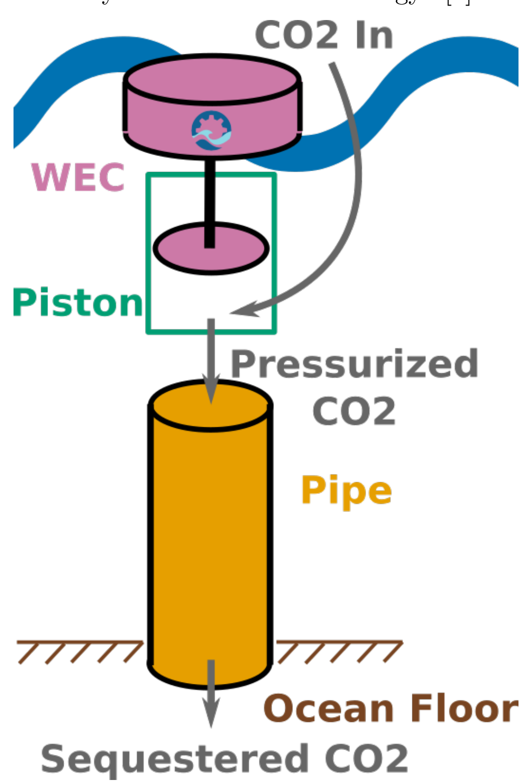

Figure 1: Schematic of the CASHEW concept.

1.2 Proposed System, Subsystem, or Component

The basic concept of CASHEW is shown in the system schematic Figure 1. In the schematic the WEC is shown to resemble a heaving point absorber style WEC, but the specific architecture of the WEC could change. The WEC is connected to a piston, and as the WEC moves up and down with the waves, the piston is driven to compress liquid CO_2. The compression of the CO_2 causes flow down the pipe and into the ocean floor where it can be sequestered.

The requirements for the system are listed in Table 1.

Table 1: Table of requirements for CASHEW conceptual design.

High level requirement	**Notes**	**Derived requirement**	**Notes**
At scale, sequester CO_2 at a rate of at least 1 Gt/yr	Can be accomplished with a global fleet of 31 arrays of 100 WECs, with each WEC sequestering 0.32 Mt/yr, for example	Provide sufficient pressure to achieve this flow rate, either overcoming natural seabed permeability via diffusion, or by fracturing the seabed to lower permeability. Pressures are given in [5].	Pressure for fracture is lower than for natural flow, so fracture is assumed. Required pressure varies with injection depth, see Figure 2 below.
CO_2 cannot rise back to the surface during pumping	During periods of low wave activity, CO_2 should not float up and backdrive the WEC	Can be met by maintaining a minimum pressure at the surface, or through the inclusion of check valves	Check valves are assumed since calculation of the minimum pressure and simulation of irregular waves is out of scope right now
CO_2 cannot rise back to the surface after sequestration	-	Pump liquid CO_2 to a depth where its density equals that of water in a stable configuration (gravitational trapping).*	The gravitational trapping depth is around 2700 m but depends on salinity and temperature.
CO_2 must not disrupt deep sea ecosystems	-	CO_2 must be contained $\geq$ 200 m under the seafloor	A gravitationally trapped deep sea CO_2 lake does not meet this requirement
Pipe does not fail due to hydrostatic pressure differential at depth	-	-	-
System must be long-term economically viable compared to onshore carbon sequestration	-	Lifetime cost below \$148/tCO_2 when scaled	-
System must be short-term economically viable compared to offshore carbon sequestration with offshore wind or floating solar power	-	-	-
System must be short-term economically viable compared to offshore carbon sequestration powered with onshore renewables	-	-	-
Inteface with CO_2 delivery method	-	-	-
CO_2 pressure and flow must be achievable with WEC force and velocity in realistic wave conditions	-	Maximum PTO force of 10 MN, maximum PTO velocity of 5 m/s, and obey the radiation limit of power (equation 10).	Drives piston area

*A derived requirement of a subsea chemical reaction could also fulfill the high level requirement, but this only works in certain seabed geologies. We chose gravitational trapping with the goal of expanding possible locations. This is an assumption to be revisited in the future.

These requirements are organized as high level requirements, which are driving requirements of what the system must achieve, and derived requirements, which are features that must be true in order for the system to achieve the high level requirement. High level requirements and derived requirements are typically functional and design requirements respectively, although not exclusively.

The key physical parameters of the system are shown in Table 2.

Table 2: Physical parameters for CASHEW system.

Parameter	**Symbol**	**Value**	**Unit**
Piston area	A	0.01	m^2
Piston type	-	Double acting	-
Pipe inner diameter	D	0.26	m
Injection depth below seafloor	$z_{injection} - z_{seafloor}$	200	m
Effective pressure required at injection depth	$P_{CO_2}(z_{injection}) - P_{pore}(z_{injection})$	2	MPa
Water depth	$z_{seafloor}$	2700	m
Pressure required at surface	$P_{CO_2}(z=0)$	3	MPa
Average massflow CO_2	$\dot{m}$	10, 0.32	kg/s, Mt/yr
Nominal WEC amplitude	x	1	m
Nominal wave frequency	ω	0.7	rad/s
Average power at nominal conditions	$\dot{W}$	965	kW
CO_2 phase	-	liquid	-
CO_2 temperature	-	0	C
Pipe material	-	steel	-
WEC type	-	oscillating surge/pitch	-

The governing equations of the CASHEW system are below. First, to achieve fracture of the seabed to reduce the permeability ("fracking"), the pressure of the CO_2 at its injection depth must exceed the pore pressure (pressure of the trapped fluid beneath the seabed) by some threshold P_{frack}.

$$P_{CO_2}(z_{injection}) = P_{pore}(z_{injection}) + P_{frack} \tag{1}$$

The pore pressure is typically between 1 and 1.8 times the hydrostatic pressure at the relevant depth [9]. Here, it is assumed to equal the hydrostatic pressure.

$$P_{pore}(z_{injection}) = P_{atm} + \rho_w g z_{injection} \tag{2}$$

The fracking pressure depends on the injection depth below the seafloor (as well as the seabed material strength, not currently modeled) [5].

$$P_{frack} \approx 700(z_{injection} - z_{seafloor})^{1.5} \tag{3}$$

The pressure at the surface is computed by taking the pressure at injection and adding increments of pipe major loss and gravitational head, using the pressure-dependent density of CO_2 at each depth to account for the compressibility of liquid CO_2. The pipe diameter was set somewhat arbitrarily, and was later found to have a large impact on performance since pressure drop due to major loss in a pipe scales with D^4. Future work will involve more detailed pipe sizing to balance cost and performance.

$$P_{CO_2}(z=0) = P_{CO_2}(z_{injection}) + \sum_i \left(\frac{1}{2}\rho_{CO_2,i} v_i^2 f \frac{\Delta z_i}{D} - \rho_{CO_2,i} g \Delta z_i \right) \tag{4}$$

The average fluid velocity in the pipe also changes with depth.

$$v_i = \frac{\dot{m}}{\rho_{CO_2,i}\frac{\pi}{4}D^2} \tag{5}$$

The piston is the interface between the WEC mechanical domain and the CO_2 fluid domain, and connects pressure and flow rate to force and velocity. The absolute value comes from the double-acting nature of the piston.

$$|F_{PTO}| = P_{CO_2}(z=0)A \tag{6}$$

$$|v_{PTO}|A = v(z=0)\frac{\pi}{4}D^2 \tag{7}$$

The power provided by the WEC is the product of piston force and velocity, or equivalently pressure and flow rate:

$$\dot{W} = F_{PTO}v_{PTO} = P_{CO_2}(z=0)\; v(z=0)\frac{\pi}{4}D^2 = P_{CO_2}(z=0)\frac{\dot{m}}{\rho_{CO_2}(z=0)} \tag{8}$$

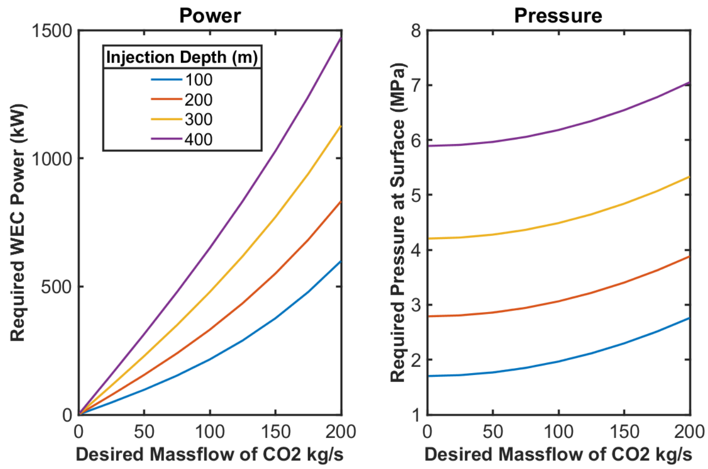

Figure 2: Required power and surface pressure as a function of CO_2 average massflow and injection depth.

Thus the WEC power requirement depends on the desired CO_2 massflow $\dot{m}$, the injection depth $z_{injection}$, the seafloor depth $z_{seafloor}$, and the pipe diameter D. Figure 2 shows the pressure as a function of $\dot{m}$ and $z_{injection} - z_{seafloor}$, with $z_{seafloor}$ and D held constant.

The power that the WEC can actually provide depends on the floating body dynamics of the WEC in waves:

$$(m + A)\ddot{x} + B\dot{x} + Kx = \Gamma\zeta + F_{PTO} \tag{9}$$

where m is the WEC mass, A is the hydrodynamic added mass coefficient, B is the hydrodynamic radiation damping coefficient, K is the hydrostatic stiffness, Γ is the excitation coefficient, and ζ is the wave elevation. At this stage, rather than explicitly model the WEC dynamics, the signal x is set to a sinusoid with amplitude 1 m and frequency 0.7 rad/s, typical of many WECs and sufficient to demonstrate feasibility of the concept. Since the WEC dynamics are not modeled explicitly, the maximum radiation power is used to further ensure feasibility. The maximum power of a WEC based on the radiation limit is:

$$\dot{W}_{wave} = G\frac{\rho_w g^3 A^2}{4w^3} = 2.5e5\ G\frac{A^2}{w^3}. \tag{10}$$

where the gain G is 1 for heave motion and 2 for surge/pitch motion [10]. For a 1 m, 0.7 rad/s wave, this gives 730 kW in heave and 1460kW in surge/pitch. Thus, a surge/pitch device meets the requirement.

Time domain modeling is used to further demonstrate feasibility of the system. One challenge of the sequestration process is the compressibility of CO_2. The compressibility of the fluid opens the possibility for the CO_2 to just compress and expand in the piston without actually going down the pipe and sequestering into the ground. To aid in the time domain modeling, the Simscape two-phase fluid library was leveraged, which is capable of modeling compressible fluids (and has CO_2 as a predefined fluid). The model can be found in the *src/pump_model* folder of the Git repository: `https://github.com/symbiotic-engineering/CASHEW`. One noteworthy component of the model is the pipe, which is modeled as 40 discrete pipe links, with a different set of fluid properties (notably density and pressure) used each link. The 40 links was selected after a convergence study using the initial analytical model determined 40 links only had an error of 1.7% error when compared to a 2700-link pipe, while saving compile and simulation time required for the Simscape model. Through this time domain model a piston area of 0.01 m^2 was verified to satisfy the maximum PTO force (force on WEC $<$ 10 MN). Simulation results are shown in Figure 3. It's also important to note that the average power predicted by the Simscape model (965 kW) is considerably larger than the initial analytical power prediction (30 kW). This demonstrates the importance of the transient dynamics in the system.

There are a number of factors to consider when selecting a location for a wave powered sequestration device. Most important is the seabed geology as some forms of carbon sequestration only work under specific geologic conditions. It is also important to consider the depth and density of the sea water. In some areas where the seawater is more dense due to salinity, like the Gulf of Mexico, the CO_2 will never reach a point where it becomes denser than the seawater, creating potential of carbon leakage for non-chemical forms of sequestration. Since the system relies on wave energy, which is not distributed equally, it is also important to place CASHEW in an area with high amounts of wave activity. Lastly, it is optimal to locate the CASHEW system at abandoned offshore oil rigs. Utilizing the oil rigs in the CASHEW system will reduce the amount of infrastructure and capital investment needed to secure the pipe. The Atlantic Ocean is considered the most probable location for the CASHEW device, due to the balance of depth, density, wave activity, and presence of some offshore oil platforms.

One challenge that is of particular concern when interfacing with the oil rig platform is the corrosive nature of CO_2. Although some onshore oil rigs perform CO_2-enhanced oil recovery and are designed to pump CO_2 without much corrosion, most offshore oil rigs were not built with CO_2 transport in mind. Therefore the pipe from the oil rig down to the ocean floor will need to be retrofitted or replaced to accommodate the corrosive nature of the CO_2.

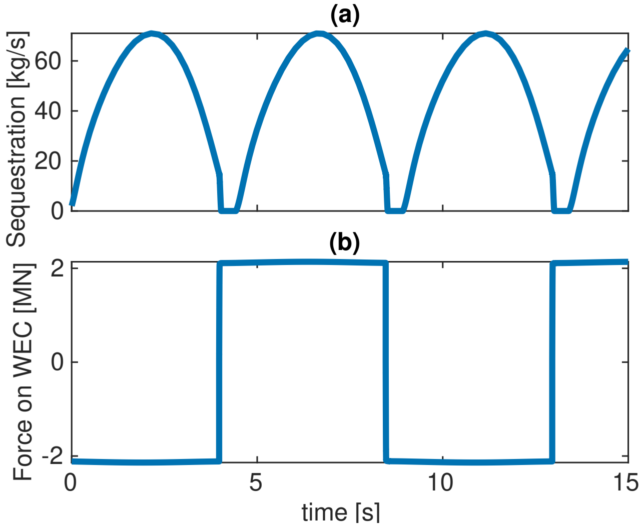

Figure 3: Simscape modeling results showing rate of sequestration **(a)** and force on the WEC **(b)** vs time.

The lifetime of the system is estimated at 20 years, based on standard WEC lifetimes [11]. Offshore oil platform design lifetimes are typically 25 years [12], so the pipe is assumed to have a similar lifetime.

One way this application of wave energy is particularly suited to the nature of WECs is the lack of additional energy storage requirements. Nothing depends on CO_2 sequestering having the ability to meet a specific demand at a particular moment on time (unlike power grid applications), so there is no need for long-term (> seconds) energy storage. For short-term ($\leq$ seconds) storage, the compressibility of the CO_2 acts as its own accumulator, eliminating the need for any additional power smoothing methods. This gives carbon sequestration a leg up in suitability of power, even when compared to a similarly non-grid connected system like desalination, where the working fluid is incompressible and therefore additional architecture is needed for power smoothing [13, 14].

The cost of the system is of major importance. In particular, the CASHEW system must meet requirements of long-term viability compared to onshore carbon sequestration, and near-term viability compared to offshore carbon sequestration powered by other energy sources including onshore renewables, offshore wind, or floating solar. The levelized cost of carbon $LCOC$ (\$/t-CO_2) is used to assess economic viability of carbon capture and storage projects. It is expressed as the ratio of annualized costs C_{ann}, \$/yr, (including both capital and operating expenses for energy and of other items) to the yearly carbon sequestered. The yearly carbon sequestered is the product of annual energy production AEP (Wh/yr), the efficiency η of generated energy to useful energy, and $\frac{1}{EI}$ (t-CO_2/Wh) the inverse of the energy intensity of the sequestration process.

$$LCOC = \frac{C_{ann,energy} + C_{ann,other}}{AEP\ \eta\ \frac{1}{EI}} \tag{11}$$

Since $C_{ann,energy}/AEP$ is typically defined as the levelized cost of energy $LCOE$, we write:

$$LCOC = \frac{EI}{\eta}\left(LCOE + \frac{C_{ann,other}}{AEP}\right) = \frac{EI}{\eta}\left(LCOE + \frac{C_{ann,other}}{\dot{W}\ 8766}\right) \tag{12}$$

where the annual energy production is expressed in terms of the average power $\dot{W}$ and the number of hours per year. $C_{ann,other}$ can be expressed as $FCR\ capex_{other} + opex_{other}$, using a fixed charge rate and capital and operational expenses, but here is kept as a single variable for clarity. EI is a function of the carbon sequestration process not the energy source, so a simpler figure of merit FOM to be minimized, is selected for this conceptual analysis:

$$FOM = \frac{LCOC}{EI} = \frac{1}{\eta}\left(LCOE + \frac{C_{ann,other}}{\dot{W}\ 8766}\right) \tag{13}$$

This allows analysis of whether an energy source with particular values of $LCOE$ and η is more competitive. CASHEW is direct drive so has $\eta \approx 1$, but the economic immaturity of wave energy means it has higher $LCOE$, perhaps \$0.50/kWh. More traditional renewable energy sources have $\eta \approx 50\%$ due to the electrical to mechanical losses in the pump, but lower $LCOE$, perhaps \$0.03/kWh onshore and up to \$0.25/kWh for floating offshore wind (NREL ATB). These combinations are visualized in Figure 4 for $\dot{W} = 1MW$ and various values of $C_{ann,other}$. We can see that depending on the value of $C_{ann,other}$, the wave powered system can be more or less viable than an onshore energy source, and for all $C_{ann,other}$ tested, wave is more viable than offshore wind. Future analysis can estimate more precisely the value of $C_{ann,other}$ for offshore carbon sequestration.

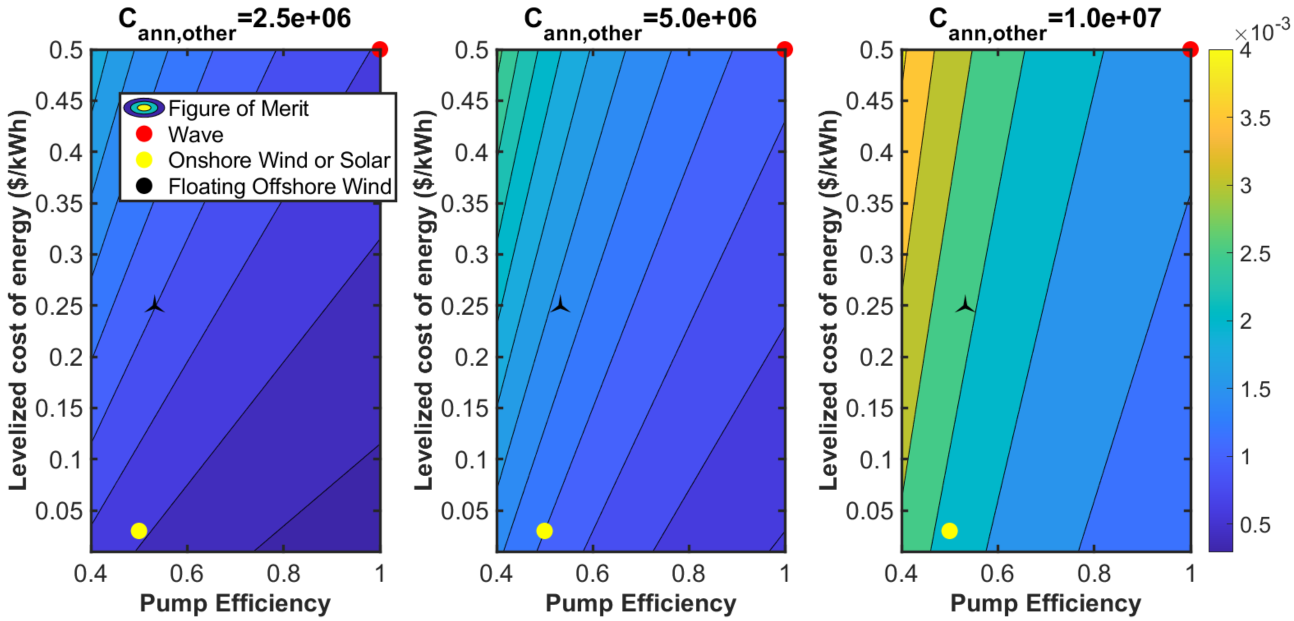

Figure 4: Economic comparison for the levelized cost of carbon figure of merit for solar, wind, and wave energy sources. Lower figure of merit (blue) is more viable.

The TRL of this system is 2-3, since we have demonstrated an analytical proof of concept but have not demonstrated feasibility experimentally. The system is based on subsystems that have individually achieved high TRL. For example, some wave energy converters have achieved TRL 9 [15], and wave driven desalination systems (which use a similar idea behind the PTO) are commercially available at small scales giving them a TRL of 9 as well [16]. Additionally, startups performing marine carbon capture are at TRL 6, with one pilot capturing 1000t/yr in progress [4].

1.3 Team Engagement and Planned Development

Our team is committed to increasing diversity, equity, and inclusion (DEI) in science, technology, engineering, and mathematics (STEM). DEI's first goal to increase the number of women and underrepresented groups in the STEM field was met through the formation of the team, which is predominantly female and includes underrepresented minorities. The research team on this project is committed to enhancing the recruitment of researchers from underrepresented backgrounds. This is done by creating an environment that is inclusive for everyone, and providing training, mentoring, and professional development opportunities for trainees. The future DEI goals in our project are to recruit additional undergraduate, MS, and MEng students who are females or from underrepresented backgrounds. The team continuing on to the DEVELOP phase will consist of the team lead, PhD student Becca McCabe, alongside PhD student Nate DeGoede, undergraduate students Cecily Pokigo and Ehina Srivastava, as well as SEA Lab Principal Investigator Dr. Maha Haji. In addition, two new undergraduate students will be hired onto the team.

The team is conscious of and strives to mitigate risks in the technical design and economic viability of the system. One risk is to become too locked in a particular set of requirements and assumptions regarding the carbon sequestration process without continuously interrogating their appropriateness. For example, this initial concept viability study required gravitational trapping, which implies CO_2 in the liquid phase, but other marine CO_2 storage could be done in the supercritical phase if mechanical or chemical trapping is used. Moreover, the fracking requirement drove our pressure and energy, and we will confirm whether this makes sense compared to storage in existing low-permeability reservoirs. We mitigate these risks through regular design reviews and discussions with others in the community, and ensuring clear traceability of the requirements. A second risk is the difficulty of experimentally validating the system, since both WECs and high-pressure CO_2 require high capital cost for even scaled tests. This risk can be mitigated by partnership as discussed below. Finally, a risk in the system economics is that the viability of carbon capture and storage projects more broadly depends heavily on government incentives such as carbon credits, and the policy landscape is difficult to predict and may vary state to state. This risk will be mitigated by considering deployment locations in many regions, and staying up to date with policy developments.

The team has utilized the Power at Sea Prize competitor support mechanisms as well as the support from third parties. The Power at Sea webinars helped us ensure our concept was a good fit for this competition. Kent Satterlee from the Gulf Offshore Research Institute provided valuable insight into some advantages of utilizing decommissioned oil rigs, as well as considerations we would need to make in system design to make the interaction work. James Niffenegger of NREL gave us insight into his experiences with marine carbon dioxide removal with a focus on what makes this problem particularly challenging. Additionally, Jocie Kluger of MathWorks was assistive in our efforts to model the dynamics of the sequestration

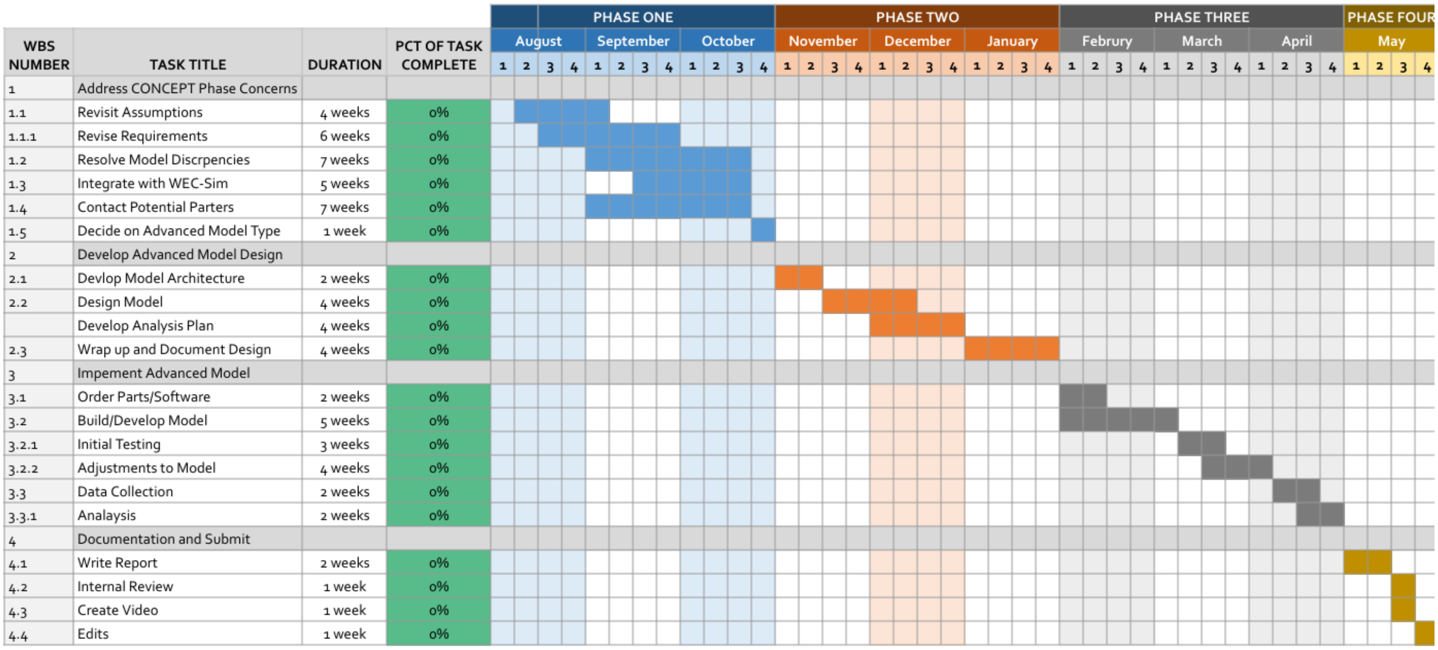

Figure 5: Preliminary CASHEW DEVELOP Phase GANTT chart.

system in Simscape.

If we receive award funding for our CONCEPT phase participation, we would use it to expand our team for the DEVELOP phase. Specifically, a $10,000 prize would allow us to hire 4 undergrad research assistants for a semester, assuming 10 hours/week, 15 weeks/semester, and the lab standard wage of $16-17/hour.

In the DEVELOP phase, we plan to refine the modeling and analysis presented here, finalize technical specifications, create CAD of the system, create an advanced model of the system. See the GANTT chart in Figure 5 for a breakdown of the plan for the DEVELOP Phase.

One potential advanced model is a physical prototype to further validate our models. Our lab does not have any experience working with high-pressure CO_2, so instead of creating a prototype internally, we would hope to leverage competitor support mechanisms to partner with other organizations who have high-pressure CO_2 prototyping capability. A possible partner is the Department of Energy Supercritical CO_2 Tech Team (`https://www.energy.gov/supercritical-CO$_2$-tech-team`), who work on advanced Brayton cycles. Expertise from those who work with hydrogen storage may also be useful, since hydrogen is also a compressible fluid stored at several MPa. Partnerships with groups investigating coastal onshore CO_2 capture, or with startups in the marine CO_2 direct ocean capture industry such as Captura, SeaO2, and CarbonBlue, may also be pursued. Finally, while our group has substantial experience modeling WECs, fluid dynamics, and economic viability of emerging systems, we have limited expertise modeling seabed geology, and partnership with engineers in this area would benefit us in the DEVELOP phase.

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