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Seawater Photovoltaic-Hydrogen Generation

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Swarthmore College
Engineering Senior Design Project
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May 5, 2023

Abstract

A Seawater Photovoltaic-Hydrogen Generation System is developed with the goal to produce a safe, user friendly, cost effective, and realistically scaled hydrogen generation system using seawater, particularly for remote regions as well as storage alternatives for renewable energy. An iterative design process was implemented within three prototypes, the first primarily focused on proving the concept of electrolysis, the second to create a robust hydrogen generation system resistant to corrosion using forward osmosis, and the third to scale up our system while also aiming for safety, user friendliness, and cost effectiveness. In the final iteration of our project, an integrated three chamber acrylic tank was created using primarily forward osmosis technology, carbon electrodes, and a palladium tank. This system holds seawater in the first chamber, transfers pure water into the second for electrolysis, converts water into oxygen with electrical current from a PV system, then sends the hydrogen into a palladium tank. All three prototypes successfully yielded hydrogen from seawater. With additional improvements to make our design more mechanically robust, efficient, user friendly, and culturally accepted, this system could become a promising system that can be integrated within communities, particularly remote regions.

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Preface

About the Authors:

Huiying: Huiying is an Environmental and Renewable Energy Engineer who has been involved with technical as well as social renewable engineering work. She has been at the forefront of renewable energy campaigns, working as a solar intern to increase solar deployment and accessibility in the Philadelphia area. Her work is informed by solar and renewable energy policy, finance, and market research conducted during her time as a solar intern. At Swarthmore, she has served as a Green Advisor (GA) and Presidential Sustainability Research Fellow (PSRF) with the Swarthmore Office of Sustainability to serve her community in achieving sustainable cultural transitions. She has also designed a microgrid system to meet off-grid needs for rural and developing countries while also intentionally designing for community independence and empowerment. Additionally, she has independently designed, manufactured, and installed a 460W Solar Array at Swarthmore's Our Food Garden while also researching and designing an innovative passive liquid cooling and water recycling-capture system for photovoltaic panels to increase PV panel efficiency. Huiying's culminating interests in renewable energy design work are explored through this senior Engineering design project and Environmental Studies capstone project. Through her senior Engineering design project, she aims to design a seawater PV-hydrogen generation system that can be integrated within remote areas to provide an off-grid clean and renewable fuel generation system to meet needs such as cooking and energy storage informed by work she has completed while abroad in Australia. Her senior Environmental Studies capstone project aims to engage individuals in exploring elements of community accessibility and agency in renewable energy technology as a way to achieve a just energy transition. Her collaborative project aims to be the catalyst for a community that is more engaged and works actively to promote a just transition and mitigate and adapt to the impacts of the climate crisis in order to create thriving communities. She hopes to synergistically combine technical, social, and cultural understandings to intentionally design for communities.

Thomas: Thomas is a Generalized Engineer whose work has focused primarily on the development and integration of energy systems. While at Swarthmore he has conducted research work into optical sensing via laser systems in conjunction with Professor Lynne Molter, as well as into various embedded systems. His interests in the implementation of renewable energy generation and storage solutions was pursued over the course of this senior Engineering design project, with the goal of producing a photovoltaic hydrogen generator capable of cleanly producing hydrogen in off-grid scenarios. This work has been at the junction of several key technical and social areas that are essential to facilitating the transition to a clean-energy economy at scale, and he has found it to be of immense interest and value.

Acknowledgements:

We wish to thank the following individuals for their contributions to this project. Without their advice, assistance, engagement, and inspiration none of the following work would have been possible! Listed alphabetically, they are:

- Cassy Burnett, Engineering Department Administrative Coordinator, Swarthmore College
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- Chris Graves, Associate Professor of Synthetic Inorganic Chemistry and Environmental Studies, Swarthmore College
- J. Johnson, Machinist and Shop Supervisor, Swarthmore College
- Sam Scoma, Biological Technical Specialist, Swarthmore College
- Sophia Plata, Visiting Assistant Professor of Engineering, Swarthmore College
- Samuel S. Veroneau and Daniel G. Nocera, authors of *"Continuous electrochemical water splitting from natural water sources via forward osmosis"* paper that inspired much of the design decisions made on this project
- Kathryn Riley, Assistant Professor of Analytical Chemistry, Swarthmore College
- University of New South Wales (UNSW) Faculty, Staff, and Students who inspired the project through fieldwork completed in Fiji and facilitated the Sustainable Energy in Developing Countries Course

1 Introduction

Photovoltaic (PV) and hydrogen electrolysis technologies are currently widely used as ways to fight global warming and climate change by diverting energy production from burning greenhouse gas emitting fossil fuels. This design project implements both technologies together to generate hydrogen from seawater, Earth's most abundant resource. The project designed, constructed, and tested 3 different prototypes with three goals: to prove the concept of electrolysis; to create a fully functioning seawater hydrogen generation system using passive forward osmosis; to introduce PV, scale the system for higher hydrogen yield and reduce costs of production and rare minerals use. This project aims to be integrated within developing countries' applications to provide an off-grid renewable fuel generation system to meet needs such as cooking and energy storage.

1.1 Motivation

Hydrogen is one of the most abundant elements in the universe that can be found in many natural resources, particularly water, the most abundant resource on Earth. It is very versatile and can be used in a variety of ways, including generating electricity through fuel cells, fuel for cooking, energy storage etc. Hydrogen used as fuel also yields only water and oxygen as byproducts , making it a very clean fuel compared to other alternatives like traditional fossil fuels. When hydrogen is produced with other renewable energy sources like PV technology, hydrogen production becomes a renewable energy generation source that does not deplete Earth's limited resources.

The integration of PV in hydrogen generation is important due to its renewable nature, allowing clean energy to be generated from sunlight, an unlimited resource. The scalability of the technology allows continuous scaling of hydrogen production to meet energy demand needs. This also makes an off-grid system viable, particularly for applications in which a reliable grid is not available.

1.2 Background

A Photovoltaic-Hydrogen Generation System will be prototyped in this project to explore its opportunities to sustainably and cost effectively deliver power in remote and developing areas while also being a storage alternative for other renewable technologies such as solar power. Hydrogen can be produced from resources as simple as water and emit near-zero greenhouse gasses. Hydrogen can be used as a sustainable fuel or be converted back into electrical power using a fuel cell and emitting only water vapor and warm air.

1.3 Existing Technology

Hydrogen and PV technology has already been widely used to power fuel cell electrical vehicles (FCEVs), used as a means for renewable energy storage, an off-grid power supply for remote areas, and many more applications. Many simultaneous developments have been made within the combination of PV and hydrogen energy that could suggest opportunities for our work to be integrated to better meet all of our aims.

Hybrid PV-Hydrogen Technologies for Remote Applications and Storage:

Many hybrid PV-Hydrogen off grid power projects have already been implemented for rural applications. The Remote Area Power Supply System (RAPS) Based on Hydrogen Energy Storage project led by the University of New South Wales (UNSW) has prototyped a "PV primary energy coupled to an electrolyser, fuel cell and hydrogen storage, to meet the electricity consumption in remote areas" (Hydrogen storage and battery technology group, UNSW) for application in remote regions of Australia and internationally that are not served by the main electricity grid. Their project directly uses PV technology as primary energy and diverts the excess energy to an electrolyser to generate hydrogen for storage. Shown below is the schematic diagram for the project:

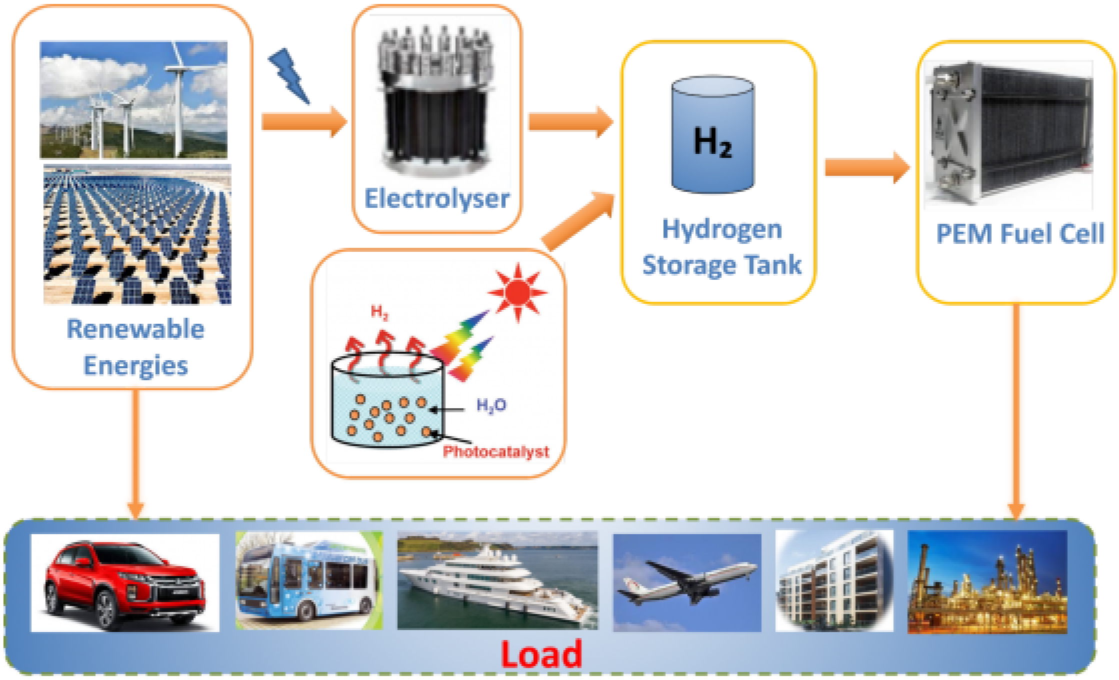

Figure 1. *Hydrogen Microgrid Schematic for Remote Area Power Supply System (RAPS) Based on Hydrogen Energy Storage project led by the University of New South Wales (UNSW)*

Large Scale Solar Plant Applications:

A similar form of solar-powered hydrogen generation system has been implemented at the Swiss Federal Institute of Technology. Using a parabolic reflective dish, sunlight was concentrated onto an especially efficient photovoltaic cell, which then powered a polymer electrolyte membrane (PEM) electrolyzer to produce roughly 500g of hydrogen over an 8 hour period (approximately 2 kilowatts). Although much larger than the system we investigate in this project, it represents a successful test case of the renewable production of hydrogen and could serve as a model for large-scale installations forming the basis of a hydrogen-centered energy grid.

1.4 Objectives

Our project sought to achieve several primary goals related to the implementation of hydrolysis technology and its integration with photovoltaic energy as a renewable resource. These were as follows:

- Prototype an osmotic electrolyzer capable of extracting hydrogen from seawater and running with minimal electrode corrosion.
- Construct this system on a scale capable of producing amounts of hydrogen that are relevant for potential real-world use cases.
- Power this system using a photovoltaic electricity source so as to produce hydrogen exclusively from the renewable resources of solar energy and seawater.
- Develop the system as a prototype of a potential consumer system capable of performing in off-grid conditions and enabling easier decentralized production of hydrogen. These goals served to guide the progression of the project and the development of several successive iterations of the technology we were investigating.

1.5 Engineering Design Specifications

Our design process is informed by NFPA 2, Hydrogen Technologies Code. Within our project, we recognize two major constraints categories: technological constraints and project implementation constraints. Technological constraints include the rate of material corrosion relative to hydrogen generation within the electrolyser (particularly pertaining to the electrodes), process efficiency as a method for energy conversion and storage, and its ultimate merits compared to other existing technologies. Project implementation constraints included the ability to safely store and handle the apparatus as well as end products within our design project—primarily hydrogen gas. While we recognized many additional opportunities for improvements, we were also limited by time constraints to obtain all necessary apparatus and time to construct designs, and our limited knowledge and experience with chemistry. Given our aim is to help meet energy needs for rural and developing communities, we are also limited by the ability to consult the communities to ensure sociocultural feasibility as well as further spaces for improvement, particularly within the user experience domain.

However, we aimed to mitigate those constraints throughout our project to the best of our ability. Safety precautions were reinforced by making sure that interactions with electrical connections as well as leaks were limited. For example, we ensured that elements containing gaseous oxygen and hydrogen do not interact to make very explosive compounds. Any and all hydrogen generation processes were performed safely in a fume hood. Electrical connections are also all insulated to protect against potential electrical hazards. Within the consumer end product, we designed with the intention to make the area where consumers would interact with as simple and safe as possible. For example, the space designed to be filled with seawater was made to be as open as possible and electrical connections made to be insulated. The project also attempted to design the product so that maintenance could be easily performed if applicable in the future. For example, the design was made in the electrolysis chamber such that the lid to hold the electrodes can be removed to easily replace electrodes. The chamber to hold the saltwater was also designed to be easily cleaned. And the chamber for storage is designed to be accessible to easily replace any broken storage tanks. In order to further ensure that our design was best informed by chemical principles, we also consulted various chemists in the process of our design for not only feasibility but opportunities for improvements. To design with sociocultural intent, our work was also informed by fieldwork notes of individuals from the University of New South Wales (UNSW) who have traveled to several remote communities to provide direct community insights on needs and wishes.

In conjunction with these goals, we sought to test the feasibility of producing hydrogen via electrolysis at a scale in keeping with real-world applications. As such, our work attempted to progress from small-scale technology demonstration prototypes to larger-scale implementations that would explore the feasibility of this. Although we did not have a specific production quantity goal, we wished to see an increase in production capacity over the course of our project and the various iterations of devices we would develop. This would allow us to explore the challenges specifically associated with scaling osmotic electrolysis devices, which would undoubtedly be a critical factor in their utility as an element within a broader overhaul of fossil fuel-dependent energy systems. In addition, this goal added relevance to our final prototype as a potential example of how such a device could be constructed that would enable sufficient production levels to justify its use in place of or alongside other technologies.

2 Theory

2.1 Hydrogen Alkaline Electrolysis

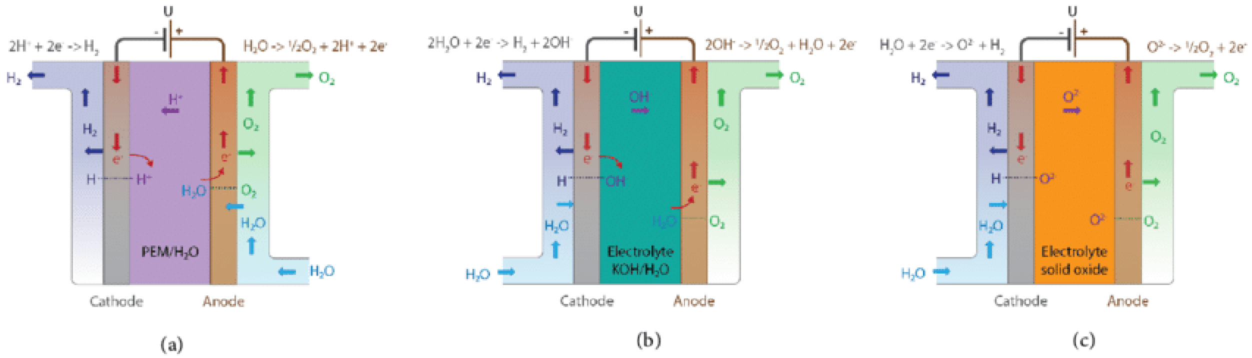

Figure 2. *Types of electrolysers: (a) Acidic (PEM: Polymer Electrolyte Membrane); (b) Alkaline (AEL); and (c) Solid oxide (SOEC) electrolyser cells.*

Several hydrogen-producing electrolysers currently exist, including alkaline electrolysers, electrolyte membrane (PEM) electrolysers, and solid oxide electrolysis (SOE). Polymer electrolyte membrane (PEM) electrolysers perform under acidic conditions, alkaline electrolysers perform under alkaline conditions, while high-temperature solid oxide water electrolysis produces hydrogen via high-temperature steam.

This E90 project primarily focused on alkaline electrolysis, the oldest, most industrially advanced and cheapest water electrolysis technology (Grigoriev 2022). In alkaline electrolysis, two half cell reactions occur: hydrogen evolution reaction (HER) and oxygen evolution reaction (OER). HER is the reaction where water is reduced at the cathode (negative or reducing electrode) to produce H2, and OER is the reaction where water is oxidized at the anode (positive or oxidizing electrode) to produce O2. Alkaline electrolyzers operate by transporting hydroxide ions (OH-) through the electrolyte from the cathode to the anode with hydrogen being generated on the cathode side.

At the cathode, water reduction takes place according to:

$$2\mathrm{H}_2O + 2\mathrm{e}^- \rightarrow \mathrm{H}_2 + 2\mathrm{OH}^- \ (E^o{}_C = -0.828\ \mathrm{V})$$

At the anode, the oxidation of the hydroxyl ions takes place according to:

$$2\mathrm{OH}^- \rightarrow 1/2\mathrm{O}_2 + \mathrm{H}_2\mathrm{O} + 2\mathrm{e}^- \ (E^o{}_A = +0.401\ \mathrm{V})$$

This results in the overall reactions:

$$\mathrm{H}_2\mathrm{O}_{(liq)} \rightarrow \mathrm{H}_{2(g)} + 1/2\mathrm{O}_{2(g)}$$

In alkaline electrolysis, two electrodes are immersed in an alkaline aqueous electrolyte such as NaOH or KOH aqueous solution, both of which have been commercially available for many years, with a typical concentration of 20–40 wt%. KOH is preferred for its higher conductivity compared to NaOh, with KOH providing a specific conductivity around 95 Sm−1 at 50 °C, while NaOH reaches a value around 65 Sm−1 at the optimal weight percentage.

2.2 Passive Forward Osmosis

Our design integrates passive forward osmosis technology to reduce rates of electrode corrosion when working with a saltwater solution in hydrolysis. The following figure depicts a schematic of a forward osmosis cell:

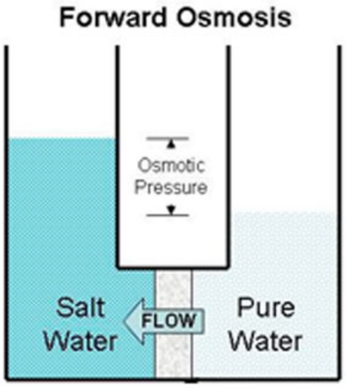

Figure 3. *Forward Osmosis Schematic Obtained from AIChE*

Forward Osmosis (FO) is an osmotic process using a semipermeable membrane to treat water by separating pure water from other dissolved elements in a solution like salts. The process is driven by osmotic pressure differences that are created by concentration differences between a feed and draw solution. In order to induce the osmotic pressure to desalinate seawater as a feed solution, a draw solution with a higher concentration is needed. This process is a passive process that requires continuous replacement of the draw solution.

Integration of passive forward osmosis into hydrogen electrolysis was informed by the following schematic depicted in Veroneau and Nocera's "Continuous electrochemical water splitting from natural water sources via forward osmosis" paper :

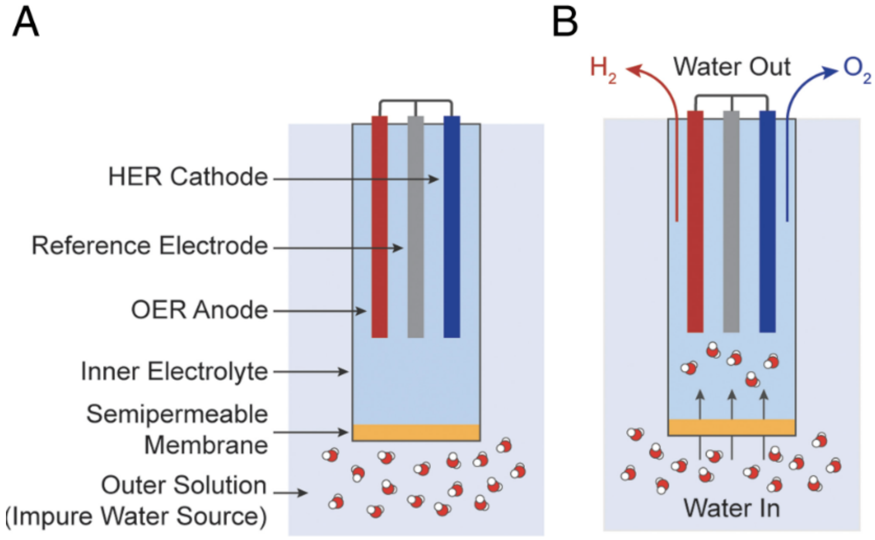

Figure 4. *Forward Osmosis-Water Splitting (Veroneau and Nocera, 2021)*

2.3 Photovoltaic Technology

Photovoltaic panels will be used to deliver electric current to the electrolysis cell. A photovoltaic panel consists of multiple cells which can be represented by the following circuit:

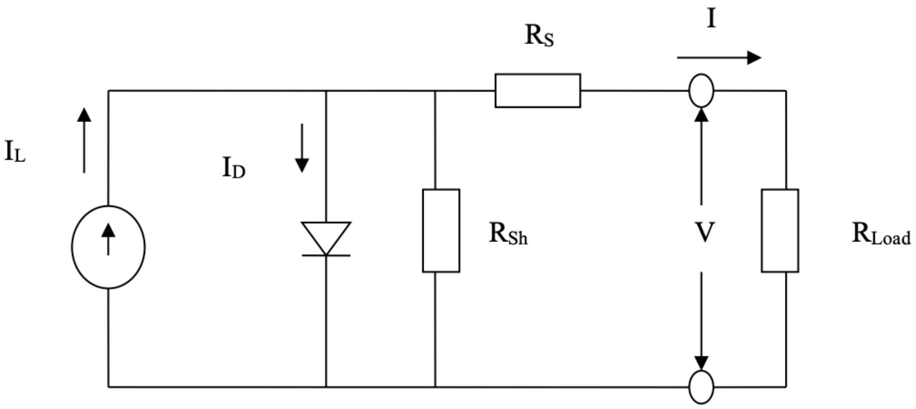

Figure 5. *Circuit Schematic of Photovoltaic Cell within Solar Panel from E. Carr Everbach, Swarthmore College Engineering 35: Solar Energy Systems (2021)*

The photovoltaic cell is driven by the photovoltaic effect as shown in the following figure:

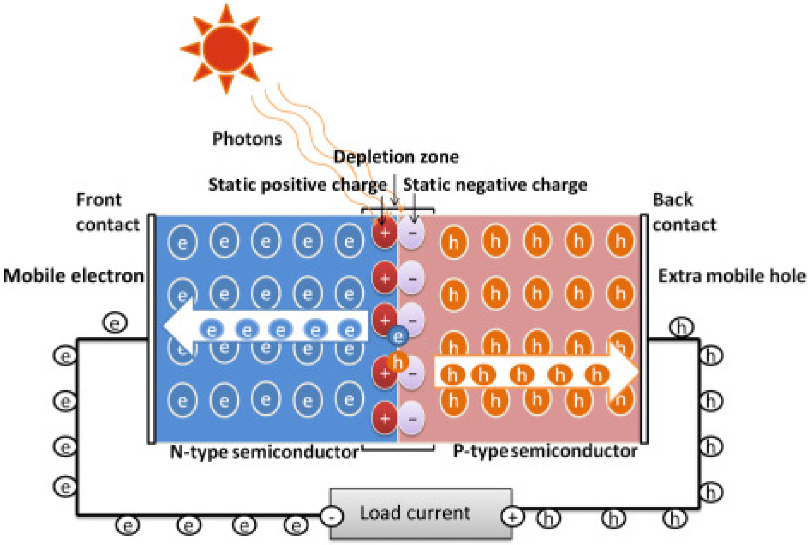

Figure 6. *Photovoltaic Effect Obtained from Simya et. al. (2018)*

When photons from the sun strike a photovoltaic solar cell, the photons excite the electrons, converting the solar energy into DC electricity using a p-n semiconductor junction. The p-n semiconductor junction is a boundary between two semiconductor materials with a p-type side with holes, an n-type side with excess electrons, and a depletion region.

When photons energize electrons, the electrons either create an electric current, I, in an electrical load or create an internal junction current, I_D, that is then dissipated as heat. The panel and its electrical connections will also have some internal resistance that cannot be completely eliminated, which dissipates energy as heat, which can be modeled as the series resistance, R_s, and the shunt (parallel) resistance, R_{sh}.

2.4 Electrode Material Selection

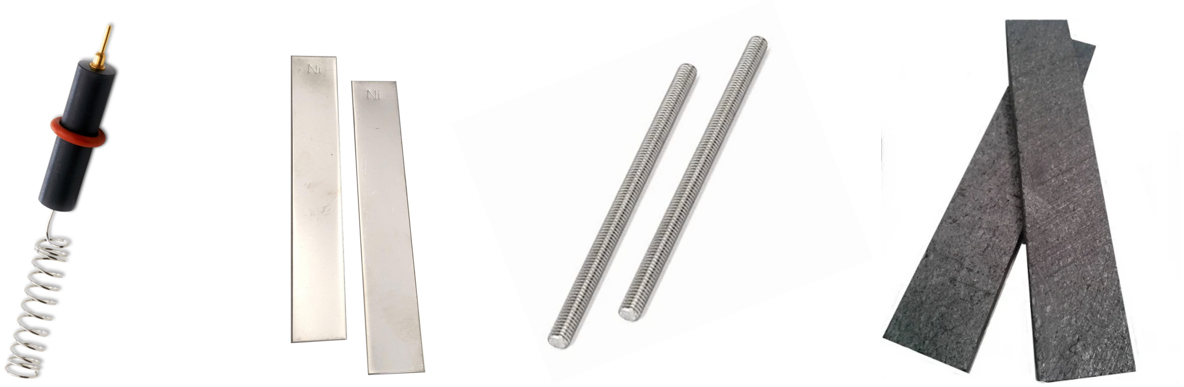

Figure 7. *Platinum, Nickel, Stainless Steel and Carbon/Graphite Electrodes (Images obtained from BASi, Science Kit Store, Amazon, Mini Science)*

Electrode material selection is also a key component of hydrogen electrolysis. The electrode material directly dictates the efficiency, durability, and economics of the system. Our project directly integrates various electrode material decisions in order to reduce costs while also increasing the efficiency and lifespan of the electrodes. The specific chemical composition of electrodes is an active area of research, with the catalytic advantages of various materials being explored as a means to improve overall efficiency and increase gas output. Some of the most commonly used materials include platinum (Pt), Nickel (Ni), and Stainless Steel.

Platinum (Pt) is commonly used due to its high efficiency as a catalyst for HER. Platinum electrodes also do not participate in redox reactions while the cell is working, unlike other metals. (University of Toledo) This makes it particularly useful for alkaline electrolysis and seawater applications in which high pH ions and the presence of chloride ions would cause corrosion that significantly reduces the lifetimes of other electrode alternatives. Platinum's high catalytic activity and stability at high temperatures as well as its stable electrical properties makes it great for electrolysis. However, platinum is a limited and rare metal that comes with a high cost, making it very cost ineffective for large scale applications.

Nickel (Ni) is also commonly used as an electrode because of its high catalytic properties for HER. It is low cost compared to other electrode materials like platinum, making it a good electrode selection for large-scale hydrogen production. They are also particularly compatible with alkaline electrolysis given their resistance to corrosion in alkaline environments. However, they are susceptible to corrosion within environments with chloride ions, such as seawater.

Stainless steel is another commonly used electrode that is low-cost and durable. It is resistant to corrosion and can operate at high temperatures. However, compared to other electrode alternatives, stainless steel is not as efficient as a catalyst for HER.

Carbon (CO), in the form of graphite, is a low cost electrode that is stable with the ability to withstand harsh operating conditions like high temperatures and pressures. It is also compatible with alkaline environments and not prone to corrosion from seawater. Carbon is also a renewable material, making it a sustainably better alternative than other electrodes like platinum.

Multiple technologies also exist combining the different materials in order to meet different needs of projects. For example, steel is commonly used as a main cell frame material and covered with a layer of porous nickel to improve the charge of transfer kinetics given its high catalytic activity in the reaction of cathodic HER.

Our design evaluates the advantages and disadvantages of various electrode material selections to meet our criteria on efficiency, durability, and economics.

2.5 Adsorptive Hydrogen Storage

The ability to capture and store hydrogen produced via a solar powered electrolytic system is of utmost importance for the system's viability as a component in any realistic energy infrastructure environment, as usage needs will be time-independent from the production of hydrogen during the solar day. However, this poses a particular challenge as in its pure form hydrogen typically requires either extremely low temperatures or extremely high pressures to be maintained in its storage system. These factors raise the complexity and thus the commensurate cost of apparatuses designed for hydrogen storage, and have been a major barrier to the adoption of hydrogen-based technology on a wider scale.

Because of these concerns, adsorption-based storage systems are of particular note when examining methods for hydrogen storage. These are based on the adhesion of gaseous molecules to the surface of a certain material via weak bonding, which can then be reversed via the application of heat or reduction of pressure. (University of Warsaw) In particular, platinum serves as an especially effective adsorber of hydrogen, enabling it to capture and hold gaseous hydrogen at close to room temperature and atmospheric pressure. (Indian Institute of Technology) This enables the construction of an adsorptive hydrogen tank including a filler material of a foam-like structure (to maximize surface area) coated in a platinum substrate. Although relative trade-offs exist between this variety of storage systems and more standard methods in mass, expense, and effectiveness, the technology proves promising as a method for use when higher pressure or lower temperature systems are impractical due to safety or energy usage concerns. As such, we incorporated an adsorptive platinum-based hydrogen tank for the storage of hydrogen generated by the electrolyzer in this project.

2.6 Full Design Considerations

Our project integrates the theories explored above to sustainably produce hydrogen as shown in the following schematic:

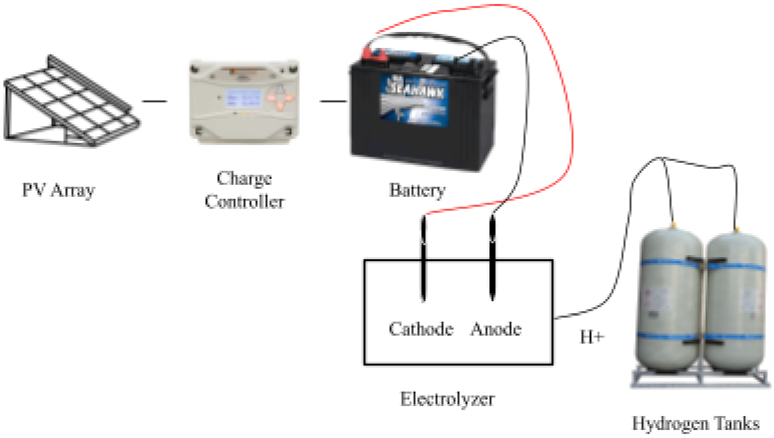

Figure 8. *Diagram of PV-Electrolyzer System*

From a high level perspective, passive forward osmosis can be integrated with hydrogen alkaline electrolysis to allow the extraction of pure water from seawater. An inner chamber containing the electrolyzer is filled with a high molarity alkaline solution, while an outer chamber containing a lower-molarity feed solution is connected to the inner chamber via an osmotic membrane. This setup allows pure water to enter the electrolyzer chamber via forward osmosis, while the removal of water via electrolysis serves to balance water influx and outflux and maintain molarity. We can similarly choose our electrode material carefully to minimize corrosion within the electrolyzer. The electrical current input for the electrolysis cell is delivered through photovoltaic technology as expressed in section 2.3 and the gas output is transferred to an adsorptive hydrogen tank as outlined in section 2.5.

3 Design/Construction

3.1 Prototype I

Our initial prototype was constructed as a simple, proof-of-concept design intended purely to demonstrate the production of hydrogen via electrolysis. It incorporated simple steel electrodes threaded with steel washers to increase the surface area of the electrodes to facilitate higher rates of hydrogen generation. Plastic hoods were fitted over both electrodes to ensure that the gasses were separated and to facilitate the capture of gasses produced with output tubes. A diagram of the device is shown here:

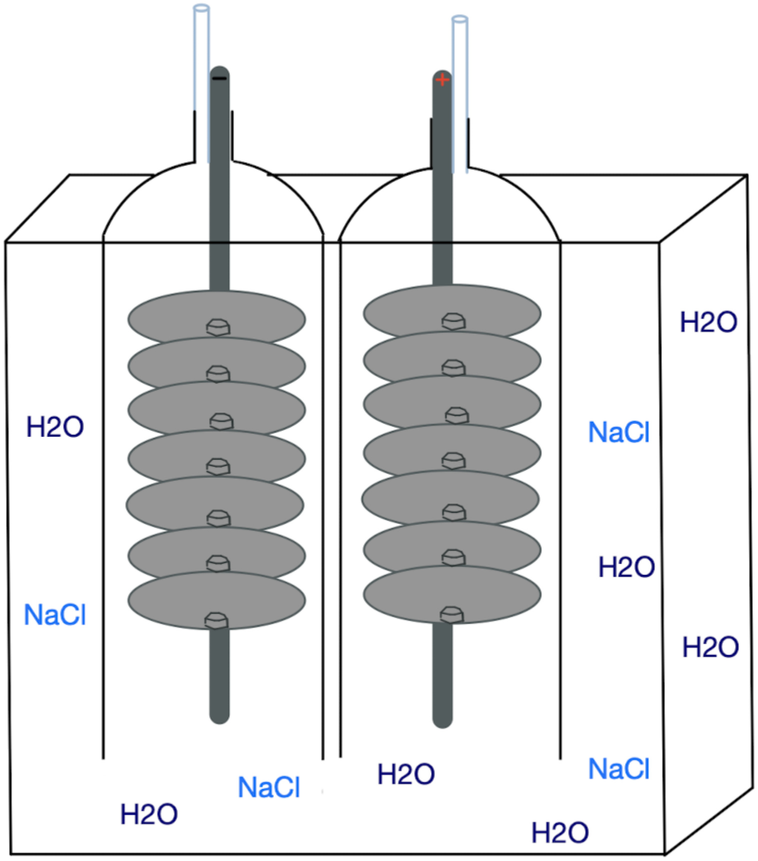

Figure 9. *Prototype I diagram*

This prototype neglected to address the corrosive concerns associated with steel electrodes, the use of an osmotic system to enable a seawater feed solution, or a host of other components in favor of simplicity and the ability to rapidly produce and test the device. It was constructed using materials readily available from the Swarthmore Engineering Department, and was tested immediately thereafter in conjunction with a power supply mimicking the 12V applied power eventually available from the PV system. It was subject to several deficiencies which provided insight into design considerations relevant for future prototypes—poor seals in its gas capture tubes prevented it from being especially efficient at capturing hydrogen, and most prominently, it suffered from fairly extreme corrosion of the electrodes after limited operation time. Nevertheless, the results from this first prototype were encouraging; despite its simplistic design, it was shown to be capable of producing hydrogen and vindicated the basic premise of this project. Shown below are images of the prototype following its completion and following a 15-minute period of test operation (note the buildup of iron oxide):

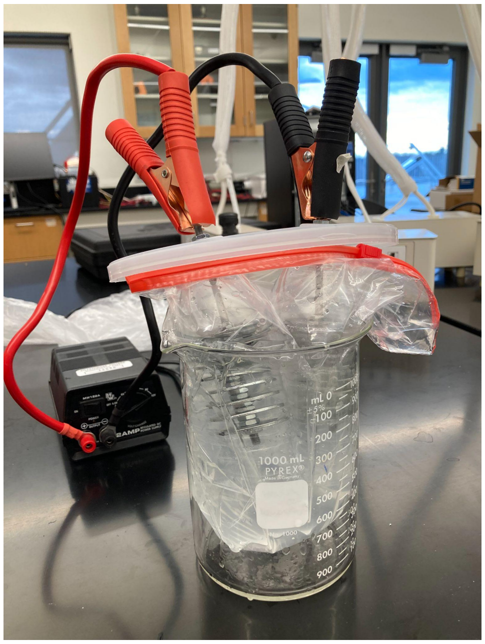

Figure 10. *Prototype I prior to operation*

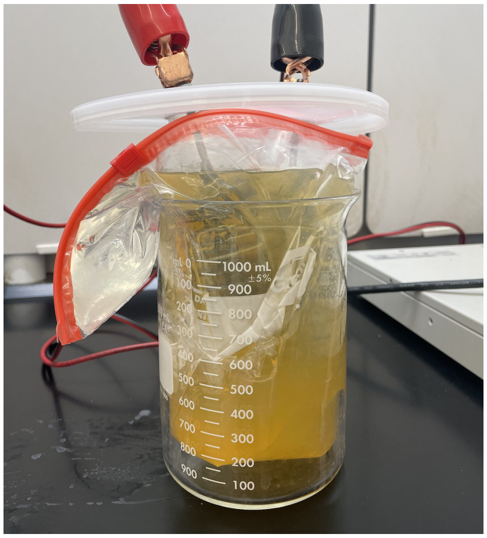

Figure 11. *Prototype I following 15-minute operation period*

3.2 Prototype II

Our second prototype incorporated a much more complex design informed by Samuel S. Veroneau and Daniel G. Nocera, authors of “Continuous electrochemical water splitting from natural water sources via forward osmosis”. In this design, a forward osmosis system was integrated into an alkaline electrolysis system as outlined in the theory subsection above. Its inner chamber was made up of a partially subdivided cylindrical chamber derived from a test tube, with each half serving as its own gas separation and capture chamber while allowing for fluid and electrical current to flow at the base. The inner electrolysis chamber was filled with a higher molarity sodium phosphate, $NaPO4$, solution to facilitate electrolysis. Each half of the inner chamber contained a wire electrode and a gas capture egress tube, with a reference electrode additionally present in the anode half. The top of the electrolysis chamber was entirely sealed with silicon sealant with the exception of the gas capture tubes. The bottom held a membrane to allow forward osmosis to occur. This chamber was mounted within an outer chamber which took the form of a beaker filled with lower-molarity, sodium phosphate, $NaPO4$, feed solution. A diagram of the device is shown here:

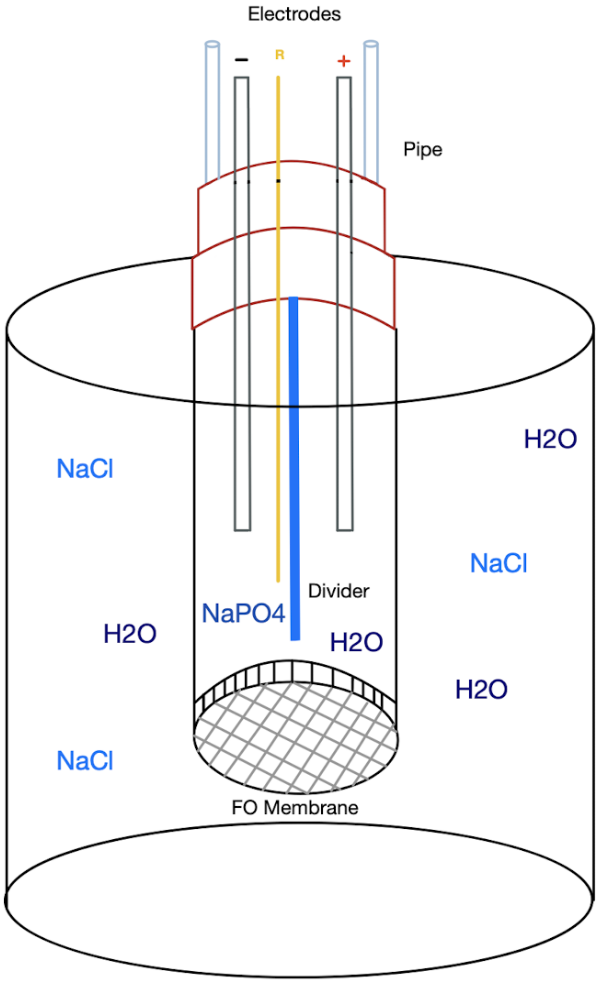

Figure 12. *Prototype II diagram*

In order to construct the inner chamber, a test tube was initially separated into anode and cathode sub chambers using a thin acrylic divider fitted to grooves cut in the tube walls and epoxied in place. A hole was drilled into the screw-cap of the tube to allow water flow through the osmotic membrane, with the screw-cap now forming the bottom of the chamber:

Figure 13. *Inner chamber during construction*

The initial design of the chamber head incorporated a rubber stopper pressed into the top of the chamber, through which a series of holes were drilled to allow the placement of the anode, cathode, reference electrode, and two gas egress tubes:

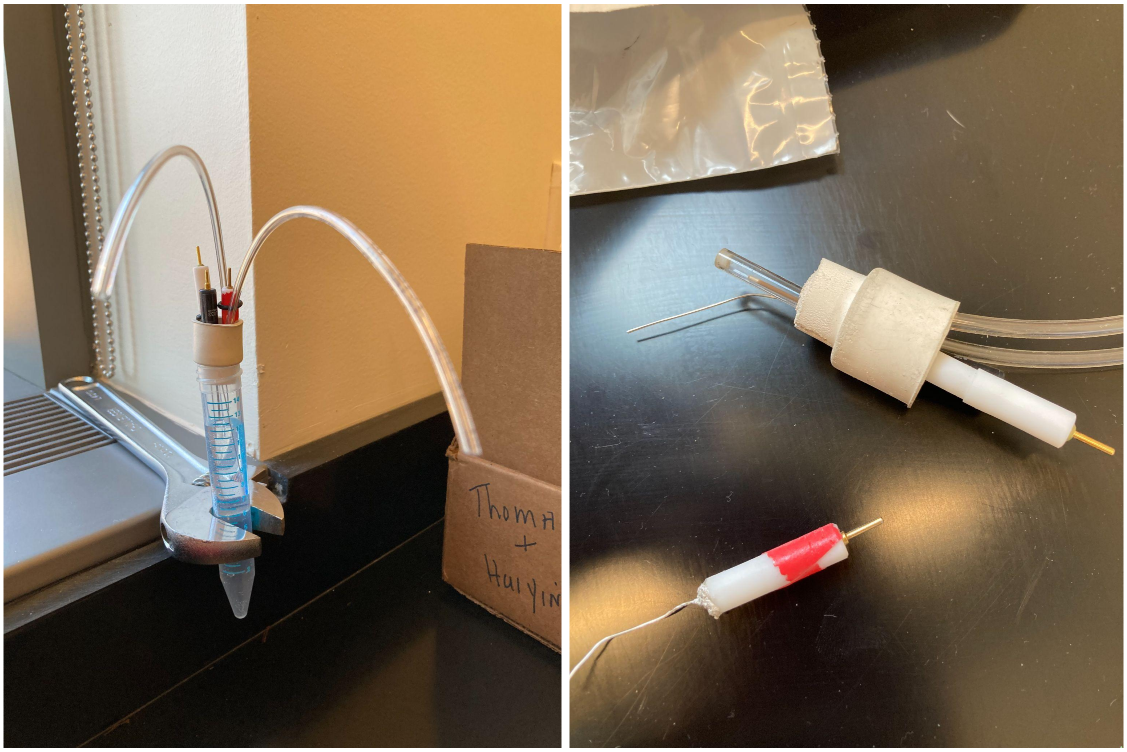

Figure 14. *Initial chamber head design*

However, this design presented a number of problems. It failed to achieve a seal across the top of the two inner sub chambers, thus allowing the mixing of hydrogen and oxygen outputs from the device and rendering it unable to effectively capture hydrogen. In addition, the precise placement of holes within the rubber top proved quite difficult. Our attempt to thread the electrodes through it resulted in the separation of one wire electrode from its lead. A repair job of this electrode was subsequently attempted using conductive silver epoxy, but failed to achieve a sufficient electrical connection between the wire and its lead:

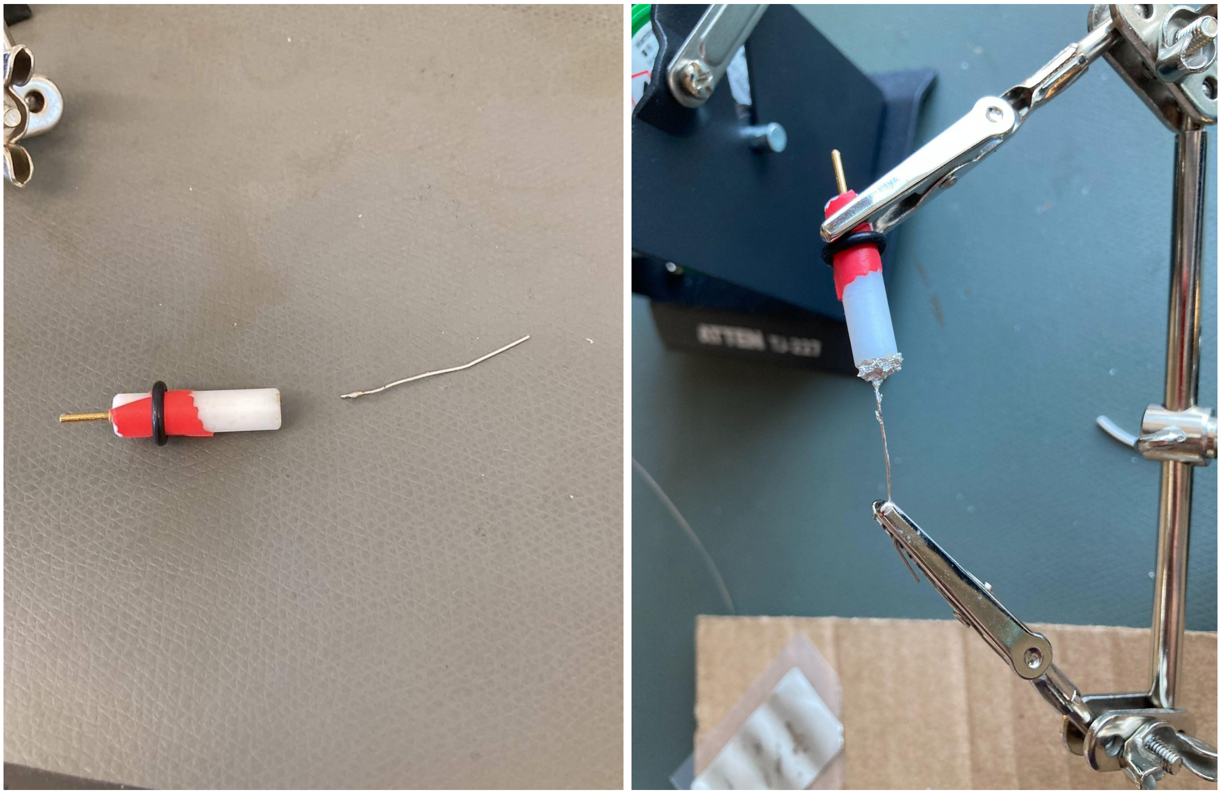

Figure 15. *Damaged platinum wire electrode and subsequent repair attempt*

Given these difficulties, the chamber head was redesigned to incorporate a flat plate of acrylic epoxied across the top of the chamber, through which the aforementioned holes could be drilled and the associated components mounted. The components were then fixed in place and gas leaks were prevented using silicone sealant applied to the top of this acrylic plate. The broken platinum wire electrode was replaced with a steel wire electrode of the same gauge. This design proved significantly easier to assemble and achieved the desired structural integrity for the top of the inner chamber. The revised top section of the chamber is shown in the following figures:

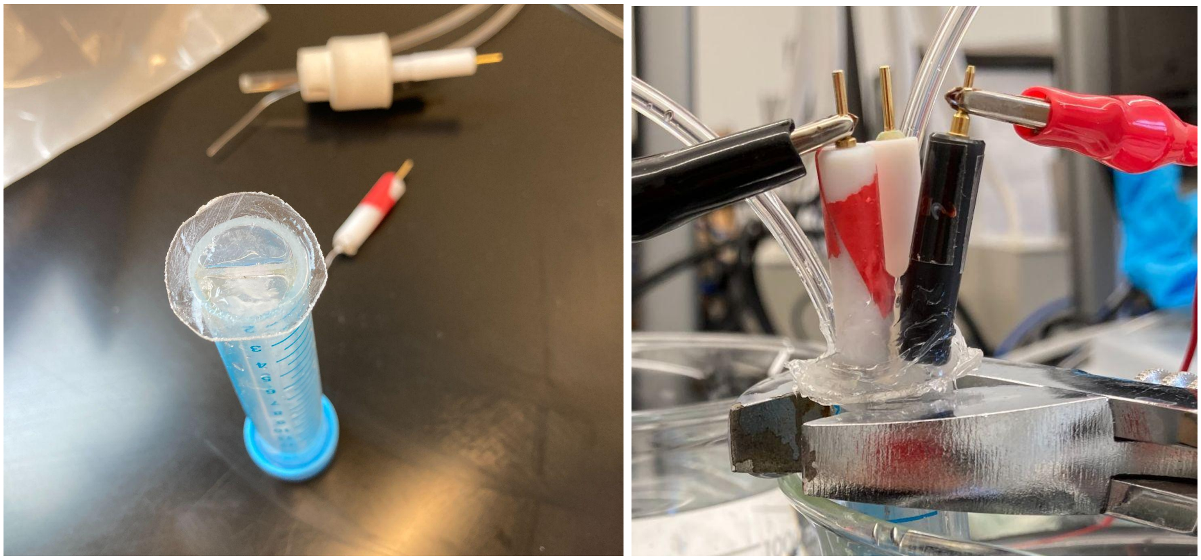

Figure 16. *Acrylic head plate and completed chamber head*

To complete the device, an osmotic membrane was cut to size and inserted into the base of the inner chamber, clamped between the threads of the cap and the chamber. The inner chamber was then suspended in a 1000mL beaker serving as the outer chamber. A variable power supply was connected to the electrode leads and the hydrogen egress tube was submerged in a secondary beaker filled with water to facilitate the release of hydrogen bubbles. The final assembly is shown in the figure below:

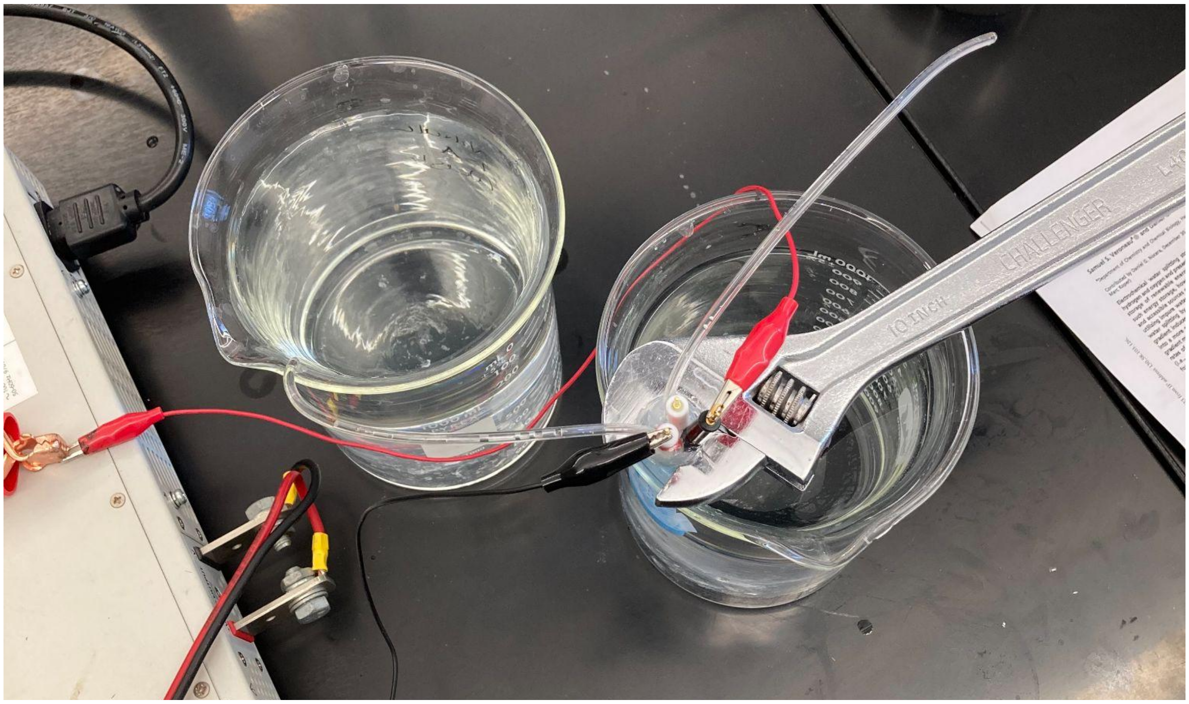

Figure 17: *Prototype II final assembly*

Several material upgrades were attempted relative to the first prototype. As previously mentioned, we had sought to incorporate platinum wire electrodes to address the corrosive issues posed by steel, but the destruction of one of these electrodes during the assembly process necessitated its replacement with a steel wire electrode. The feed solution present in the outer chamber was comprised of a 0.6-molar NaCl solution, while the solution present in the inner chamber was a 0.8-molar NaH2PO4 solution in order to facilitate improved hydrogen generation and reduced corrosion through forward osmosis. The results of this second prototype were similarly positive. Although we were unable to fully replace steel with platinum, the corrosion observed in the initial prototype was not as prominent, and despite its smaller size, it produced combustible hydrogen, indicating the promise of the osmotic electrolyzer design. Images of the complete device are shown here:

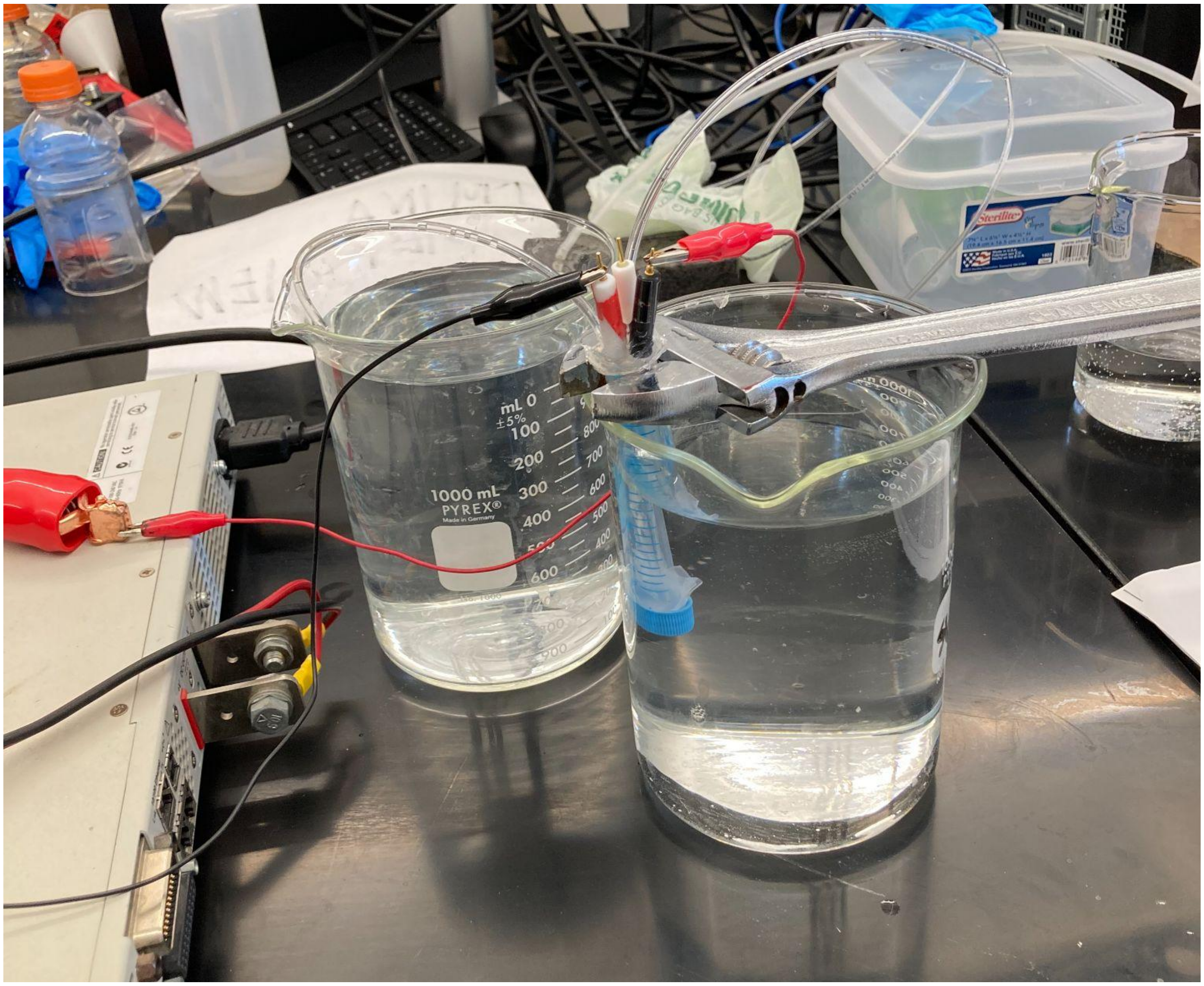

Figure 18: *Prototype II prior to testing*

3.4 Prototype III

Prototype III represented the most ambitious design created during this project. It aimed to replicate the success of the osmotic electrolyzer developed as Prototype II on a larger scale and in a more robust, cost effective, and user friendly way. It replaced the concentric chambers of Prototype II with two adjacent chambers similarly separated by an osmotic membrane. In this prototype, the central chamber contained the electrolyzer mechanics and its chamber contained the lower-molarity feed solution, separated by an osmotic membrane. An additional adjacent chamber held the palladium-foam tank capable of storing hydrogen produced by the device. As in Prototype II, the electrolyzer chamber was divided into two sub chambers, each of which held one of the electrodes as well as a gas egress tube exiting the top of the chamber. A diagram of Prototype III is shown here:

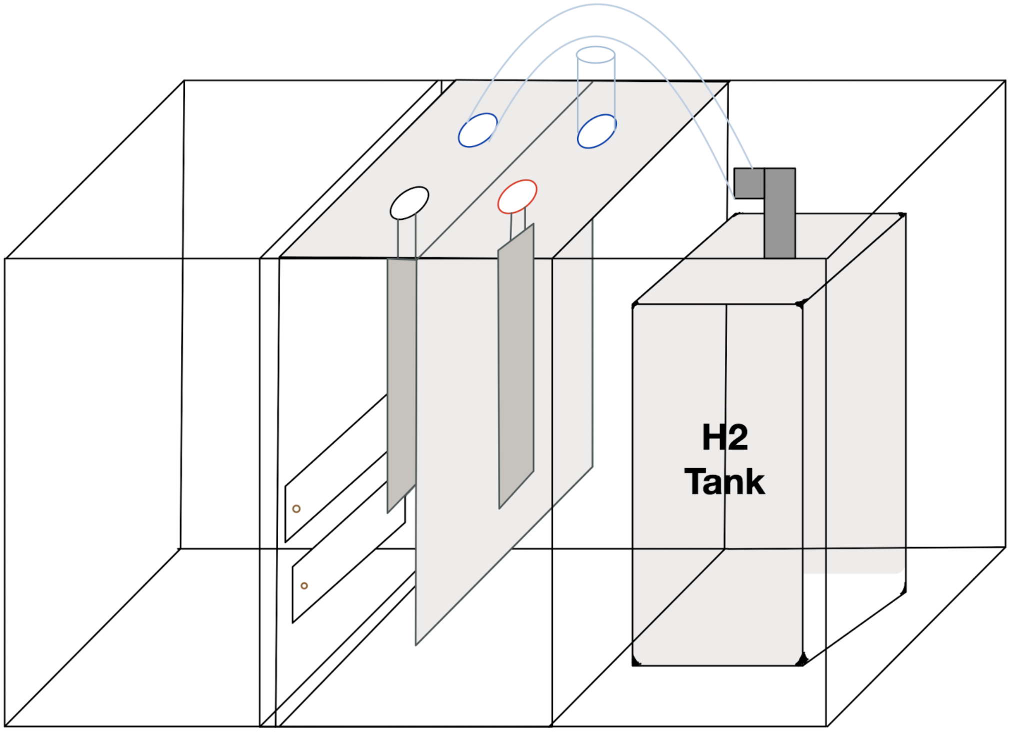

Figure 19: *Prototype III diagram*

To begin the construction of the device, sheets of acrylic were cut to size and subsequently fused together using acrylic welding solvent. The cut sheet is shown below:

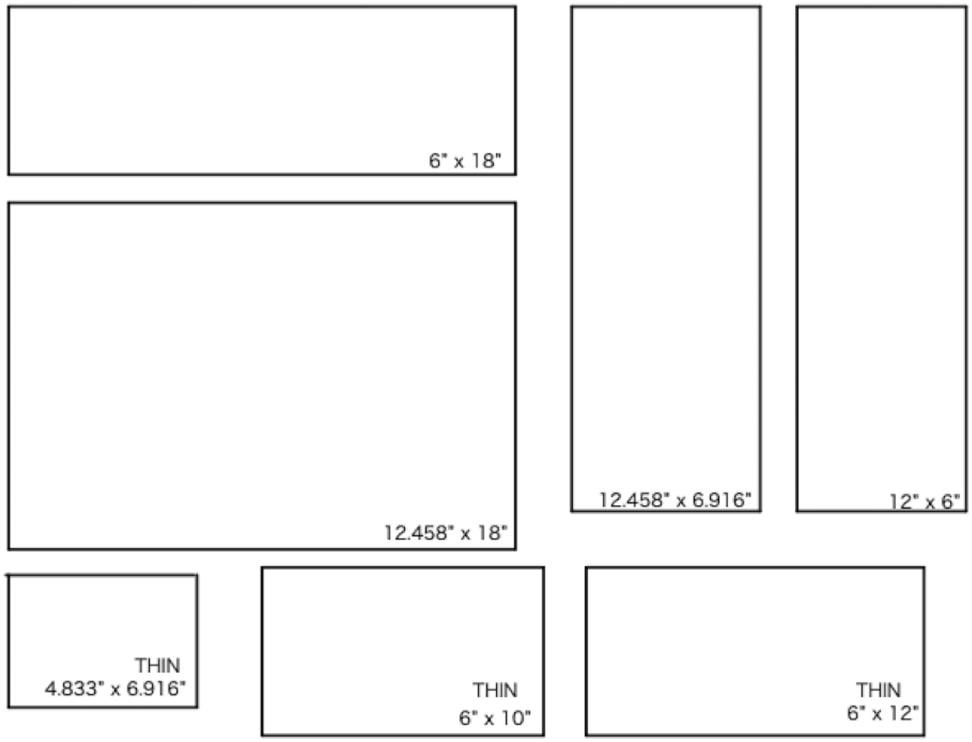

Figure 20: *Prototype III Acrylic Tank Cut Diagram*

This provided the primary structure of the three chambers and enabled mechanical robustness in keeping with its increased size.

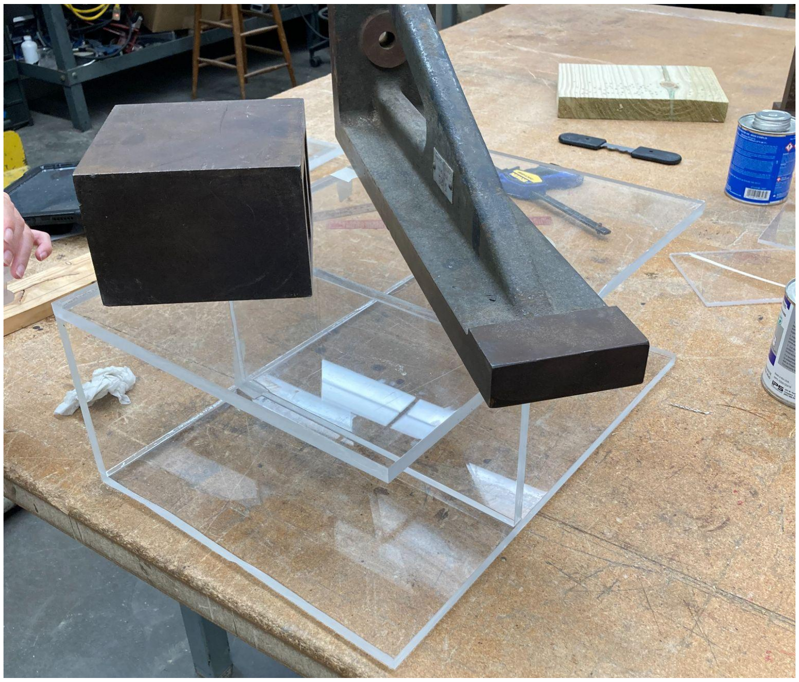

Figure 21: *Acrylic sheets being welded to form the basic device structure*

To form the wall between the feed solution and electrolyzer chambers, two holes were machined out of a piece of acrylic to allow the mounting of two osmotic membranes, thus maximizing the surface area available for water transfer between the chambers. In order to facilitate the easy removal and replacement of osmotic membranes, this wall was designed with a screw-on plate duplicating the holes for the osmotic membranes. The membranes are then clamped between the plate and the wall during operation, and secured using additional screws.

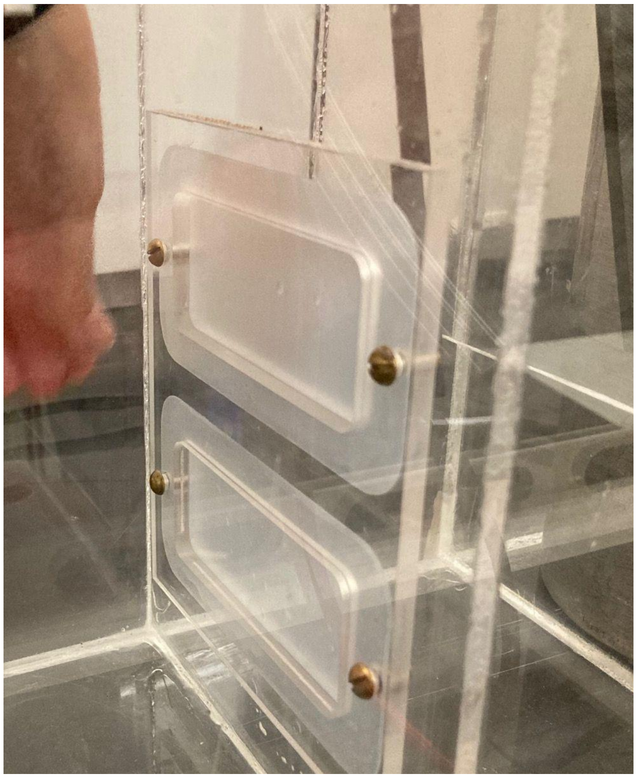

Figure 22: *Architecture to hold osmotic membranes*

The design of the electrolyzer chamber was split between anode and cathode sub chambers in a similar manner to the chamber from Prototype II. In order to allow easier access to the inner side of the osmotic membranes and the removal of electrodes, the lid of the chamber was designed to be removable in contrast to the fully sealed chamber from Prototype II. The initial design incorporated a rubber gasket around the lip of the chamber roof, which would theoretically be pressed against the upper chamber walls and provide an airtight seal. However, issues with this gasket led us to seal the chamber roof to the main device body using silicone sealant for final testing. The future design seeks to improve upon the mechanical sealing of the chamber. For the electrodes, graphite strips were incorporated in an effort to maximize conductivity and minimize the corrosion seen in Prototype I, while avoiding the costs associated with implementing platinum at this prototype's increased scale.

***Figure 23:** Electrolysis chamber design*

The palladium foam tank was placed in the third adjacent chamber of the device, and was connected to the cathode subchamber of the electrolyzer via flexible vinyl tubing.

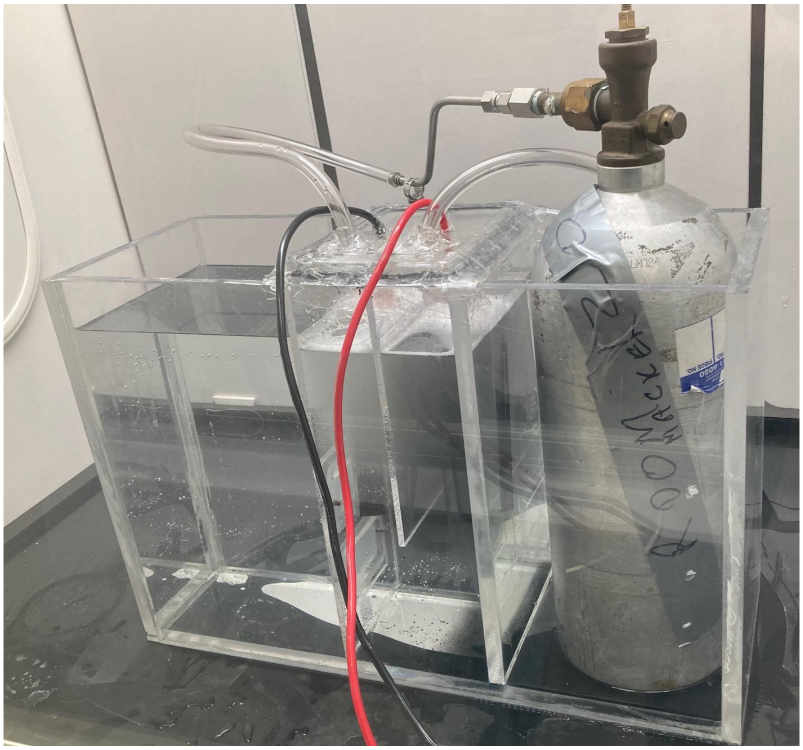

***Figure 24:** Completed Prototype III*

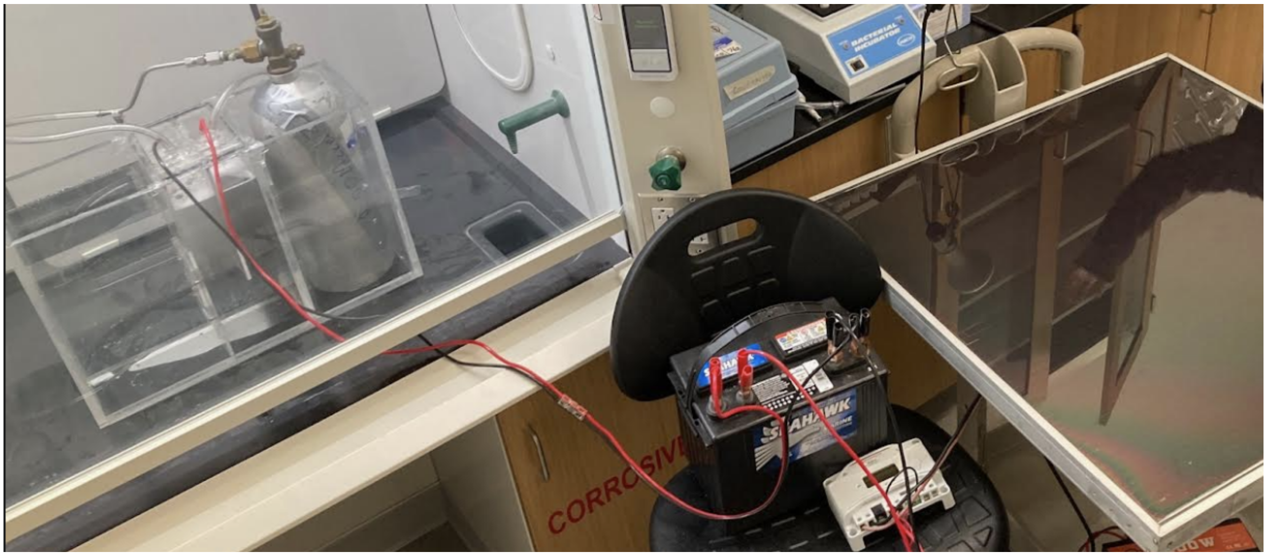

Figure 25: *Completed Prototype III with PV System Integration*

Results obtained during the testing of this prototype were largely positive. Using the same chemical solutions for both the feed and electrolysis chambers as were used in Prototype II, hydrogen was produced by the device at a much larger scale commensurate with the increased surface area of its electrodes and its much larger size. It was run using a large-scale 12V battery charged via a photovoltaic power array, allowing the production of hydrogen using clean energy and vindicating the basic premise of the project. Imperfections in the silicone caulk seal at the top of the chamber undermined the capturability of the generated hydrogen, with leakages at the chamber edge preventing the buildup of sufficient pressure to push hydrogen out. In addition, moderate erosion of the anode was observed over 45 minutes of device operation, as shown here:

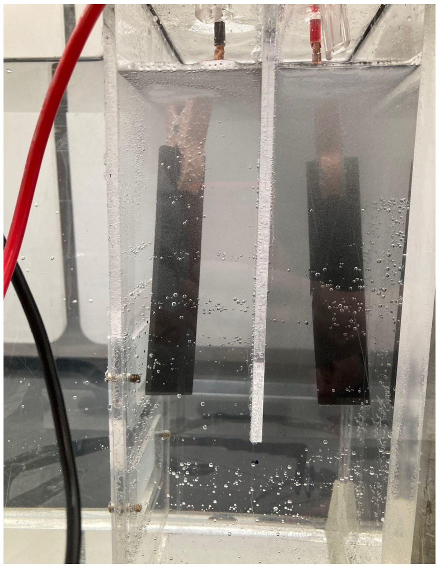

Figure 25: *Anode corrosion following 45 minutes of operation*

However, these issues would likely be resolvable in future iterations of this design, and potentially with modifications made to this system itself. An improved mechanical seal for the chamber lid could maintain an airtight boundary for the electrolyzer chamber while simultaneously preserving the ability to access electrodes, while further experimentation with electrode chemistry could likely yield improved results.

4 Estimating Project Impact

This project aimed to create a safe, user friendly, cost effective, and realistically scaled hydrogen generation system using seawater. The following sections discuss our ability to achieve the aforementioned goals that we had set out to achieve.

4.1 Estimated Efficiency

Due to the imperfect seal at the chamber lid, we were unable to precisely establish the rate of production of hydrogen within our final prototyped device. However, a rough estimate based on the apparent volume and generation rate of bubbles in the cathode chamber suggests that approximately 1 liter per 15-minute time period is likely within the range of the device's output. Given the system's measured power consumption of 21.36 watts, this suggests that the use of roughly 19,224 joules of electrical energy over a 15-minute period could produce roughly 13,027 joules of energy stored in hydrogen, a potentially impressive efficiency for energy conversion. Although these numbers are somewhat arbitrary owing to their hypothetical nature, a successful sealing of the chamber lid should allow a trial of the device capable of precisely determining its rate of hydrogen production. This would enable real values to be determined and inform future work and experimental expectations accordingly.

4.2. Estimating Project Cost

The project cost is estimated for our final prototype to assess the financial viability of our culminating system design. Our main costs come from the acrylic tank, wiring, nuts and bolts, carbon electrodes, and hydrogen tank, and sodium phosphate solution. Additional costs will include a solar panel, battery, and charge controller. Costs for the seawater is negligible given that it is assumed to be sourced from an existing body of water at no additional cost. We estimated using an acrylic sheets distributor that for ⅛" thickness acrylic, the cost was about $\$0.025/in^2$. Given our total area used for the tank being about 837 in^2, we estimate the tank to be about \$20.93 for the cost of the tank. We estimated the wiring we used was \$0.825 per ft. We used about 3 ft of the 10 gauge wire, resulting in about \$2.8 for the wiring costs. From McMaster Carr, we estimate \$1 for the nuts and bolts used. \$4.75 was the cost of 2 carbon electrodes. Our sodium phosphate solution obtained from the The Curated Chemical Collection was \$35.99. We had used an existing hydrogen tank for our system, but an equivalent hydrogen from Cal Gas Direct, costing \$95, would be an adequate replacement. While we used solar power equipment already existing in our labs, we determined that a 100W 12V Solar Panel + 10A Charge Controller + 21Ah Gel Battery solar kit from a company like Expert Power could be an adequate substitute for our existing equipment. At the current time of search, this kit could be purchased for $169.99. Combining all costs, this system is $329.46. This system represents an initial investment with minimal costs needed in future systems. For many areas in which communities depend on constantly purchasing fossil fuels, this initial investment could theoretically offset the costs in a relatively short period of time.

4.3. User Experience and Safety

User experience was one of the key criteria that we had set out for in designing our final system. Our final system consisted of separated chambers with a very large chamber dedicated to holding the seawater. This chamber will make it convenient for seawater to be filled with larger margins of error to prevent spilling. The openness of the chamber will also ensure easy maintenance for cleaning purposes as well as parts replacement purposes. In particular, the design to hold the osmosis membranes was also developed for convenient maintenance. One could easily remove the screw on plate to replace the membranes while securing it through brass screws. The electrolysis chamber in the center was designed as well for convenient maintenance The top lid was formed so that it could be easily removable. The wire leads for the electrodes allow easy replacement of the original electrode with any electrode. It can be changed by simply unclamping the carbon electrodes and replacing it by clamping on any other desired electrode. Wire leads were also ensured to be insulated where necessary. The other ends of the wire were crimped and fitted to wire connectors so that the connection to the electrical source could be easily facilitated. The aforementioned ensure that electrical hazards are mitigated as much as possible. The system was also designed to be integrated such that one can fill in seawater and obtain hydrogen through a tank on the other side in a single system. These design considerations combined all ensured that we were steeping our design in safe and positive user experiences.

5 Conclusion

Our project set out to create a safe, user friendly, cost effective, and realistically scaled hydrogen generation system using seawater. This project iteratively designed our final prototype such that we were able to relatively successfully meet all of the goals that we set out to achieve. Through combining a forward osmosis system, cost effective carbon electrodes, and an easily maintainable and integrated hydrogen generation system, we were able to extract pure water from our seawater solution to be electrolyzed to safely and sustainably produce hydrogen. Further exploration of this project should consider quantifying the rates of production and refining the efficiency of the system. This could take the form of integrating currently active research on better electrode alternatives, improving the mechanical sealing, and enhancing the hydrogen capturability of the system. Additional research should also be conducted on the physical, financial, and cultural feasibility of this system. In further improving the system to become more mechanically robust, efficient, user friendly, and culturally accepted, this system could become a promising system that can be integrated within communities, particularly remote regions.

5.1 Future Improvements

This project represents a first stage of investigation into the implementation of osmotic electrolyzer technology in a practical context. Our main goal was to demonstrate the ability of this technology to effectively produce hydrogen from a saline water source, and explore the challenges associated with constructing a device capable of performing this. Although our efforts were largely successful, this work remains preliminary. While effective in an experimental context, our design does not yet represent a consumer-ready iteration of the concept espoused. Several areas of its design provide targets for improvement, and with further research could likely be improved drastically. These could represent potential topics for future E90 projects, or simply serve as inspiration to any group or individual seeking to pursue this technology further.

Foremost, a future design would likely seek to improve on the efficiency of our device in terms of the hydrogen produced per unit of electric energy consumed by the device. Our design was not optimized for this metric, and instead prioritized its demonstrative capabilities over the absolute economic use of energy. Potential design alterations could include increasing the surface area of electrodes, redesigning the electrolyzer architecture to minimize the fluid separating the anode and cathode (and thus its resistance), and improving the rate of capture of hydrogen generated. An optimized design might also seek to avoid the use of a battery as an intermediary stage between the photovoltaic power source and the electrolyzer, instead directly running the electrolyzer from the photovoltaic system. Improvement of these characteristics would increase the chances of the device's economic viability, or even simply its utility, were it to move towards implementation outside of a lab setting.

Second, a wide range of improvements could likely be made to the device chemistry to improve overall functionality and performance. Further research into the degradation of electrodes due to electrochemical corrosion may suggest novel materials and techniques for increasing electrode lifespan, thereby allowing longer operation without servicing and decreasing operating costs and frequent maintenance requirements. Alternate chemical solutions could be substituted within the electrolyzer chamber to minimize both electrical resistance and reactivity while maintaining the molarity required to extract water from the feed solution. Additionally, a precise investigation into the rate of hydrogen generation by the device (and thus water removal from the electrolyzer chamber) would enable the solution molarities to be tweaked and allow water influx and outflux to be aligned. Furthermore, additional investigation into the absorptive properties of palladium may allow substitutes for the palladium foam tank that are similarly able to capture and store hydrogen at standard temperature and pressure, which would drastically reduce the cost of device production.

Finally, a future device could pursue design changes to enable a more seamless user experience and move closer to a device ready for field use. The present design could likely be scaled up even further to allow production of hydrogen on a consumer scale, potentially increasing utilizability in certain scenarios. Various aspects of the user interface with the device from solution loading to membrane and electrode maintenance/replacement could likely be improved upon in subsequent design iterations. Some additional considerations may also include automating the process through implementing a pumping process into the sweater chamber as shown in Figure 26. In addition, the design could be altered to deemphasize aesthetics and lab-based functionality in favor of increased robustness and streamlining. These changes would likely encourage more widespread adoption of this technology as an energy solution.

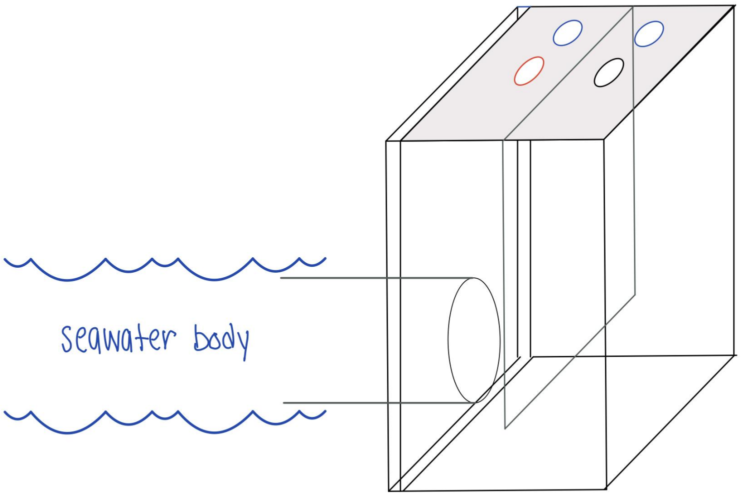

Figure 26. *Prototype IV*

These suggestions represent merely a small subset of possible future research regarding this design. The underlying technology it explores represents a fascinating application of fairly straightforward scientific principles to meet a need not currently well addressed by energy production systems. As the climate crisis continues and the urgent need to transition away from nonrenewable energy sources becomes ever more apparent, novel approaches to the capture and storage of energy will in all likelihood gain greater importance than ever in the coming decades. Exploratory though it may be, it is our hope that this investigation might contribute to the vital work of accelerating humanity's adoption of cleaner energy systems, and that this technology might find a place in assisting this progression. As the culmination of our time studying engineering at Swarthmore and the final contribution we submit towards our degrees we hope that all students who come after us might gain as much from this project as we have, and that we might all build a brighter future together.

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