Chumbe Water Energy Nexus Challenge

Madison Engineering Capstone Project Report

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by

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Executive Summary

Chumbe Island is a small, privately operated coral and forest reserve in rural eastern Africa. "Since the opening of tourism on the island in 1998, annual average occupancy rates on Chumbe have ranged from a low of 21% (in 1999) to a high of 89% (in 2007)" [2]. Amenities on the island include all-inclusive food and drinks, snorkeling, nature walks, and spa visits. The main goal of Chumbe Island is to conserve the coral reefs and forest ecosystems on the island, educate local communities on preserving the environment, and promote eco-tourism. In order to fund conservation efforts for the island, The island is home to a luxurious eco friendly resort. Chumbe Island uses solar panels to power it's seven bungalows and visitor center. The island currently stores their energy in four led acid batteries. As the energy demand continues to increase elements of their system including their inverter and charge controllers cannot meet the demand causing a decrease of usable power across their entire system. Chumbe Island has requested a new power generating system to help them with the increasing energy demands.

Chumbe Island Capstone Team is developing a sustainable energy storage and distribution system that can provide for Chumbe Island's energy needs. The design process began with gaining a strong understanding of the scope, history, and culture of Zanzibar and Chumbe Island. The cultural influence of the surrounding area will highly impact the design. Because of this, the main objective is to design a system for Chumbe that will be eco-friendly and allow the island to expand their conservation efforts in the future. Also the design must have minimal power losses, be easily maintained by the staff on the island, and have low operating cost. During the summer of 2019, team members had the opportunity to travel to Chumbe Island to meet with key stakeholders. The goal for this trip is to obtain feedback on the chosen design of a Vanadium Redox Flow Battery. Feedback from the trip to the island allowed the team to finalize a solution and move towards the prototyping phase.

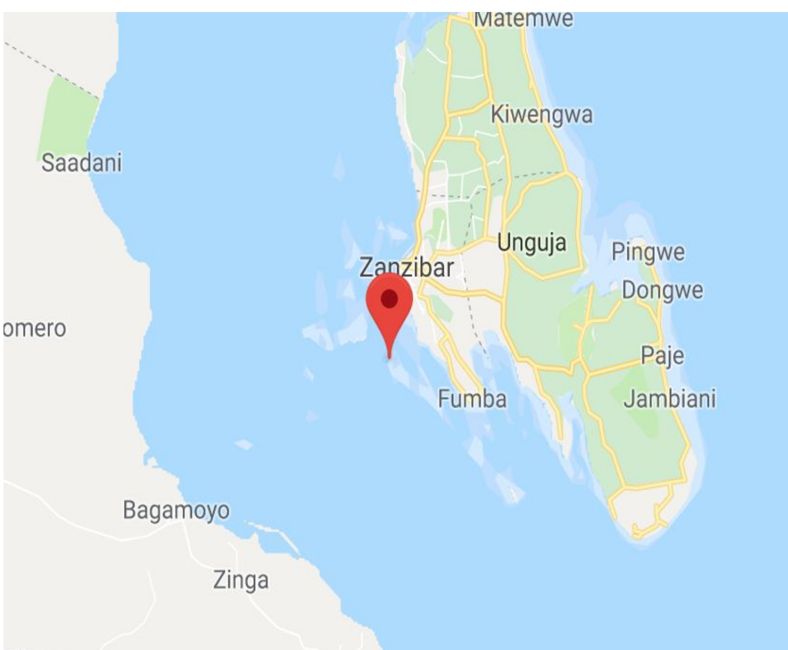


Figure 1: Chumbe Island, located 6km off the coast of Zanzibar (right) and approximately 30 km from Tanzania on the Eastern coast of Africa (left). **Image from Google Maps.**

1 INTRODUCTION

The Chumbe Water Energy Nexus Challenge Capstone Team will be working to provide Chumbe Island, Zanzibar with a robust eco friendly energy storage and distribution system that will provide the Island with an abundance of power. This document provides a detailed account of what the Chumbe Team has accomplished.

1.1 Problem Statement

Six hundred million people in Africa are living without electricity. Across 36 countries, 2 in 5 people do not have access to reliable electricity. Africa's power infrastructure is problematic. Not only are people faced with high electrical bills, but also, most of the electrical systems cannot support the power demand causing the system to become very unreliable. Some countries face outages from 50 to 4600 hours a year. That means, some people will not have electricity for more than half of the year. Africa's electrical shortages are causing an increase in the use of diesel generators. The diesel generators emit air pollutants. These pollutants are not only harmful to the environment, but also, harmful to human health. Air pollutants are known to cause cardiovascular and respiratory illness, pregnancy complications and even death. If people in African cities cannot power their homes, how is a one-mile-long island off the coast of Zanzibar going to power a luxury resort?

1.2 Broader Impacts

Chumbe Island Coral Park is a private island off the coast of Zanzibar and is used for educational purposes to students of Zanzibar and an eco-friendly resort. There are seven eco friendly, self sustaining bungalows that attract tourists from all over the world. The western side of the island is a marine protected area aimed to preserve the underlying coral reef. The coral reserve is directly affected by the actions the island takes. The high sensitivity of the reef forces the island to be constantly aware of their everyday operations. Minimal waste is produced on a day to day basis. Chumbe Island's main mission is to educate the local community with emerging eco technology as well as the vast coral life surrounding the island. Chumbe uses solar panels to provide the necessary energy needed to run the resort.

The current chokepoint is the distribution method of that power. Currently, it is not able to keep up with the demand which in return does not provide the island with the minimum power demand during a specific time. The redesigned and revised distribution system has the potential to be used toward the continuous education efforts of the island. The system has the potential to provide students with basic knowledge of eco friendly and self sustaining methods. Based on the current method he island is using, students have the opportunity to visit the island and learn about the coral reef as well as the marine life surrounding it. The sustainable energy distribution system can coincide with these efforts. Not only will the design be functional to create power and energy for the island, it can also be used to give these students hands-on experience with power generation. The design will be focused as a sustainable design to promote the island's values. The new distribution system has the potential to lessen the amount of fuel used to carry water and other supplies to the island, which in turn will mean less pollution to the coral around the island which will prevent further destruction of the coral reef.

1.3 Proposal Overview

The current project proposal strives to provide the island with a more efficient distribution system that will accomodate for the fluctuation of necessary power demand. While visiting the island, the team observed the high usage fluctuation of the system. The Visitor Center relies on four 12 Volt common car batteries to store the energy and distribute the demanded load. The solar energy is produced by 2 arrays of solar panels. The high efficiency of the solar panels has allowed for a vast energy production system. The island will greatly benefit from a more efficient distribution system to allow Chumbe to grow at the rate they wish. Throughout the proposal, the current faults in their system will be exploded and used to understand what necessary changes need to be made. This project will provide the island with a more robust distribution system with hopes that Chumbe can expand its capacity in the future and continue to educate the local efforts on their continuous efforts to maintain the marine protected area.

2 BACKGROUND

With previous knowledge of the client and stakeholders, two members of the current team had the opportunity to travel to the island where they incorporated skills acquired in the classroom to tackle real world problems. Located between mainland Tanzania and autonomous region Zanzibar, Chumbe Island has promoted eco technology along with preserving the local coral reefs in the area for over 10 years. To aid the efforts in preserving the coral reefs, Chumbe Island became a 5 star eco friendly resort striving to bring awareness to the coral reef. The implementation of eco technology has driven their message to preserve the marine protected area at all costs. The resort can accommodate up to 18 guests at a time. Once guests arrive on the island, they will quickly have adapted to advanced eco technology.

Each bungalow is equipped with two solar panels. One to provide power to the water heater and the other to power the four LED lights located throughout the bungalows. Both run off of DC current and do not need an inverter to deliver the power. Along with the bungalows, Chumbe also has a visitor center which is the main gathering area for all guests. Here, guests can access wifi, charge portable devices and eat all meals. The current challenge the island has is the storage and distribution of the consumed solar energy.The current method uses batteries which have a decreasing capacity and low efficiency. The island will continue to strive to maintain their eco friendly initiative and the increased usage of batteries goes directly against that mission. The batteries are hard to dispose of since the island goes through them at such a mass quantity.

Small islands have difficulty finding sustainable ways to power themselves. Chumbe's current method of solar panels have been accommodating the current energy needs of the island, but the delivery system is flawed. With hopes for expansion in the future, the energy storage and distribution system will need to be able to accommodate the increase in population on the island.

2.1 Problem Background

Peak power consumption is defined as the amount of energy being drawn per unit time when the island is at maximum capacity. Peak power will occur when the island is solely running on the stored energy within the battery due to the solar panels only producing energy during the day. The maximum consumption time period occurs when the visitor center is in full use, generally occurring at night.

2.2 Technical Background

It was necessary to begin by calculating the total power consumption (in watts) of the island. This includes the peak power consumption of the island and it's variations between energy use throughout the day and by seasons based on available data. The data will provide the achievable energy of the storage and distribution systems, and allow for a prototype to be designed centered on the capabilities of providing excess energy generation for the island. The extensive process, results and implementation plans will be documented in the final project report. The final alpha/beta prototype must be able to provide a distribution system that accommodates for the peak power consumption.

There are three different sources that draw power from the visitor center. First, the refrigerators, which run on the DC current. Secondly, the wifi system located in the office of the visitor center draws power 24 hours a day. Lastly, the computer system and AC current charging system will depend on the energy distribution system. The limits and exclusions to the project includes a high necessity to be maintained by workers on the island with available tools and materials. The design will also need to be constructed from available materials in the local area. Lastly, if the design is not physically built on Chumbe, it will need to be able to be transported from Zanzibar to the island, which is about a 45 minute boat ride. A second constraint that will need to be taken into account is the time difference between the United States and Zanzibar. This is a constraint that will be accepted and can be easily managed. The design will need to be maintained by the staff on the island. Enock, a primary stakeholder in the project, is the facilities manager of the island. He is in charge of making sure every system is running correctly. Enock will add great value throughout the design phase. Maintenance of the prospective system is of great value throughout the design process.

Once the schematics of the current system were identified, the main default was able to be located. Once this was identified constraints and objectives for the new system were identified. Based on these parameters, the new storage and distribution system will greatly value the eco friendly initiative of the island. Batteries will be used at a minimum since they are very difficult to dispose of. Educating visitors on the island will also be greatly valued. This could potentially influence the location of the system and the manual attached to the system. This current goal for the manual is to provide two copies, one in English and one in Swahili.

3 Stakeholder Analysis and Engagement

There are several key stakeholders involved in the project. Most importantly Chumbe Island Coral Park. As well as the department of engineering, and finally the visitors of the island.

4 Requirements and Constraints

Chumbe Island has unique and specific requirements. Although Chumbe Island is an international stakeholder, It is understood that each requirement and constraint will be used to produce a design that will better suit the island's needs than their current energy system.

4.1 System Description and Scope

Chumbe Island Water Energy Nexus strives to provide a small coral reef relief reserve off the coast of Tanzania with a sustainable energy storage and distribution system that will accommodate the specific fluctuating needs of the island. In this context, sustainability is defined as the system containing minimal power losses, the maintenance of the system capable of being completed on Chumbe Island, a minimal impact on the coral reef reserve, and the system being low cost to build and implement. Chumbe Island Coral Park Ltd. (CHICOP) is a privately owned nature reserve whose objective is to preserve the surrounding coral while encouraging education throughout the local communities. Their eco technology allows for the entire island to be environmentally friendly, which aids in the preservation of the coral. As communication continues with the international stakeholders, constraints and objectives become more prevalent in hopes to provide the island with an advanced system that can be implemented in the future.

Chumbe Island Water Energy Nexus team strives to provide the island with a more robust energy and generation system that accommodates their peak power consumption needs. A sustainable energy storage and distribution system is being developed that accommodates for the fluctuation of Chumbe Island energy needs. The goal is to create a system that can be run and be maintained on the island without a large amount of support from the mainland, to operate said system.

Currently, the restraints and constraints revolve around the accessibility of resources on the island, a budget set forth by the engineering department, communications with the island due to time change and internet accessibility, the system needing to qualify as sustainable, and the ability of the system to operate at peak times in the peak season.

4.2 Project Requirements

The process of creating an energy storage, generation, and distribution system provides the need for numerous requirements. Several requirements originated from the current pain points of the staff and visitors on the island. The designed power system must be sustainable and eco-friendly. In the context of the design, sustainability is defined as containing minimal energy losses, maintenance can be done on the island by the staff members, minimal impact of the system on the coral reef reserve, and the system requiring a low cost to implement and operate. A comprehensive chart of the requirements is in Appendix 5.

4.3 Process for Defining Requirements

In the summer of 2018, team members traveled to Chumbe Island and experienced the constraints of and needs of the island first hand. This was the foundation of defining the requirements of the project. For example, during the concept generation phase, the design of the solar system will need to consider all transportation between the United States and Tanzania. The power system will need to be able to fly in a plane and be able to be transported on a boat from Tanzania to Chumbe Island.

In the summer of 2019, additional team members will be traveling to Tanzania to justify the preliminary system design and verify the requirements and constraints set forth by the stakeholders, as mentioned above in Section 4.1. This will ensure sufficient communication with the stakeholders to keep their needs and the constraints of the country and the island are considered and accounted for within the project.

Requirements are created to support the island's environmental initiatives. This is how the renewable and pollution requirements came to being and how the system generation subsystem was defined as renewable. Nextly transportation and maintenance of the system was taken into account for the design. Enock needs to be able to maintain the design since in the past the solar panels were installed and he had no knowledge of how to maintain or fix the equipment; therefore, the design that is implemented at the island needs to be in his ability of expertise.

4.3.1 Translating Stakeholder Needs

The staff and population of CHICOP are the main stakeholders that provide information for the to be designed power system. The energy creation system needs to be built around the needs and constraints of the island. The staff have provided a consolidated list of equipment on the island that require power. That list included LED light bulbs, a computer, printing, and two refrigerators. In communication with the staff, it was also noted that the lightbulbs, and refrigerators all operate on DC current. Since this list was vague, some estimations of power consumption were assumed to start preliminary calculations.

Currently, the solar panels at the two locations are storing the surplus energy in batteries for night time power usage. The staff has expressed their discomfort of batteries and the energy storage system will strive to limit the amount of usage of battery storage for energy. The conflict is that the island uses solar panels for their power which requires batteries to store their DC power. This will be a difficult challenge to provide a solution efficient to supplying enough power for the night time power usage that also includes minimal to no battery requirement to satisfy the people of Chumbe's needs.

4.3.2 Benchmarking

A range of assorted energy sources and equipment that can possibly be implemented to create enough energy and power for the peak consumption of the island. The first item benchmarked was batteries, followed by wind turbines, solar panels, and desalination. Citations and charts of each benchmarked item can be found in Appendix 6 Table 6a-d.

The batteries that were benchmarked were the Tesla Powerwall 2 (lithium ion), the Trojan Batteries (flooded lead acid), and the SimpliPhi AccESS batteries (lithium ion). They were benchmarked based on the type of battery each one is, the energy output, the parallel capability, exterior regulation required, the dimensions, the weight, and the cost. From the research, it was concluded that for batteries on Chumbe to work, the system implemented should have an internal regulation system installed. In addition, lithium ion batteries are eco-friendly and can store more energy than the flooded lead acid battery.

Three types of wind turbines were benchmarked based on their weight, rotor diameter, rate wind speed, operating temperature, and design life. The three types of turbines that were benchmarked were 20kW wind turbine, 100kW wind turbine variable pitch, and 50kW wind turbine variable pitch. Based on the research, it was concluded that the weight and power produced is correlated to the size of the rotor in the turbine. The design life and operating temperature do not affect the size of the turbine.

Monocrystalline silicon panels, polycrystalline silicon, and thin film solar panels were also benchmarked. The panels were researched based on the materials required to build them, their functionality, the cost, the efficiency, assorted applications, their longevity, tops brands, and their power ratings. It was discovered that the monocrystalline silicon solar panels would probably be the most viable option if implemented on Chumbe Island; however, more research should be done to conclude this theory.

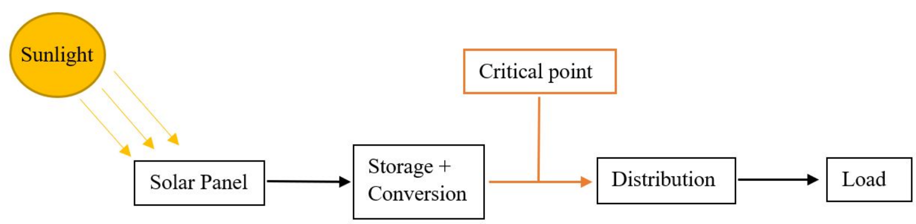
The last tool benchmarked was desalination brands. The three brands benchmarked were Crystal Quest, Rainman USA, and Hydrobuilder. These three were studied by the costs, power required, water output, weight, dimensions, operating power and pressure. The previous capstone team focused on building a desalination system for the island. Benchmarking other top brands will help determine how much output power to account for when determining the peak power consumption of the island. Further testing will be needed to determine the actual output power, however, this research provides qualitative numbers that can be expected.

4.3.3 Qualitative Modeling

A black box model was generated as the first qualitative model. Solar panels were chosen because they are Chumbe's main source of power generation. It is necessary to learn exactly how they work. This will lead to a better understanding of the problem Chumbe is facing with their power production, storage, and distribution.

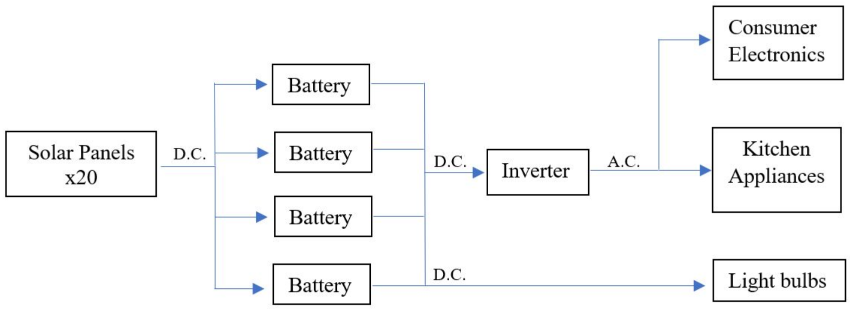
The system black box model shows the keep point of the energy creation storage and distribution of the design to be put into place. The critical point of the system is where the energy being pulled from the storage system is most limited.

Figure 3: System Black Box Model



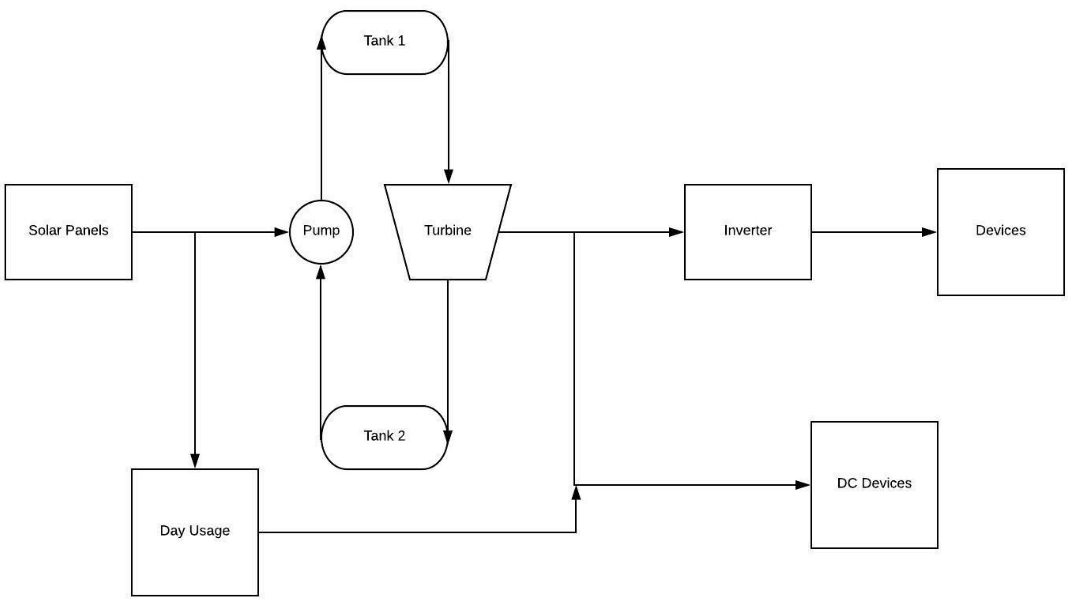
Model 2 shows the second solar station located atop the mosque on Chumbe. The solar station consisted of twenty solar panels which creates D.C. power that charge four 12V, 200Ah batteries. These batteries provide power for all of the visitor center. The light bulbs in the visitor center are D.C. LED bulbs that run directly from the batteries. Any other electronics in the visitor center such as computers, kitchen appliances, or consumer electronics run on A.C. power, therefore the battery power must be converted by an Inverter first.

Figure 4: Solar Station Black Box Model



Model 3 is the first concept generated, to improve the energy and power systems for chumbe island. The batteries are replaced with a hydro turbine generator cycle using elevation to store energy for night usage. Water will be pumped to tank 1 during the day and stored using solar energy from the solar panels. At night the water will release from tank 1 and drop to tank 2 where the hydro turbine generator will create energy for the visitor center at night.

Figure 5: Concept generation #1



4.3.4 Codes and Standards

When prototyping begins, codes and standards of Tanzania and the United States will need to be considered as the prototype will be built in the States and be shipped overseas to Tanzania. Since the project will be multinational, international standards and codes need to be considered in the energy storage, generation and distribution system [7]. Section 1204.2, in the 2018 International Fire Code focuses on the placement of solar photovoltaic power systems by stating, for example, that the panels placed on roofs must be accessible by firefighters in an emergency situation [7]. Individually, the countries do not state specific building codes that concern the solar panels that will be prototyped. As prototyping will begin and continue, contact with Chumbe Island will be upkept to ensure the solar panel energy storage, generation, and distribution system will meet the codes and standards. More information about Tanzanian building codes and standards can be found in Appendix 7.

4.3.5 Preliminary Calculations

The most important preliminary calculations are the power and energy consumptions of the island at peak times over the peak season. From this, the amount of energy needed at a given time, will be the main requirement for the design. Chumbe island currently has batteries that can only deliver energy at a certain rate (Watts), the maximum flow of energy the island has during a course of a day does not provide enough power for expansion of the resort of the island and current peak power times. Water consumption of the island, given by the Desalination Unit will add to the amount of energy required by the island at peak times. These will be added to the preliminary calculation.

The second calculation in need of collecting is the wind and solar environment of the island. This will be used for concept generation for possible solutions to the energy needs of the island and will supplement the current information we have on the energy infrastructure of the island already.

The equations used for the calculations in Appendix 3c are as follows:
$P=IV$, Power is equal to Voltage times Current. Power is measured in watts.
$E=P*t$, Energy is equal to Power times time. Energy in this context is measured in Watt hours.
$V=IR$, Voltage is equal to Current times Resistance. Voltage is measured in Volts, Current is measured in Amps, and Resistance is measured in Ohms.

5 Concept Generation and Selection

Only one method was implemented to begin concept generation. The morphological matrix focuses on concept solutions that have already been created and are available for use via catalogs or patents.

5.1.1 Concept Generation Method 1: Morphological Matrix

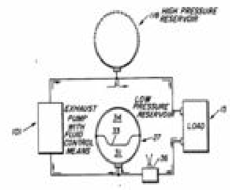
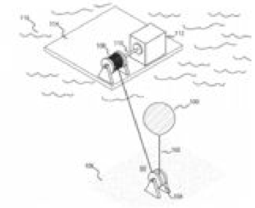
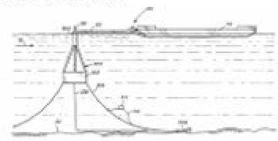
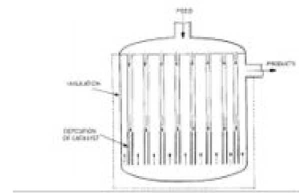
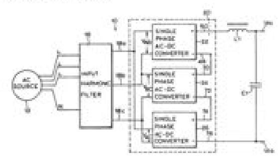
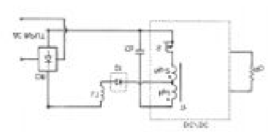
	Catalog 1	Catalog 2	Paten 1	Patent 2
Storage	Long-Life Sealed Large-Cell Battery (2920K1) 	Large-Cell Battery for continuous use (71805k81) 	Hydraulic Energy Storage system 	Buoyancy Energy Storage 
Generation	Solar Panels 	Gas Generator 	Wave power Energy Generation 	Bio-ethanol 
Conversion	AC to DC Motor Speed Control 	Reversing Enclosed AC to DC Motor Speed Control 	Polyphase AC/DC converter 	Single-Stage AC/DC conversion 

Figure 6: Morphological Matrix

The morphological matrix below was created using design catalogs and patent databases to produce multiple potential solution principles for the different functions listed in the matrix. For each function of the design four solutions were found that could be used to solve that function of the design. Two of the four solutions are from design catalogs and the remaining two were sourced from patent databases. This matrix was meant to be a first step in the generation of a concept to a future design. It acted as a jumping off point for the generation of concepts by providing a base knowledge of what systems or equipment currently exist that may be able to be integrated into a future design.

5.2 Concept Evaluation

The criteria used to evaluate the generated concepts include:

- the system's ability to store 17 kW of power
- able to support a peak power of 3.5 kW
- does not cause pollution that could harm the coral
- fits on the 12 X 4 boat
- can be maintained to the extent that Enoch’s knowledge of systems and resources can allow
- how accessible materials for repair would be to the island
- how efficient it is, efficiency being the systems ability to use 50% of the produced energy with minimal losses
- able to fit in a 10’ x 10’ x 10’ space
- how much the system costs
- and its ability to provide power once the sun sets, estimated as 12 hours.

Three methods were used to evaluate the generated concepts. These included a pugh chart, analytic hierarchy process (AHP), and a weighted matrix. The pugh chart rated how desirable a concept was based on criteria that was formed from the requirements of the project such as if it can store the desired amount of power, the difficulty of maintenance, cost, etc. From the pugh chart, a weighted matrix, evaluated storage and power solutions, but gave a weighted value to the importance of each requirement for the island’s power and storage system. An AHP was also created with the concepts narrowed down to lead-acid batteries, flow batteries, super capacitors, and wind turbines. The AHP ranked each concept based on which had the highest score in each criterion.

5.2.1 Concept Evaluation Analysis 1: Pugh Chart

	Stores 17 kW	3.5kw Peak Power	Coral Friendly	Fits on Boat	Maintenance Difficulty	Materials accessibility	efficiencies	size/space	cost	runs 12 hours	total
Current System	0	0	0	0	0	0	0	0	0	0	0
Capstone Batteries	1	1	-1	1	0	-1	1	1	1	1	5
Compressed Air	1	1	-1	-1	-1	-1	1	-1	-1	1	-2
Fuel cell hydrogen energy storage	1	1	1	1	-1	-1	-1	-1	-1	-1	-2
Chemical Storage	1	1	0	1	1	1	1	1	1	1	9
Flywheel	1	1	1	1	-1	-1	1	1	-1	-1	2
Superconducting Magnet	1	1	1	-1	-1	-1	1	-1	-1	-1	-2
Supercapacitors	1	1	-1	-1	-1	-1	1	-1	-1	1	-2
Flow Batteries	1	1	1	1	1	1	1	1	1	1	10

Figure 7: Current Pugh Chart

Used early in the design process the Pugh Chart allowed for concept evaluation to begin. A set criteria based on mandatory requirements were used during the evaluation process. Each of these design requirements were weighted based on necessity. The current concepts were then graded based on fitting the requirements. The Pugh Chart allowed for the evaluation of concepts as a whole, rather than specific subsystems. At the end the grade it was given created an avenue for future research into subsystems to make sure it will still fit the criteria.

5.2.2 Concept Evaluation Analysis 2: Weighted Decision Matrix

		Concepts																	
		Datum		Batteries		Compressed Air		Fuel Cell		Chemical Storage		Superconduction Magnets		Flow Batteries		Super Capacitors			
Criteria	Wgt	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score		
Stores 17Kw	0.1	0	0	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1		
3.5kW Peak Power	0.15	0	0	1	0.15	1	0.15	1	0.15	1	0.15	1	0.15	1	0.15	1	0.15		
Coral Friendly	0.05	0	0	-1	-0.05	-1	-0.05	0	0	0	0	1	0.05	1	0.05	1	0.05		
Fits on Boat	0.15	0	0	-1	-0.15	-1	-0.15	0	0	1	0.15	-1	-0.15	1	0.15	1	0.15		
Maintence Diffcultly	0.1	0	0	0	0	-1	-0.1	1	0.1	1	0.1	-1	-0.1	1	0.1	-1	-0.1		
Material Accessiblity	0.15	0	0	-1	-0.15	-1	-0.15	1	0.15	1	0.15	-1	-0.15	1	0.15	1	0.15		
Effcience						1		1		1		1		1		1	0		
Size/Space	0.1	0	0	1	0.1	-1	-0.1	1	0.1	1	0.1	-1	-0.1	1	0.1	1	0.1		
Cost	0.05	0	0	1	0.05	-1	-0.05	1	0.05	1	0.05	-1	-0.05	1	0.05	-1	-0.05		
Runs 12 Hours	0.15	0	0	1		1	0.15	1	0.15	1	0.15	-1	-0.15	1	0.15	1	0.15		
Total	1		0		0.05		-0.2		0.8		0.95		-0.4		1		0.7		

Figure 8: Weighted Matrix

Each necessary criteria was given a different weight based on necessity of design. This weight will influence the score of the concept. This allowed for the evaluation into specific subsystems of the concept. It visually showed the positive and negative aspects of each individual concept. This method ensured that the concept was not thrown out based solely based on the overall score. The weighted matrix opened up the possibility for different subsystems to be combined to ensure the design meets all necessary requirements.

5.2.3 Concept Evaluation Analysis 3: Analytic Hierarchy Process

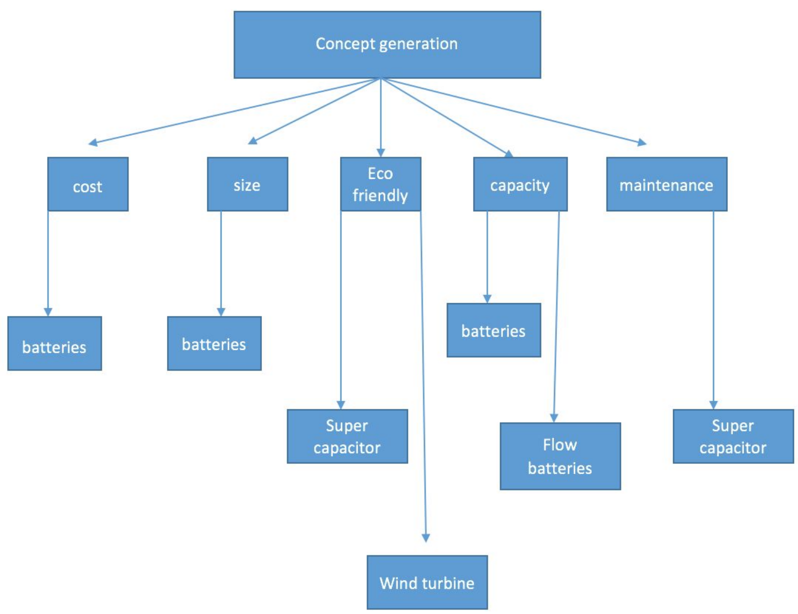


Figure 9: AHP Model

The AHP was made by looking at five specific criteria and seeing which concept rated the highest in that concept. The criteria included cost, size, capacity, maintenance, and how eco-friendly the solution is. The reason these criteria were chosen is because they are considered to be the most important, and contain all of the requirements succinctly. The concepts to be evaluated included lead-acid batteries, super capacitors, flow batteries, and wind turbines. The reason that only four concepts were being evaluated with this analysis is because these were the concepts that have been narrowed down from the previous evaluation methods. The analysis shows that lead-acid batteries have the most compact size and are the least inexpensive. Lead-acid batteries also tied with flow batteries as being capable have holding the highest capacity. The most eco-friendly options were super capacitors and wind turbines, and the easiest to maintain was a super capacitor.

5.3 Concept Selection and Iteration

In continuation after concept generation phase the team moved into concept evaluation phase. Many evaluation methods were used such as a pugh chart, decision matrix, TRIZ, and the analytic hierarchy process. All of these evaluation techniques showed that a flow battery is the best solution. A flow battery can not only meet the demands of chumbe islands energy needs, but also supports chumbes eco-friendly initiative. After completing each of the evaluation methods, the team started to create mathematical models to see if a flow battery was feasible to put on Chumbe Island. The team modeled tank size, concentration ratios, and voltage vs temperature. The models proved that a vanadium flow battery was feasible and the team should move forward with the flow battery as the final solution.

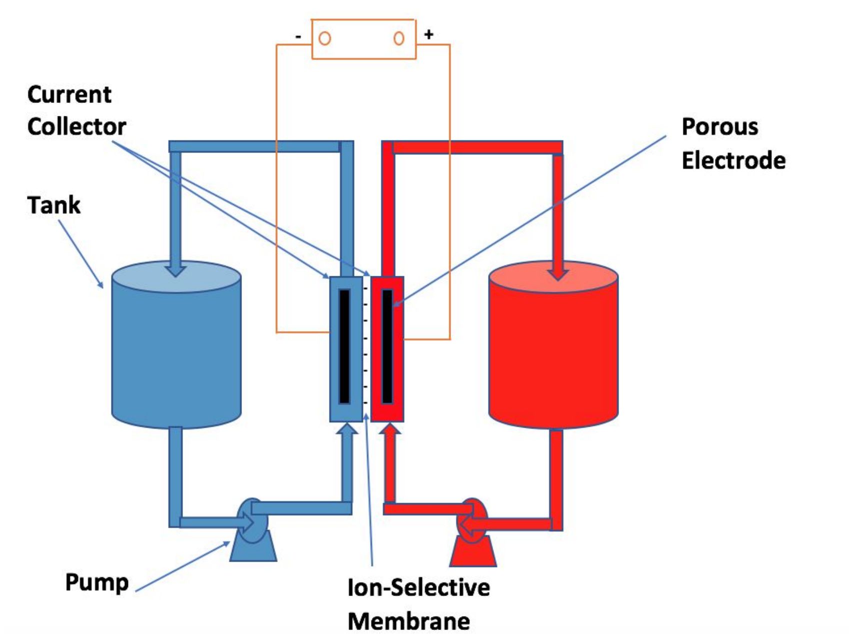


Figure 10: Flow Battery

Based on the evaluation of the storage designs about the following was selected to be created as a prototype for Chumbe island. Many of the concepted generated are rejected from the analytical hierarchical process based on feasibility, size, and maintenance. For example the hydro turbine generator cycle is not feasible since approximately 200,000 gallons of water needed to hold 150ft in the air. Since the island doesn't have any elevation the size is not possible. After that the weight matrix and pugh chart dialed in the remaining choices. From which we saw that the flow battery came out on top. The weight matrix showed that the Flow Battery would fit the island requirements and constraints the best with a score of one. The wind turbine is another change from our initial concept aimed to count into account the limitation of the storage systems available. The pugh chart and weighted matrix show that the only storage devices that will meet all the requirements are at their essence a type of battery. Therefore the wind turbine will supplement the storage subsystem which will lead to the lessening use of batteries which is the main pain point of our clients. Secondly the turbine is not adding to the deterioration of the coral and is following Chumbe island eco-friendly initiative.

There are two seperate iterations for the vanadium flow battery. The first iteration for the flow battery cells were to have them placed next to each other. However, after doing some research, the team concluded that stacking the cells would make more sense. This allows the flow battery to take up less space. A vanadium flow battery will provide for all of Chumbe’s energy needs, reduce the amount of waste on the island, and provide the guest with reliable power.

6 Vanadium Flow Battery and Optimal Solution

The optimal, or long-term, solution for Chumbe Island’s energy needs came to be a Vanadium Flow Battery as mentioned above. The Vanadium Flow Battery, also known as a Vanadium Redox Flow Battery (VRFB), is a liquid-based battery in which the negative and positive species do not interact directly but instead interact via two half-cells separated by a proton-exchange membrane. This solution was chosen because redox flow batteries can be very flexible in the way that they are designed, meaning that the redox flow battery for Chumbe Island could be designed to work around the challenges faced with Chumbe’s requirements.

7 Chemistry Team

The Chemistry team was tasked with designing the electrochemical characteristics of the battery to meet the needs of the Island. To do so it was necessary to first understand how the chemistry worked for a Flow Battery. The battery works by flowing a negative electrolyte solution through one half cell and a positive electrolyte solution through the other half cell; the half cells are separated by a proton-exchange membrane. During the charging of the battery, the negative electrolyte is reduced to a more negative state and the positive electrolyte is oxidized to a more positive state. This difference in charge is where the chemical energy is stored, and when the battery is discharged the negative electrolyte is oxidized and the positive electrolyte is reduced back to their original states while supplying electrical energy to the load. A typical redox flow battery cell’s voltage is around 1.2V, and so for the battery to operate at more standard voltages like 12V, multiple cells will be arranged together to get the desired output voltage and its corresponding power. This arrangement of cells is called the stack.

Vanadium was chosen to be the working species in the battery because of Vanadium’s unique attribute of having (at least) four stable oxidation states. This means that Vanadium can be both the positive and negative sides of the redox flow battery and act as its own redox pair. Using Vanadium will contribute to the battery lasting longer than most because contamination across the membrane from one half cell to the other will have less of an effect. This also makes mitigation and risk prevention easier because the focus is only on the possible effects of one element rather than two or more.

8 Cell Team

The Cell team was responsible for the creation of the cell and pumping system for the VRFB. This team designed the cell where the reactions take place for the VRFB and sized the pumps of the VRFB. The cell of the VRFB is the housing that allows the system to act as an energy storage and distribution system.

The battery creates the current from the dual equilibrium equations. This dual reaction takes place within the cell. A proton from one side of the cell is pushed across the nafion 115 membrane which in turns pushes an electron through the load. Design decisions were made to have as much reaction in the cell as possible. Therefore a serpentine channel through the electrode was chosen for its performance from the lineralality of the flow of electrolyte and membrane contact. The electrolyte material is the driving force for the material choices for the VRFB Cell. The endplates are made out of UHMW plastic since the solute of the electrolyte is sulfuric acid and the material also can not conduct electricity. The electrodes of the VRFB are made out of graphite for economical reasons and can resist the corrosivity of the sulfuric acid.

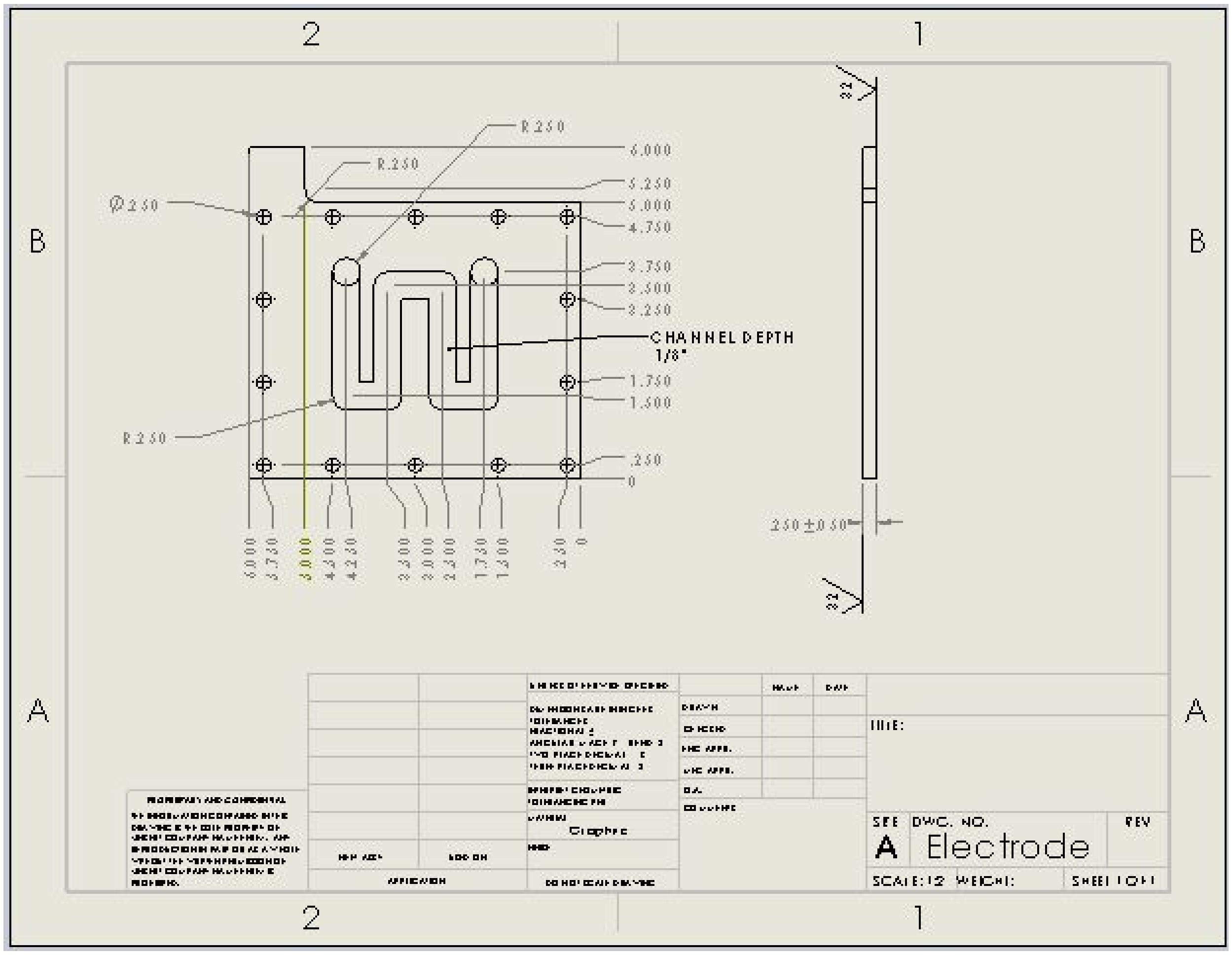


Figure 11: Electrode Plate

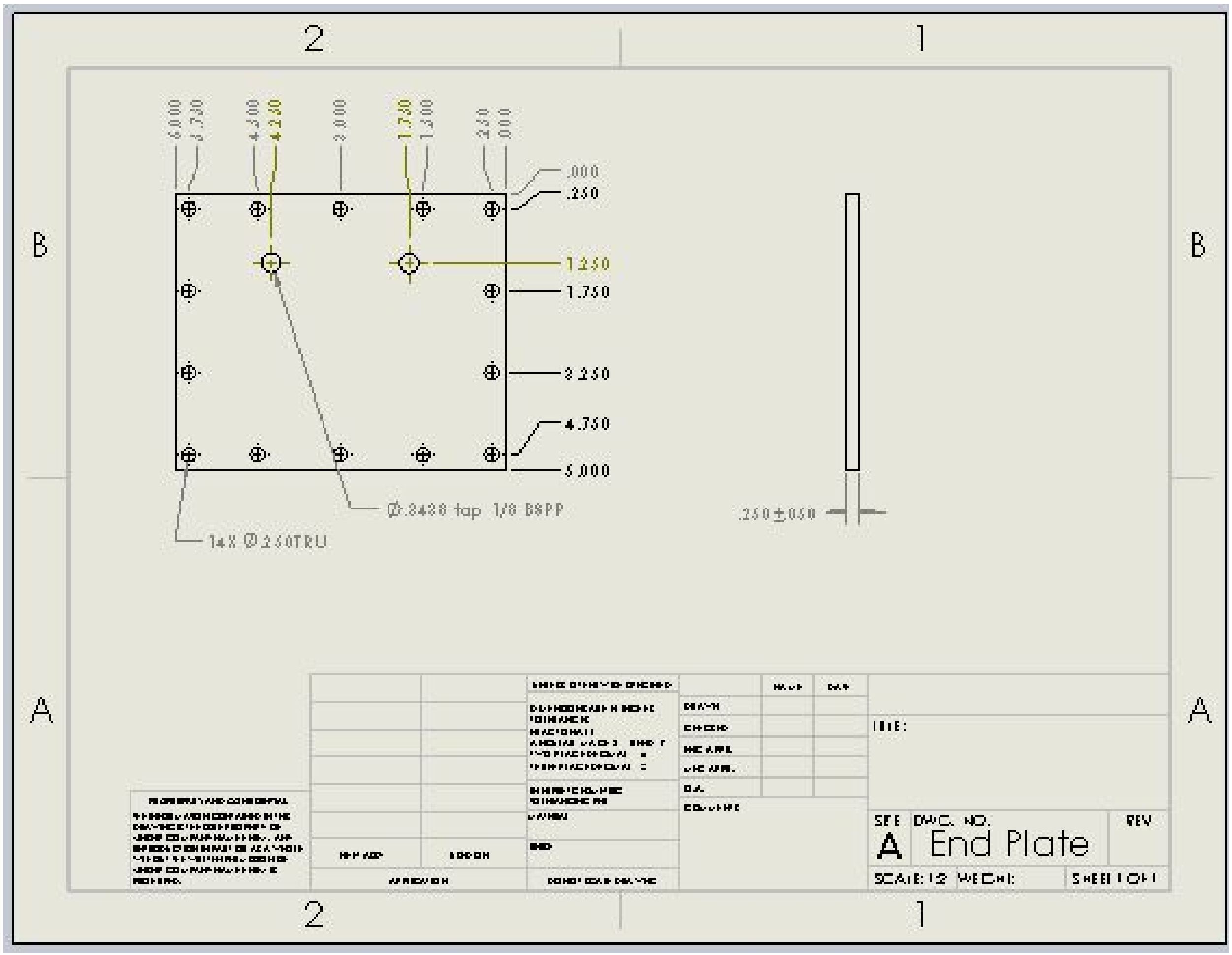


Figure 12: End Plate

9 Controls Team

The controls subteam was responsible for redesigning the system that already exists on Chumbe Island. Upon analyzing the system, the subteam determined that the system components would need to be resized to be able to accommodate the island's energy needs. The subteam separated the system into subsystems to analyze each piece. The team first calculated how much energy the solar panels are producing, how much energy the existing batteries store, and the rates of which the inverter and charge controllers can convert and distribute energy.

9.1 Solar Panels

Chumbe Island currently has enough solar panels for the system to power the entire island, the main issue with the system comes in the other components that unfortunately dissipate a lot of needed power. Since the system needs 15,000 Watt-hours, the island has to use every panel they own to generate the amount of power. They currently have:

- 9 large solar panels
  - Max Power: 200 Watts
  - Max Voltage: 18 Volts
  - Max Amps: 11.11 Amps
- 9 medium solar panels
  - Max Power: 75 Watts
  - Max Voltage: 17 Volts
  - Max Amps: 4.4 Amps
- 15 small solar panels
  - Max Power: 53 Watts
  - Max Voltage: 17.4 Volts
  - Max Amps: 5 Amps

For the needed amount of energy to be produced, the panels must all be wired in parallel so the voltage will match the battery bank (12Volts). This system can produce 24,525 Watt-hours.

9.2 Batteries

To maximize the batteries' life cycle, the batteries should only be discharged by 63%. By doing this, the batteries' life cycle will double from an average life span of two years to nearly five years. To achieve this goal, Chumbe must have a total of ten 12 volt batteries to store enough energy to allow a 63% discharge. Chumbe already has eight batteries in the bank, they would need two additional batteries to achieve this goal.

9.3 Charge controller

The charge controller is a key component to the system, as it regulated the energy going into the system for use. The team does not have enough information from Chumbe to determine what time of charge controller they currently have so an analysis was performed to first size the controllers and then determine whether a PWM, pulse width modulation, or MPPT, maximum power point tracker controller should be implemented.

PWM	MPPT
Small scale (<=150 W)	Large scale (>= 150W)
Directly connected to solar array and battery bank	
Needs to match battery voltage	Can be higher than batteries voltage
Best when battery is full	Best when battery is low
Warm weather	Cloudy weather
Less expensive	More expensive
Not much room for expansion	Better expansion capabilities
Interferes with audio equipment	

An ideal controller for this system would be one 350 amp MPPT charge controller wired in parallel to the system. The size of the controller was calculated by:

$$Amps\ required\ =\ (Watts\ produced * number\ of\ panels) \div Voltage\ of\ the\ bank$$

To ensure the controller was sized large enough, a recommended 25% safety factor was included in the calculations to achieve the 350 amps.

9.4 Inverter

The inverter is another critical piece that is needed to convert the DC current exiting the charge controller to the AC current the appliances need. The inverter in the existing system is large enough to accommodate the island's needs.

10 Deliverables

The team will be delivering a control solution to Chumbe Island. This system rearranges their current set up. This will minimize Chumbe's power struggles until the vanadium flow battery can be implemented. In order to implement the battery the capstone team is handing the project down to a future team. To continue the progression of the design process, a future capstone team will have an opportunity to focus on the energy storage issue with a long term goal so implement the desalination system. These two solutions combined will give the island an opportunity to solve both issues while opening the door to expand their conservation efforts on the island.

11 Testing

Testing the Vanadium Flow Battery was necessary to determine the validity of the battery as a solution. Unfortunately, due to the COVID-19 outbreak we were unable to complete testing of the cell. Three tests with testing plans were prepared to test important characteristics of the battery's performance.

State of charge Test: Testing for the state of charge of the battery was a very important test because the results would be used to determine the battery's lifetime. The reason that the Vanadium Flow Battery was selected as the optimal solution was because of its unusually long lifespan compared to other batteries. The state of charge test would be performed by using a Coulomb Counting method in which the battery discharge voltage is measured for a complete discharge of the battery and the recorded data is integrated over time to give the number of coulombs exchanged during the time it took to discharge. This test would be run a minimum of 20 times and the results of each trial would be compared to yield a decrease of State of Charge for the battery per cycle which could be used to calculate battery lifetime.

Voltage, Current, and Power Efficiency: Testing for voltage, current and power efficiencies are important to determine how well the battery will perform. These tests are simple and can be performed at the same time. The battery will be charged for 10 minutes and discharged across a known load for 10 minutes. The voltage across the battery will be recorded and the current output of the battery will be recorded by measuring voltage across a shunt resistor. The battery power will be calculated using the current and voltage values. The efficiencies are calculated for voltage, current, and power by dividing the discharge value by the charge value.

References

Appendix

Appendix A: Prototype and Full scale Flow Battery Electrochemical Parameters

For Prototype:
(All specifications are for a single cell)

Electrolyte:
- Concentration VCl_3: 1.3M
- Concentration $VOSO_4$: 1.3M
- Concentration H_2SO_4: 3M
- Concentration Hydrogen: 1.3M
- Follow procedure to create solutions

Flow Rate and tanks:
- Optimal flow rate: 41.72 mL/min
- Tank volume: 0.1 L

Voltage:
- Cell voltage: 1.273 V
- Ch. Voltage: 0.850 V
- Dis. Voltage: 1.697 V
- Cathodic overpotential: -1.785 V
- Anodic overpotential: 0.744 V
- State of charge held between 80-20%

Current Density:
- Limiting current density: ~100 mA/cm^2
- Cell Resistance: 0.0213 **Ω**

Cell Specifications (per cell):
- Electrode Area: 33.548 cm^2
- Channel Volume: 45.88 mL

Energy and power:
- Energy density: 29.57 Wh/L
- Max energy: 2.96 Wh
- Power density: 0.1697 W/cm^2
- Max Power: 5.69 W

For Full-Scale:
(all specifications are for a single cell)

Electrolyte:

- Concentration VCl_3: 1.3M
- Concentration $VOSO_4$: 1.3M
- Concentration H_2SO_4: 3M
- Concentration Hydrogen: 1.3M
- Follow procedure to create solutions

Flow Rate and tanks:

- Optimal flow rate: 361.077 mL/min
- Tank volume: 58 L

Voltage:

- Cell voltage: 1.273 V
- Ch. Voltage: 0.850 V
- Dis. Voltage: 1.697 V
- Cathodic overpotential: -1.785 V
- Anodic overpotential: 0.744 V
- State of charge held between 80-20%

Current Density:

- Limiting current density: ~100 mA/cm^2
- Cell Resistance: 0.0213 **Ω**

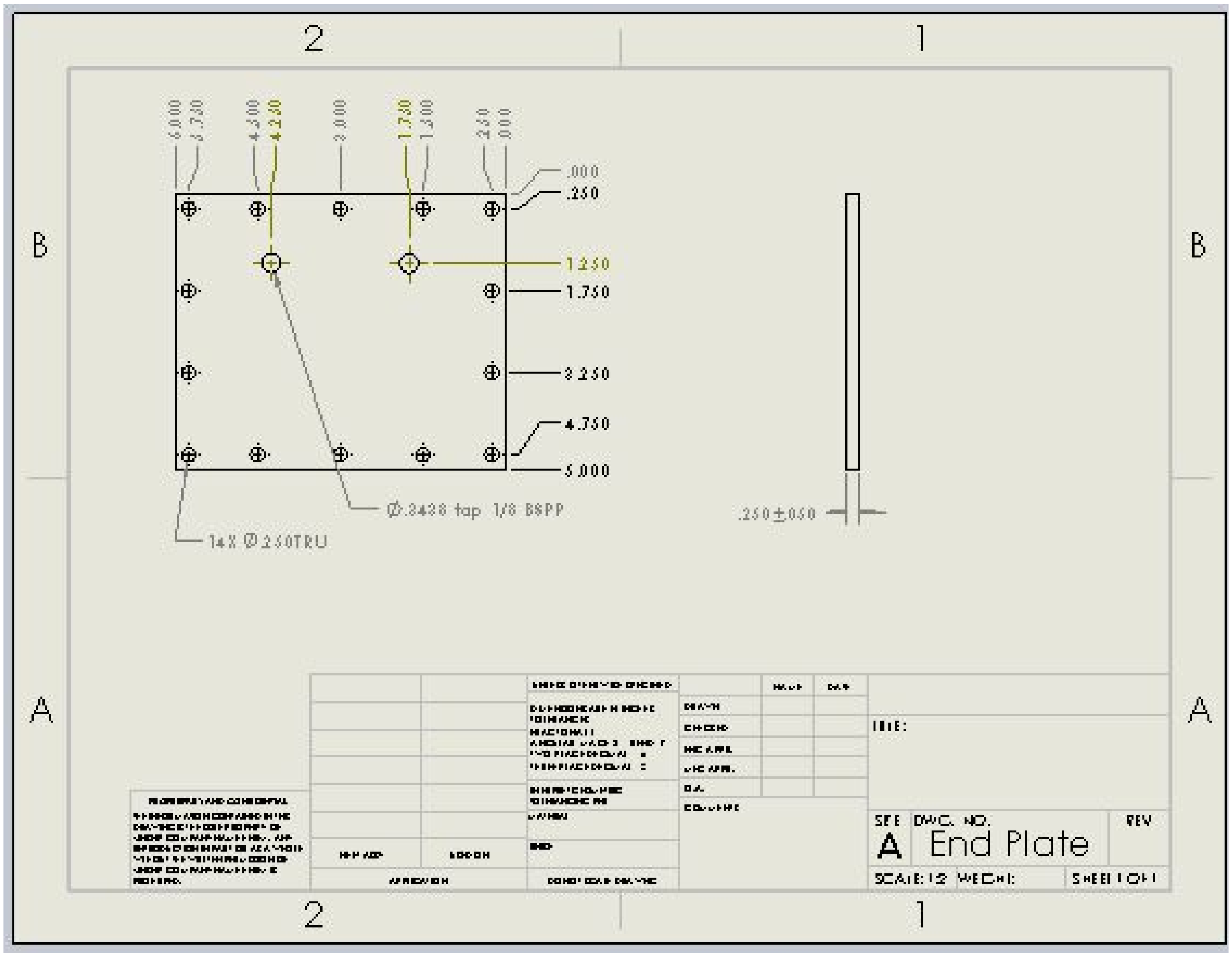
Cell Specifications:

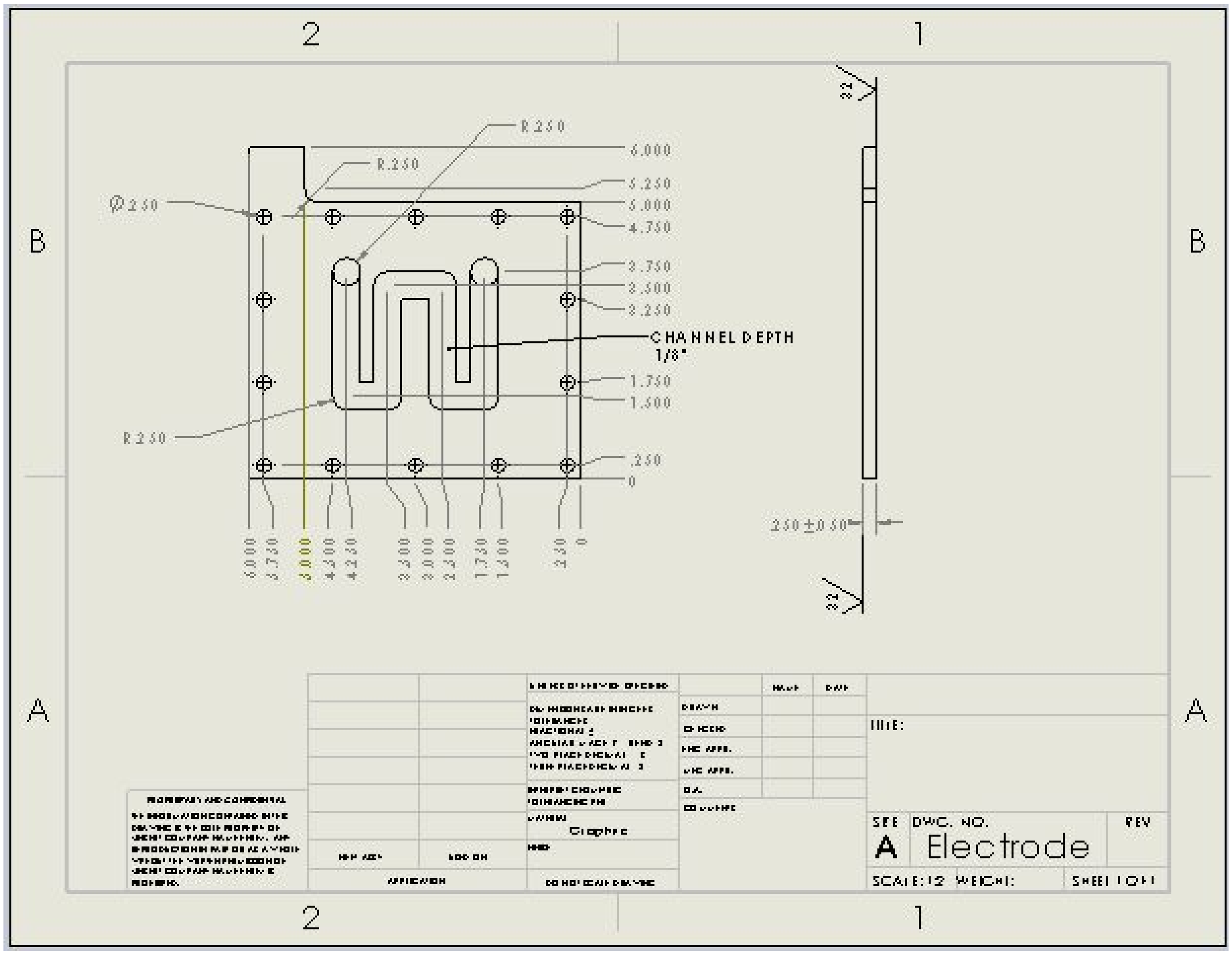
- Electrode Area: 2090.32 cm^2

Energy and power:

- Energy density: 29.57 Wh/L
- Max energy: 17000 Wh
- Power density: 0.1697 W/cm^2
- Max Power: 354.91 W

Appendix B: Engineering Drawings of Cell





R.250
6.000
5.250
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CHANNEL DEPTH
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Electrode
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SHEET 1 OF 1