Oregon State University

Semi-Intensive Aeration System Design for Rural Tilapia Ponds

Final Report

LEAF

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BEE 470 Senior Design II
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Executive Summary

Background

Aquaculture is a common farming practice in the rural subtropics that provides a sustainable source of food and income for farmers. Like all farming business, efficiency is a critical constraint, but it also serves as an opportunity to improve the livelihoods of the business owners through increased yields and minimizing of costs. Recently, engineering design has been applied to aquaculture systems in the form of aeration. Aeration is necessary for growing dense stocks of healthy, salable fish. The application of engineering principles seeks to provide dissolved oxygen (DO) to ponds to decrease mortality, to increase fish size, and/or to increase fish loading rates through cost-effective engineering system design.

Purpose

A semi-intensive aeration system was designed with the purpose of providing sufficient levels of DO to a Tilapia pond in the rural tropics or subtropics. The system is designed to be safe, reliable, and efficient, and to meet the quality standards of the client while minimizing cost so that the system pays for itself as quickly as possible.

Selected Design

A solar-powered diffuser aeration design was selected based on available technology and site considerations. The selected design harnesses the high levels of solar irradiance during the day, with a 300 watt solar panel, to charge three AGM (absorbed glass mat) wet lead acid batteries, totaling 212 amp hours. The batteries store the electricity for use during the early morning (2-6 am), where DO reaches its lowest levels. During this time, an Arduino automatically turns on the aeration system and two diaphragm compressors pump air (each running at 8 pounds per square inch and 50 liters per minute) through two pairs of 9 inch EPDM (ethylene propylene diene monomer (rubber)) fine pore membrane diffusers at the bottom of the pond. Pond aeration is achieved through diffusion across the bubble-water interface. The system is nearly maintenance free but easily accessible for infrequent cleaning and repairs.

Significance

This system provides a critical advantage to Tilapia growers. The opportunity to safely increase fish loading rates and fish growth before sale means a higher yearly income and even more opportunity to make business improvements. Full-scale implementation of this design requires significant initial capital expense (~$1000), but will be profitable in nearly every situation (internal rate of return (IRR) = 55%). The design described in the following report possesses real potential to improve the lives of Tilapia farmers in the rural subtropics and tropics of Africa.

1. Introduction

In the Fall of 2015, Hillary Egna of the AquaFish Innovation Lab requested the work of Oregon State's Ecological Engineering 4th-year Undergraduates to develop an aquaculture aeration system capable of providing dissolved oxygen (DO) levels to tilapia ponds for a specific fish loading rate. The system was developed to serve rural tropical and subtropical aquaculture operations which lack access to municipal electricity, have limited access to goods (e.g. replacement parts), and have limited financial resources. Additionally, it is assumed that pond operators possess no technical knowledge of aeration systems. Given the constraints, the system was developed to be efficient, inexpensive, and durable to provide a reliable and sufficient supply of DO which allows for greater fish yields. The system presents an enhancement of revenue large enough to pay for itself quickly and possesses a positive net present value.

2. Problem Statement

The project goal was to design and build an aeration system that keeps dissolved oxygen in a tilapia pond above 3.5 parts per million. The system is designed for a 450 square meter pond, with a depth of 1-2 meters, located in the tropics or subtropics. The system is designed to increase the pond's capacity for fish stocking by 1 fish per square meter. It is assumed the pond has algae concentrations around 0.4-0.5 grams per liter in the top 30 centimeters of the pond, and that the pond is unlined. The system is designed to not surpass the maximum budget of $1000. The design also considers social and climatic factors such as noise level, ease of use, theft, regulations, and environmental impact.

3. System Overview

The solar aeration system consists of five major components: a photovoltaic solar panel, a charge controller, two batteries, two air pumps, an Arduino microcontroller with a datalogging shield, and four diffusers. The flow of energy through the system is demonstrated by Figure 1. Solar insolation introduces energy to the system which is captured by the photovoltaic cells and converted to DC electricity. This electricity passes through the charge controller which regulates current and voltage. The charge controller outputs this current to the battery for storage and to the microcontroller for power. The microcontroller regulates the on/off cycle of the pumps through a relay switch. During periods of aeration, the batteries deliver electricity to the air pumps, which convert electrical energy into kinetic energy to push air through to the aerators located beneath a water surface. The aerators separate a continuous air flow into many very small bubbles by passing the pressurized air through small pores. These small air bubbles transfer dissolved oxygen from the air to the water through the spherical air-water interface during their ascension to the water surface.

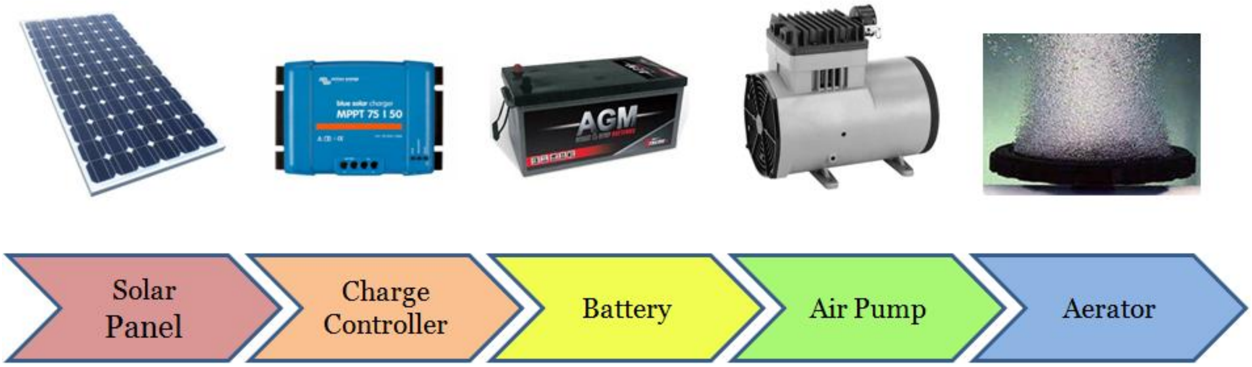


Figure 1: Unit components in series of the solar-powered aeration system.

4. Design Process

The key steps to reach the final design were technology selection, system modeling, sizing, and product selection. Each component of the system had several available technologies that could be used. Each component had different considerations when selecting the best technology. Many current technologies were assessed qualitatively for major flaws, such as incompatibility with the proposed system, or very high costs. Once the number of technologies was reduced, a quantitative assessment was performed. The specific qualitative assessment process varied by component. Batteries and aerators were qualitatively narrowed to two or three technologies, respectively, and then a decision matrix was used to determine the best technology for this system. Selection of pump technology also involved a decision matrix. However, the pressure and flow rate requirements dominated the technology selection. Charge controller and solar panel selection was based solely on the most cost effective technology, and no decision matrix was used. The differences in panel technologies were unimportant for this system, and the only criteria considered for solar panels was the cost per watt.

Modeling was completed to determine the required mass of oxygen released by the system to achieve the desired DO levels in the pond. This process was completed using the system constraints (problem statement), data from ponds in Ghana, and values from the literature. The model output was used to calculate the sizes of the system components. The chosen technologies and their sizes were used to shop for the system parts in order to compile a parts list and a system budget.

5. Charge Controller Overview

There are several different charge controller technologies currently available, but they are all of two major categories: maximum power point tracking (MPPT) and non-MPPT controllers. The differences between these two categories are cost and efficiency. MPPT controllers have efficiencies between 93-98%, meaning 3-7% of the power generated from the solar panel is lost before reaching the battery [32]. MPPT controllers cost upwards of $50, with many in the $200-300 range. Non-MPPT controllers have efficiencies between 40-80%, meaning 20-60% of the power generated from the solar panel is lost before reaching the battery [32]. Non-MPPT controllers cost upwards of $10, but can reach up to $50-70 range for higher amp controllers. The choice of charge controller will depend on the size of the system. At low wattages, a cheap, inefficient controller may be more cost effective because it could be cheaper to buy a larger panel to compensate for the inefficiency than to buy a more efficient, but more expensive controller.

6. Battery Overview

There are currently three major battery chemistries, which are nickel, lithium, and lead acid. Each of these chemistries has multiple types of batteries within them, where the different types within a chemistry all share similar characteristics. Nickel chemistries require complete discharge under regular intervals, which is not something that will be achieved in the proposed system. For this reason they were not considered in this design. Lithium batteries are very expensive, and they were not considered for this reason. Lead acid batteries are broken into starting and deep cycle applications. Our system will be a deep cycle application, so lead acid deep cycle batteries were considered.

6.1 Wet Lead Acid Deep Cycle

Social Considerations

Wet lead acid batteries are heavy, weighing around 60lb for a 12V, 100Ah battery. This makes them difficult to manually transport, which will decrease ease of use, but probably won’t deter theft. The requirement for regular maintenance decreases the ease of use for these batteries. Wet lead acid deep cycle batteries are very common, and would likely be found in cities with stores that sell large batteries. The time to receive a new battery would be much quicker than Li-ion, but could still be greater than a day depending on location. Some countries have regulations that do not allow the shipping of wet lead acid batteries. They usually have to be shipped by a store or distributor, which can increase the time it takes to receive a replacement battery. Lead acid batteries are easy to recycle, and recycling is typically available, but this will depend on location.

Economic Considerations

Wet lead acid deep cycles start around $140 for 12V, 100Ah. In this application, the expected cycle life would be 2000-3300 cycles [43]. This would give 5-9 years of operation in the proposed system. Regular maintenance would be required to maintain the water level in the cells. This would mean checking the cells at least monthly, and possibly more often in the hottest months, and filling with deionized (DI) water. There would be a cost associated with the DI water, and potentially with paying someone to check the battery. Without appropriate maintenance, the lifespan of the battery would drop significantly.

Environmental Considerations

Wet lead acid batteries have environmental impacts in potentially every stage of their life. The manufacture of these batteries requires the mining of ore, which has negative environmental impacts. During the use of wet lead acid batteries, it is possible to spill acid, which can enter the environment and cause problems. The disposal of these batteries can also have environmental impacts. If recycled properly, the environmental impacts of disposal can be reduced.

6.2 AGM Lead Acid Deep Cycle

Social Considerations

AGM lead acid batteries are the same weight as wet lead acid batteries, also weighing around 60lb for a 12V, 100Ah battery. They will have the same decreased ease of use without deterring theft. The lack of a need for maintenance improves the ease of use for these batteries. AGM lead acid batteries are not as common as wet lead acid batteries, and will be more difficult to acquire for that reason. AGM batteries do not share the same shipping restrictions as wet lead acid batteries, which will potentially decreased shipping time. AGM lead acid batteries can be recycled the same as a wet lead acid battery.

Economic Considerations

AGM lead acid deep cycle batteries start around $200 for 12V, 100Ah. In this application, the expected cycle life would be 1000-2000 cycles [43]. This would give 3-5 years of operation in the proposed system. No maintenance would be required for an AGM battery.

Environmental Considerations

AGM lead acid batteries have environmental impacts from their manufacture and disposal, which are identical to the impacts of wet lead acid batteries. AGM batteries lack any environmental impacts during their use because they can never spill acid, even if broken open.

6.3 Battery Overview Conclusion

While wet lead acid deep cycle and AGM lead acid deep cycle are both plausible alternatives for the proposed system, they each have distinct advantages and disadvantages. Wet lead acid deep cycle batteries are less expensive, the most readily available option, and have a good lifespan, but they require regular maintenance. AGM lead acid deep cycle batteries are maintenance free, but they can be more difficult to acquire than wet lead acid batteries, and are more expensive.

7. Pump Overview

Three categories of pumps were originally selected specifically for their feasibility for the system site. These are diaphragm, centrifugal, and rocking piston pumps. These technologies met basic criteria for consideration and were assessed according to parameters outlined by the pump decision matrix [44, 16, 23, 25]. Upon further use of system modeling, however, further design specification requirements revealed constraints that ended the pump technology selection process. Of the three pump technologies considered, diaphragm pumps were the only available technology that met the requirements for flow rate and pressure.

7.1 Diaphragm Pumps

Diaphragm pumps are positive displacement compressors characterized by a moving cavity (or diaphragm) which is continuously expanded and contracted, typically by an oscillating arm (for larger pumps) or by compressed air (smaller). The intake and exit valves are check (non-return) valves. The result is that the diaphragm expansion sucks air into the cavity and the contraction pushes the air out the exit valve. The mechanical system is displayed in Figure 2. They are used for relatively low power systems of less than 200 W and less than 50 V [16]. On an individual basis, this pump technology is limited in by the maximum flow rate capacity. Most diaphragm pumps do not have the capacity to meet the system needs of >100 LPM minimum flow rate. This contributed to the decision to include two pumps working in parallel, which will be explained in further sections.

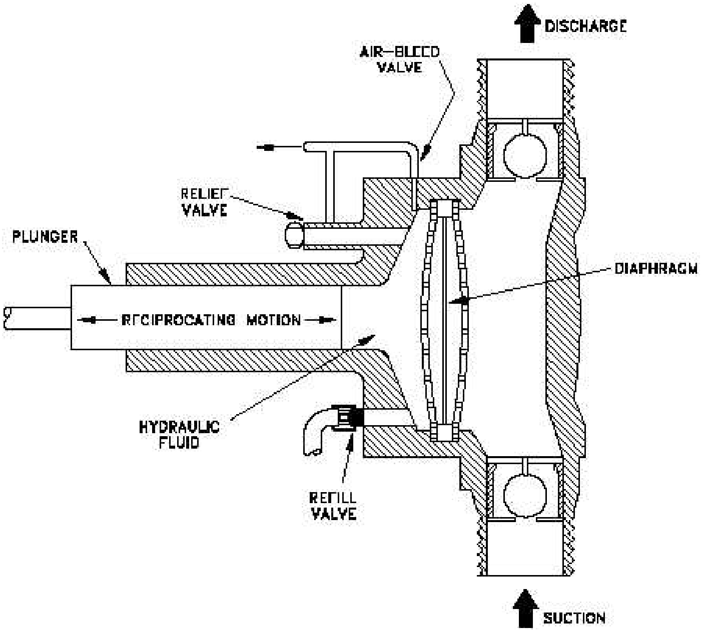


Figure 2: Diaphragm pump diagram [21].

Social Considerations

These pumps are incredibly versatile, which makes them suitable for many conditions, and cleaning and maintenance is seldom required. The diaphragm design avoids small channels for the fluid to pass through. This means the pump operates well in sludge, high viscous fluids, and high solids content fluids, making it more likely to resist fouling during dusty and windy conditions [16]. The design is also flexible to different loads of acids or abrasive chemicals because diaphragm pumps can be made of many different materials [16]. Diaphragm pumps also offer low levels of Electromagnetic Interference (EMI) and low levels of Radio Frequency Interference (RFI). These pumps are simple to operate and require minimal maintenance and cleaning. These pumps are highly durable in all material types. They are oil-free, lightweight, and extremely rugged [44].

Economic Considerations

Maintenance for these pumps is minimal during its lifetime, which eliminates operational costs. Diaphragm compressors are a relatively inexpensive technology, though the selected product(s) will likely make up the third largest in the final design cost. For compressors meeting the flow requirements ~6.5 cfm, manufacturer price estimates range from $200 to $300. The pumps found at these flow rates, however, operate at much higher pressures than required. Pumps which operate closer to the system designed pressure requirement of 9 psi typically cost between $90 and $120 but do not meet the necessary flow rate. There is an opportunity to minimize cost by joining pumps in parallel to meet criteria without oversizing due to technology restrictions.

Technical Considerations

These pumps run at low flows compared to the centrifugal blowers, but carry much higher pressure capacities. Diaphragm pumps have been found to reach efficiencies of about 50% [44]. The operational life is highly dependent on the chosen material, with the more durable material carrying lower efficiency. Typical metal diaphragm pumps last up to 10,000 operating hours. Assuming 4 hours/day and 250 days/year for our design use, this equates to 10 years of service-free life [14]. The lifetime of diaphragm pumps is largely influenced by the internal heat of the diaphragms. Higher internal temperatures will lead to faster degradation of the diaphragm material. This heat is generated through the mechanical driving and the compression of air, and is more severe under higher pressures. The expulsion of the compressed is the primary source of heat release, so conditions of high pressure and relatively low flow generate the highest continuous internal temperature. These conditions are not ideal and can be avoided by running higher flows through the pump.

7.2 Pump Conclusion

The attributes discussed above possess weaknesses and strengths in their applications to the client’s needs. These consideration categories contain analysis of the most practical and valuable traits for a pump suited for our conditions. With updated design parameters (pond sizing, loading, efficiencies), the pump technology selection process became much more precise. Ultimately, diaphragm pump technology was selected based on the availability of products which meet minimum pressure and flow rate capacity requirements. Diaphragm air compressors are suitable in this application and are commonly used in aquaculture hydraulic systems [16].

8. Aerator Alternatives

A wide variety of aerator technologies exist and can be classified in general as mechanical (brush, paddlewheel, vertical shaft), jet (e.g. venturi), and bubble diffuser (coarse and fine) [14]. Mechanical aerators tend to have low efficiencies (oxygen transfer and energy expenditure, Table 1), high maintenance requirements, high operational costs, and high noise levels [14]. Because of these very undesirable characteristics, mechanical aerators will not be considered as a design alternative for this aeration project nor any further in this report.

Jet aerators have moderate oxygen transfer efficiencies, low energy efficiencies (Table 1), moderate maintenance requirements, and moderate technical knowledge required for maintenance [13, 14]. Lastly, bubble diffused aerators on average have high oxygen transfer and energy expenditure efficiencies, moderate maintenance requirements, low technical knowledge required for maintenance, low operational costs, and are very common [1, 13, 14, 37]. Taking these factors into consideration, diffusers have been chosen as the technology to pursue in this project and report given their superior efficiencies, maintenance requirements, and costs.

Table 1: Comparison of different aerators technologies using SAE [7].

Aerator Technology	SAE (kg 02/kWh)
Mechanical Aeration	
Low-speed surface aerators	1.82 - 2.13
High-speed surface aerators	1.52 - 1.98
Brush aerators	1.52 - 2.13
Induced surface aerators	0.61 - 0.91
Vertical shaft aerators	1.5 - 1.8
Combination Aeration	
Submerged turbine aerators	0.91 - 1.52
Jet aerators	1.22 - 2.13
Diffused Aeration	
Coarse bubble	
Coarse bubble (individual)	1.22 - 2.13
Coarse bubble (wide grid)	1.52 - 2.13
Coarse bubble aerators (misc.)	1.22 - 2.13
Fine pore	
Ceramic disc/dome (grid)	3.04 - 4.26
Membrane disc/tube (grid)	2.43 - 4.26

9. Diffuser Overview

A wide variety of diffuser material and technologies exist (Figure 3). The most common of which include metal coarse pore, fine pore ceramic, and fine pore membrane (Figure 4). The following is a discussion of the different characteristics of these common diffusers on a social, economic, and technical basis. A further discussion on diffusers can be found in Appendix C and D.

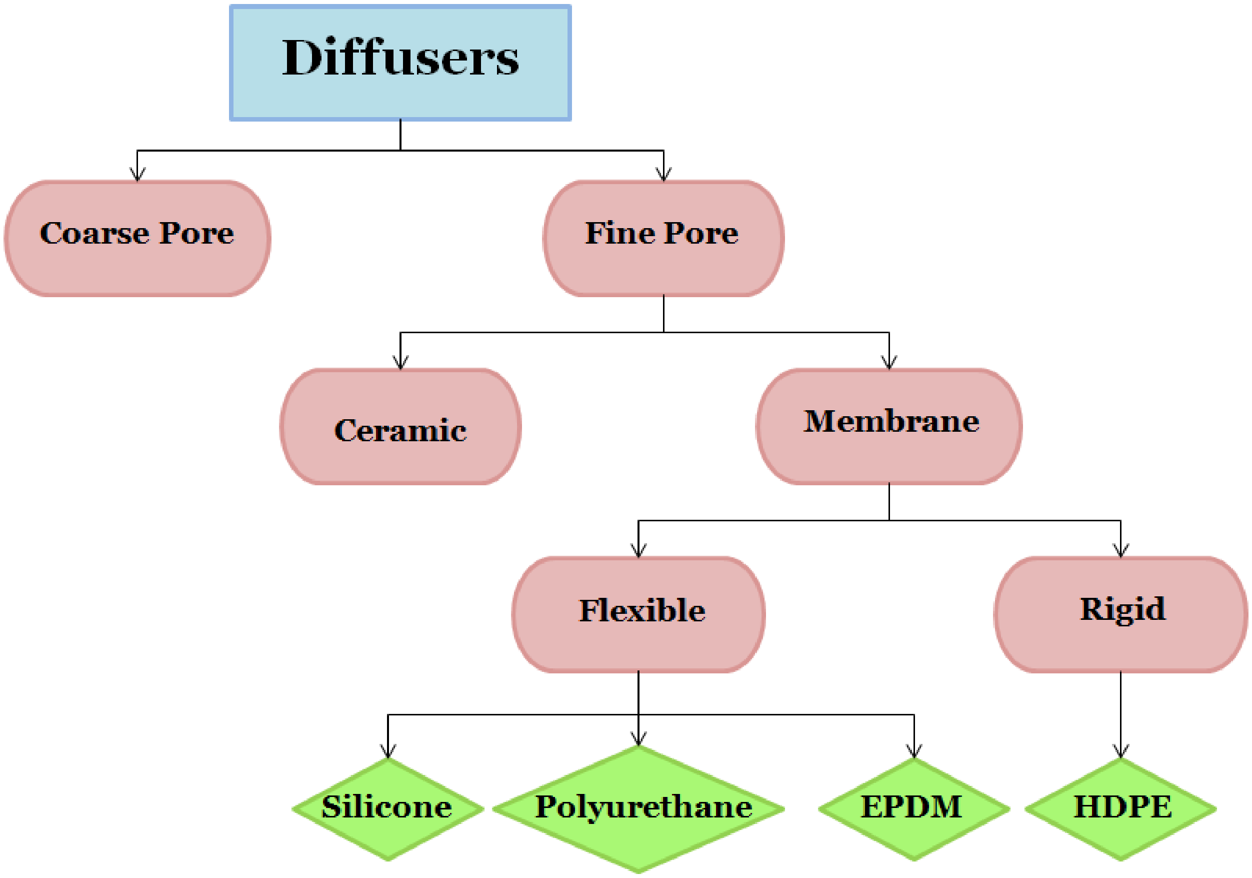


Figure 3: Flowchart showing common types and materials of a variety of diffusers.

Figure 4: Display of the various diffuser technologies considered. Clockwise from top left: ceramic fine pore diffuser (dome), flexible membrane fine pore diffuser (dome), and metal coarse bubble diffuser [15, 37].

9.1 Coarse Pore Diffusers

Coarse pore diffuser technology varies little between different products and in general they have very similar energy consumption rates, efficiencies, and materials/shapes (stainless steel tubes) [13, 21]. Therefore, this technology will largely be discussed in terms of broad advantage and disadvantages.

Disadvantages of Coarse Pore Diffusers

Disadvantages include that coarse pore technology tend to have significantly lower SAE (Table 1), SOTR (by a factor of 6), and SOTE compared to fine pore diffusers [6, 15, 17, 47]. This is attributed to the smaller number of larger bubbles produced, which results in a lower overall bubble surface area and faster bubble ascension (short residence time) which ultimately lowers oxygen diffusion rates [5, 15]. Because of these lower efficiencies, coarse pore diffusers require approximately 30-40% greater airflow than fine-pore technologies which results in greater energy expenditure and greater operational costs [5, 15, 42]. Lastly, coarse pore diffusers are generally more expensive than other diffuser types (~$100 for metal tube) and require more expensive fittings and piping [5].

Advantages of Coarse Pore Diffusers

Coarse pore diffusers are generally simple in design and relatively easy to produce [15]. As such, these technologies are widely available [15]. Additionally, due to the large size of the pores, these diffusers are generally easy to clean, clog less often (and to a lesser extent), and often cause greater degrees of mixing in basins compared to their fine pore counterparts [15, 42, 47]. Lastly, the reasonably consistent SAE data from Table 1 across different coarse pore configurations indicates that diffuser density may not be a factor in achieving maximum efficiency for this technology, which is in contrast to fine-pore diffusers (discussion below).

9.2 Fine Pore Diffusers: Efficiency and Configuration

Fine-pore diffusers are often cited as having very high efficiencies (both SAE and SOTE) when compared to other aeration technologies. However, these efficiencies are typically presented under operating conditions of high diffuser density [17, 18, 24]. From lowest to highest, diffuser density is generally divided on an individual, band (of various configurations), grid, and complete floor coverage basis [18]. The SAE and SOTE generally increase with increasing diffuser density, and it has been stated that a high density of diffusers is required to efficiently deliver oxygen (Table 2) [18, 19].

Individual diffusers have been shown to experience dramatically reduced efficiencies compared to high density systems, even under conditions of comparable ratios of tank area to diffuser coverage [4, 10, 31]. For example, data compiled by Newbry on the efficiency of fine-pore diffusers showed that the SOTE of individual membrane diffusers varied between 5.5 and 13%, whereas those in a grid formation fared much better at ranges between 22.9 and 56.95% [31].

Table 2: Comparison of SOTE between different fine pore diffusers and configurations [20].

Diffuser Type	SOTE Range (%)	Average (%)
Membrane disc (grid)	22.90 - 56.95	39.93
Membrane disc (individual)	5.50 - 13.00	9.25
Membrane tube (grid)	11.92 - 30.00	20.96
Ceramic dome/disc (grid)	22.73 - 35.83	29.28
Ceramic dome/disc (individual)	6.50 - 9.30	7.9

9.3 Ceramic Fine-Pore Diffusers

Social Considerations

Ceramic fine-pore diffusers must be cleaned periodically to reverse head loss increases and subsequent efficiency decreases caused by fouling or clogging (further discussion below). Brushing can clean the surface of these diffusers, however this does little to restore performance losses because fouling still persists throughout the internal portions [27, 28, 29]. These internal portions of are difficult to access due to their rigid and porous nature, and aggressive strong acid (e.g. hydrochloric) bathing is often necessary to sufficiently clean them [29]. Aside from their rigidity, these diffusers are also fragile and can easily break if handled incorrectly. Some ceramic diffusers are partially encased in plastic (particularly domes) which may somewhat mitigate this issue.

Economic Considerations

Important considerations of ceramic diffusers include the capital costs and the costs incurred from fouling. The capital cost of these diffusers varies widely by type/unit, manufacturer, and seller. In general, diffusers that are sold on an individual basis or that are comprised of external components (e.g. a stand or plastic encasement) are more costly (~$25-$150) than those sold wholesale or as the diffuser head alone (~$5-$25) [30]. Additionally, there are operational costs associated with fouling (decreased efficiency) of these units, which is complicated by the aggressive method required to sufficiently clean these diffusers. Significant operational decline and associated costs may occur if strong acids are not available by the operators to thoroughly clean these diffusers.

Technical Considerations

Ceramic diffusers generally have high SAE values compared to most other aeration technologies, and are roughly equivalent to membrane diffusers (Table 1). Additionally, they have fair SOTE values, albeit significantly lower than that of membrane diffusers in both an individual and grid configuration (Table 2). However, these efficiency values can significantly decrease over time due to fouling and ageing (45).

Clogging and biofouling can increase the required system pressure and in turn reduce the diffuser efficiency, increase energy requirements (increased operational costs), and reduce the lifespan [29, 37, 39, 41, 45]. Diffusers composed of rigid materials such as ceramic or HDPE membranes are susceptible to clogging and biofouling because the pores are forever open, which allows for the entry of particulates [29, 30]. This issue generally occurs in systems where the air supply is regularly removed (change in pressure causes a backflow) or where the air supply is removed for an extended period of time (particulates allowed to gradually enter) [19, 27, 47].

The backflow caused by repeated airflow removal can also result in a gradual buildup of inorganic salts (particularly calcium carbonate) which can cause fouling within the unit [19]. Additionally, the rough surface of rigid material diffusers facilitates biological growth which is likely to cause biofouling in either on/off systems or systems of low airflows [19]. Some ceramic diffuser systems include a check valve to prevent backflow in an attempt to mitigate fouling. However, empirical evidence has shown that these systems do little to limit fouling because check valves only prevent backflow into the piping network, not the diffuser itself [29].

9.4 Membrane Fine-Pore Diffusers

Social Considerations

Membrane fine-pore diffusers have characteristics that make them advantageous from a social standpoint, including that they are common, durable, and easy to clean. Membrane diffusers are very common in both municipal and aquaculture settings, and as such are widely available for purchase from manufacturers. For example, in the United States and Europe, membrane diffusers (specifically EPDM) comprise over 70% of the aerators used in aeration basins of wastewater treatment facilities [26, 27]. Additionally, membrane diffusers are resistant to impacts due to the flexible rubber or hard plastic they are composed of. Lastly, these diffusers typically only require scrubbing of the surface or the use of jets of water to clean them [20].

Economic Considerations

Because membrane diffusers are easy to clean and maintain, the primary economic consideration is the capital cost. The capital cost of these units varies depending primarily on the size, the extent of external components, and whether they are purchased individually or wholesale. In general, the capital cost increases with the size, the presence of external components (e.g. a stand), and when bought on an individual basis. Individual diffusers with bases or stands are generally priced in the \$25 to \$50 range [47]. The cost can be significantly decreased if units comprised of simply the head of the diffuser are purchased wholesale. Diffusers of this type can be found in the \$5 to \$20 range [47].

Technical Considerations

The most important consideration for membrane diffusers regarding system efficiency and operational costs is the membrane material. Over time, membranes of any material will experience increases in system pressure (headloss), energy requirement, rigidity, and bubble size with corresponding decreases in SOTE, SOTR and SAE [6, 10, 28] . However, materials have varied tendencies for the short-term clogging and biofouling and long-term ageing that cause such performance issues.

As mentioned previously, rigid diffusers experience serious clogging and biofouling issues, particularly under on/off aeration regimes. Of the membrane diffusers, HDPE is the only one that is rigid and has been shown to experience these issues [26]. Contrary to rigid diffusers, flexible membrane diffusers do not experience significant accelerated rates of clogging and biofouling in on/off systems, nor in low airflow systems. This is because each pore of the flexible membrane material acts as a check valve that closes when the air supply is completely removed (decreased fouling), and the size of the pore openings vary with airflow [20]. If fouling or clogging becomes an issue, flexible membrane diffusers generally only require cleaning of the surface, which is easily achieved by brushing or by using high pressured water or air [16,25, 31]. Aside from the broad categorization of rigid versus flexible, there are many properties of different fine-pore membrane diffusers that warrant attention. A summary of research findings investigating the performance of various membrane materials follows, and a more detailed discussion can be found in Appendix D.

Silicone diffusers have been found to have a low SOTR both in new conditions and after operation, and experience significant increases (up to ~150%) in backpressure (lower SAE) over time [15, 30, 31,]. Polyurethane diffusers have been shown to not experience significant increases in backpressure but have serious material ageing issues the render them inoperable within a few years of operation [15]. EPDM diffusers have been shown to experience increases in backpressure (up to 50% for disc shaped) and corresponding decreases in SOTR (~25%) and SAE within the first year of operation, but tend to remain steady in all parameters thereafter [15]. Additionally, diffusers of all types have been shown to experience different extents of backpressure increases depending on the diffuser shape (Figure 5). In general, tube diffusers were found to have greater pressure increases (particularly silicone) compared to disc diffusers. And, aside from ceramic plate diffusers (which are not being considered), EPDM disc diffusers suffered the lowest increase in pressure when comparing new and used units and they experienced among the lowest pressure drop when new.

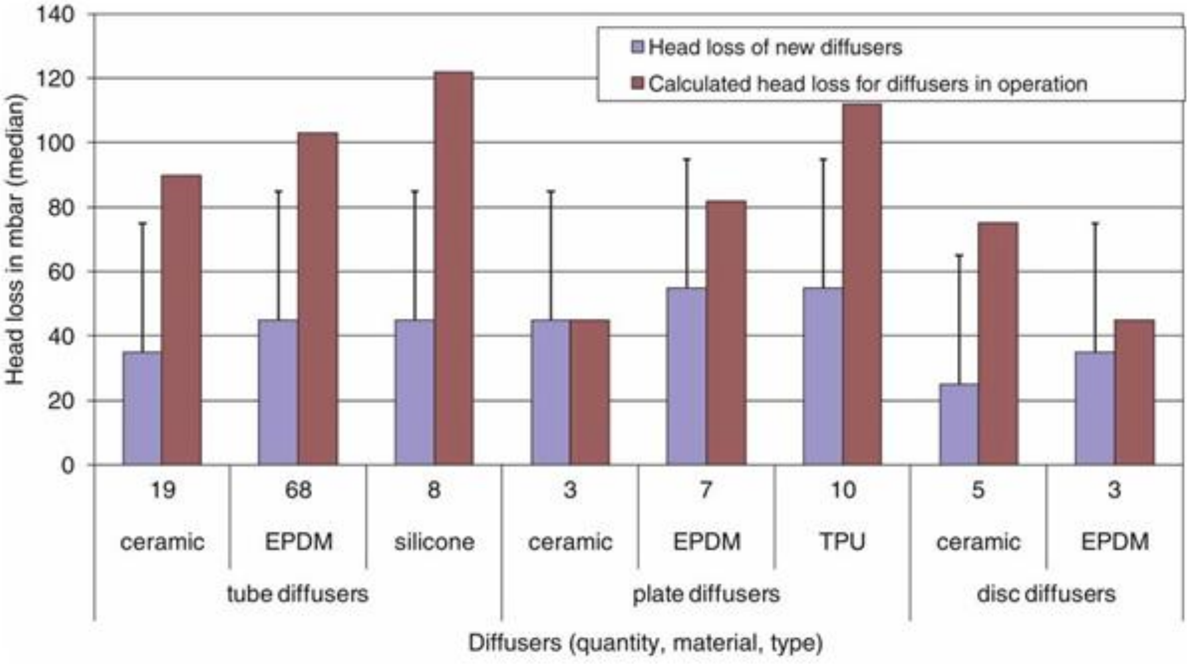


Figure 5: Comparison of new and used fine pore diffusers of differing material and shapes; values below each technology refer to the number for case studies performed [28].

9.5 Diffuser Conclusion

Of all the different types of diffusers, coarse bubble, ceramic fine pore, and EPDM fine pore membrane were considered for use in this project. The following is a summary of the main advantages and disadvantages of each. Coarse bubble tend to have lower efficiency ratings (SOTE and SAE) than fine pore, but there are indications that (unlike fine pore) these efficiency ratings are independent of the diffuser placement density. Additionally, these diffusers tend to be the most expensive of all the diffuser types. The greatest advantage of this technology is that they tend to experience very few issues with fouling or clogging, which results in consistent operation over time.

The primary disadvantages of ceramic fine pore diffusers are due to their rigid nature. This makes them rather fragile, difficult to clean, and introduces clogging and biofouling issues that lower efficiencies, particularly in on/off systems. However, ceramic diffusers generally have the lowest capital costs and, when operating properly, have high SAE and SOTE ratings that are comparable to EPDM membrane diffusers. Of the different types of fine pore membrane diffusers (HDPE, silicone, polyurethane, EPDM), EPDM experience the fewest issues with clogging, ageing, backpressure increases, and efficiency decreases. Additionally, these diffusers tend to have high rates of SAE and SOTE, low instances of clogging and biofouling, are easy to clean, and are reasonably priced (~$25).

10. Technology Selection

The selection of technology for this design was based on comprehensive assessments of qualitative and quantitative features of available alternatives. Maximum Power Point Tracking (MPPT) charge controllers are the optimal charge controller technology due to its efficient conversion of voltage which drastically increases the efficiency of the solar charging system. For Batteries, the AGM Lead Acid Deep Cycle was selected, with low maintenance requirements being a critical advantage. For pump technology, diaphragm technology was selected based on pressure and flow rate requirements. Finally, EPDM fine pore membrane was selected for the diffuser technology, with the primary advantages being high SAE, SOTE, and low risk of fouling. Selection of component technology is listed in Table 3 below.

Table 3: Selected technologies for each of the major system components.

Component	Selected Technology
Charge Controller	MPPT
Battery	AGM Lead Acid Deep Cycle
Pump	Diaphragm
Diffuser	EPDM Fine Pore Membrane

11. System Modeling and Sizing

Basic system modeling was completed using a dissolved oxygen model based on a mathematical model developed by Culberson and Piedrahita in 1996. From modeling, it was estimated that around 500 grams of oxygen needs to be added into the water each daily cycle. The input parameters used in this estimation are listed in Table A1. The model output of 500 grams of oxygen was used to calculate the size of the system components.

System sizing calculations were completed using an excel calculator. The input values were from the modeling process, the problem statement, and literature (Table A2). The calculations started from the mass of oxygen needed, the volume of air needed to add that mass, and the energy needed to displace the volume of water equal to that volume of air (Table A3). From the energy requirements, part sizes were calculated based on efficiencies and upsize values (Table A4). It was calculated that a 200 Ah battery and a 200 W solar panel were needed to power the system, and that the pump needed a pressure around 8 psi and a flow rate around 60 lpm.

12. Product Selection and System Layout

To meet the power needs of the system, two 106 Ah AGM lead acid deep cycle batteries will be paired with a 300 W solar panel and a 300 W, 12 V MPPT charge controller. A 300 W panel will used instead of the required 200 W panel because the cost increase is marginal but the potential benefits are large. This system will supply power to two diaphragm pumps, each running at 8 psi and 50 lpm, and each with its own piping system and pair of 9” EPDM disc diffusers. The rated total flow rate is 100 lpm while the required rate is 60 lpm, this is due to the real output not matching the rated output, which was discovered after scaled testing. The system will include a microcontroller (arduino) that will operate switches controlling each of the two pumps. A schematic of the system is shown in Figure 6; a summary of component specifications is shown in Table 4; and a wiring diagram of the system is shown in Figure 7.

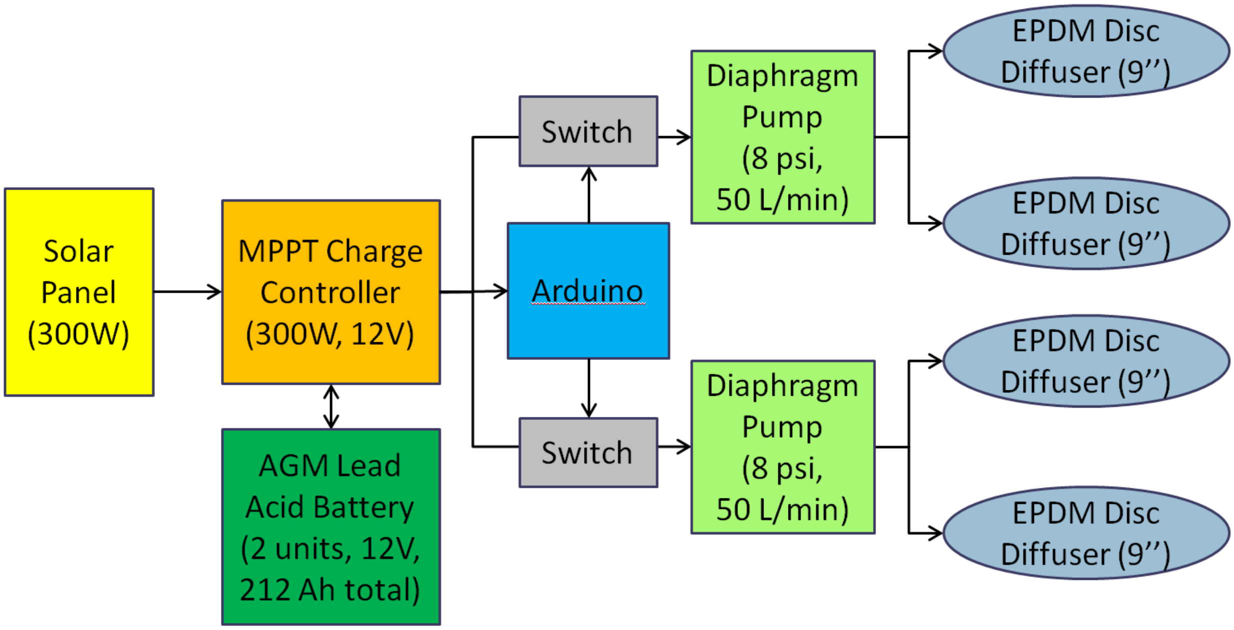


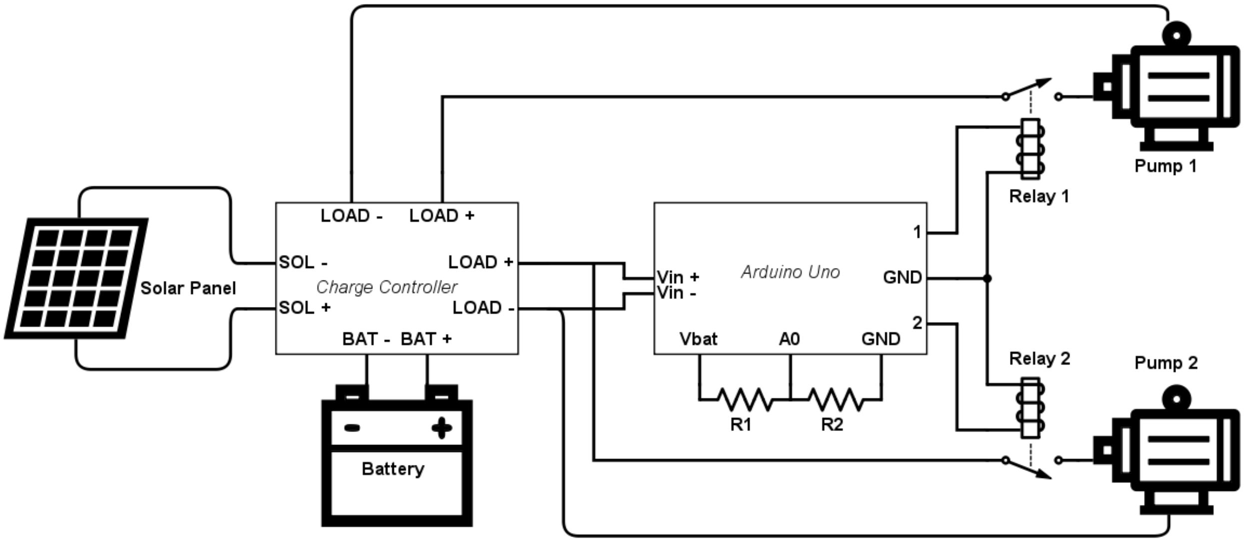
Figure 6: Diagram showing the chosen system configuration and component specifications. The diffusers are in the pond, and all other components are on shore near the pond. The connections

between the pumps and the diffusers are ⅜” weighted air tubing, all other connections shown are 8 gauge wire.

Table 4: Summary of component specifications.

Item	Details
Battery	Lead Acid AGM Deep Cycle; 12V, 106 Ah (x2 = 12 V, 212 Ah total)
Solar Panel	Polycrystalline; 300 W
Pump	Diaphragm; 8 psi, 50 lpm (x2 = 8 psi, 100 lpm total) (operating)
Diffuser	EPDM; 9” diameter (x4)
Charge Controller	MPPT; 12 V, 300 W
Air Tubing	Weighted PVC Line; 3/8"
Wires	Building Wire; 8 AWG THHN
Microcontroller	Arduino Uno

Figure 7: Wiring diagram of electrical components. The two resistor circuit off the arduino is a voltage divider used to measure the battery voltage.



13. System Management

A few management strategies will be used in the system to protect against mass fish die offs. These strategies are focused on planning for cloudy days and general system failures. The battery and solar panel sizes will help the system survive multiple cloudy days in a row. The battery alone is sized to last for three nights of aeration without being recharged if needed. The solar panel is sized such that the battery will be fully charged after one night of aeration even on a slightly cloudy day. The system will last for three nights with no charging (e.g. storms or charging malfunction), and should last at least four or five nights with some charging (e.g. partly cloudy days).

The two pump setup will provide system resiliency by providing redundancy and saving battery charge. Below a certain charge threshold only one of the pumps will be run during the night in order to reduce the load on the battery, while being able to aerate over a longer period. For example, if a low charge is detected, the system could run both pumps for one hour, or it could run one pump for two hours. Running one pump for longer will help provide an oxygen sanctuary for the fish for twice as long as running both pumps, which could be the difference between having a die off or not. With only a single pump in the system, a pump failure would almost certainly mean a die off. Having two pumps provides the redundancy necessary to prevent a total system shut down if one pump fails.

The system will have a microcontroller (arduino) connect to it that will read battery voltage levels, and control the two switches for the pumps. Battery voltage will be used as an estimate of the battery's state of charge (Table 5). If the battery is not at a full charge at the beginning of the aeration time, then the arduino will shorten the total aeration time that night in order to save charge on the battery (Figure 8). This will help extend the amount of time the battery will last without being recharged. This will provide less oxygen to the pond, and risk stressing the fish, but will help prevent a complete system failure where no oxygen is added to the pond which risks a mass die off.

Table 5: Voltage values for a 12 volt battery at different states of charge [1].

State of Charge	Voltage
100%	12.7
90%	12.5
80%	12.42
70%	12.32
60%	12.20
50%	12.06
40%	11.9
30%	11.75
20%	11.58
10%	11.31
0%	10.5

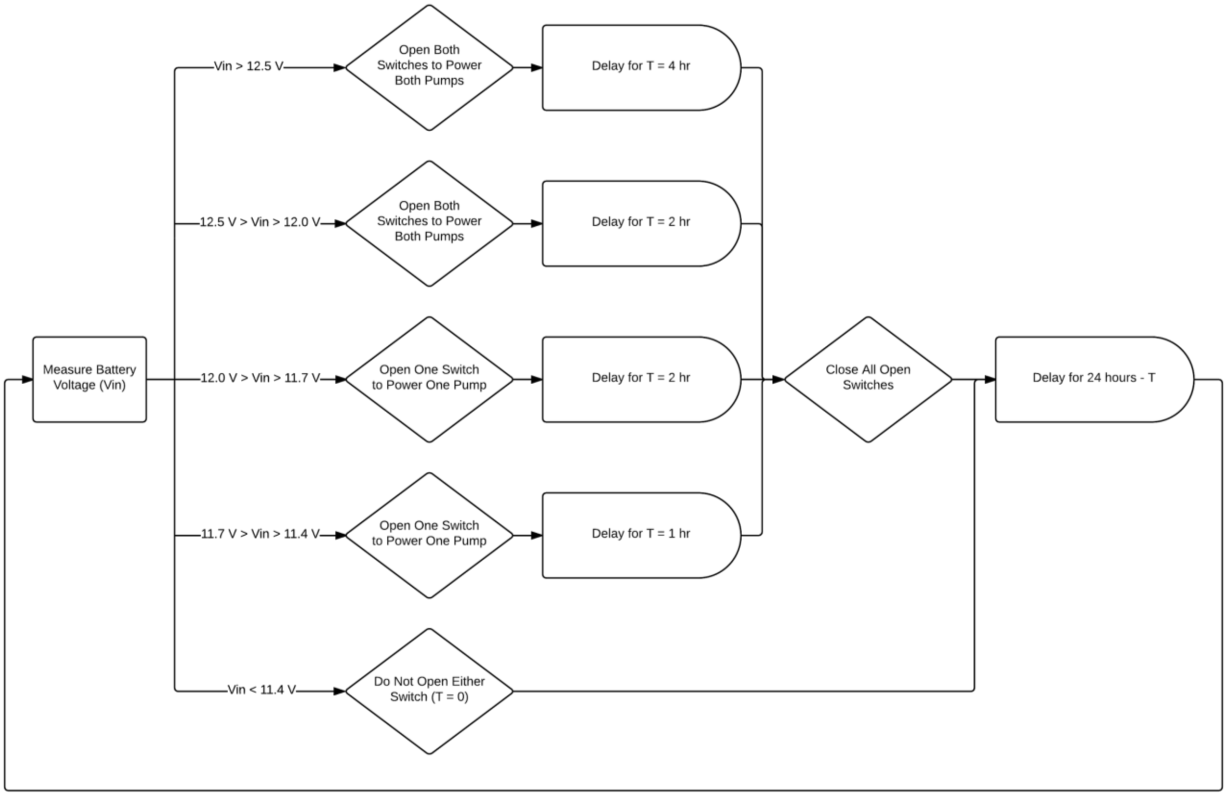


Figure 8: Arduino logic for pump control.

14. Economic Analysis

Perhaps the greatest design constraint of the system was the small budget of $1000. This value was strictly set early in the design process and, as shown in Table 6 below, maintained at its conclusion. Yearly revenues of the system were determined from the $1000 budget and by assuming the fish are being fed by algae, that the daily operation costs are equal with and without the system (e.g. harvest costs are equal and system maintenance negligible), and the values below in Table 7. Using these assumptions and values, the total additional yearly revenue was determined to be approximately 580 $/yr.

Potential system profits were considered by using the system budget (Table 6) to determine the internal rate of return (IRR) of the investment and by making net present value (NPV) considerations. An explicit NPV calculation is limited because it requires the use of a discount rate. Discount rate is a measure of the risks and uncertainties associated with an investment entity's current finances (e.g. debt and equity) and those of the venture itself. Because it depends upon an entity's finances, discount rate would need to be determined on a case-by-case basis. As such, discount rate is highly variable and it is not reliable to use a "typical" value, as one does not explicitly exist. Nevertheless, an example calculation of NPV using one estimation method of discount rate is provided in Appendix G.

The IRR is the breakeven discount rate at which the system will have a NPV of zero, and therefore represents the upper discount rate limit at which the venture is profitable. To determine IRR, NPV was plotted against various discount rates and the IRR was taken as the point at which NPV is zero (Figure 9). This resulted in a rather high IRR of approximately 55%, which is appealing because it represents a high chance of profit with the system and because more money will be generated the greater the difference between the discount rate and IRR.

Table 6: Budget for all system components, including individual component lifetimes in years.

Item	Unit Cost	Number of Units	Total Cost	Lifetime
Battery	$179.00	2	$358.00	5
Solar Panel	$216.00	1	$216.00	>20
Pump	$69.99	2	$139.98	9
Diffuser	$25.00	4	$100.00	10
Tubing	$1.43	50	$71.50	5
Fittings	$5.00	10	$50.00	>20
Charge Controller	$46.00	1	$46.00	>20
Wire	$0.26	50	$13.00	>20
Microcontroller	$10	1	$10.00	>20
		Total Cost	**$1004.48**	

Table 7: Values and assumptions used to determine yearly revenue gain with the system.

Consideration	Value	Source or Reason
Additional fish with system	1 fish/m^2	Design calculations
System service life	20 yr	Point at which majority of system components expected to fail (Table 6)
Pond volume	675 m^3	Designed volume
Yearly fish harvest	1350 fish/yr	Twice yearly harvest assumed
Global tilapia production	4,823,294 tonnes	[19]
Global tilapia value	$8,248,827,000 USD	[19]
Fish market value	0.43 $/fish (1.7 $/kg)	Above FAO values
Additional revenue	**580 $/yr**	

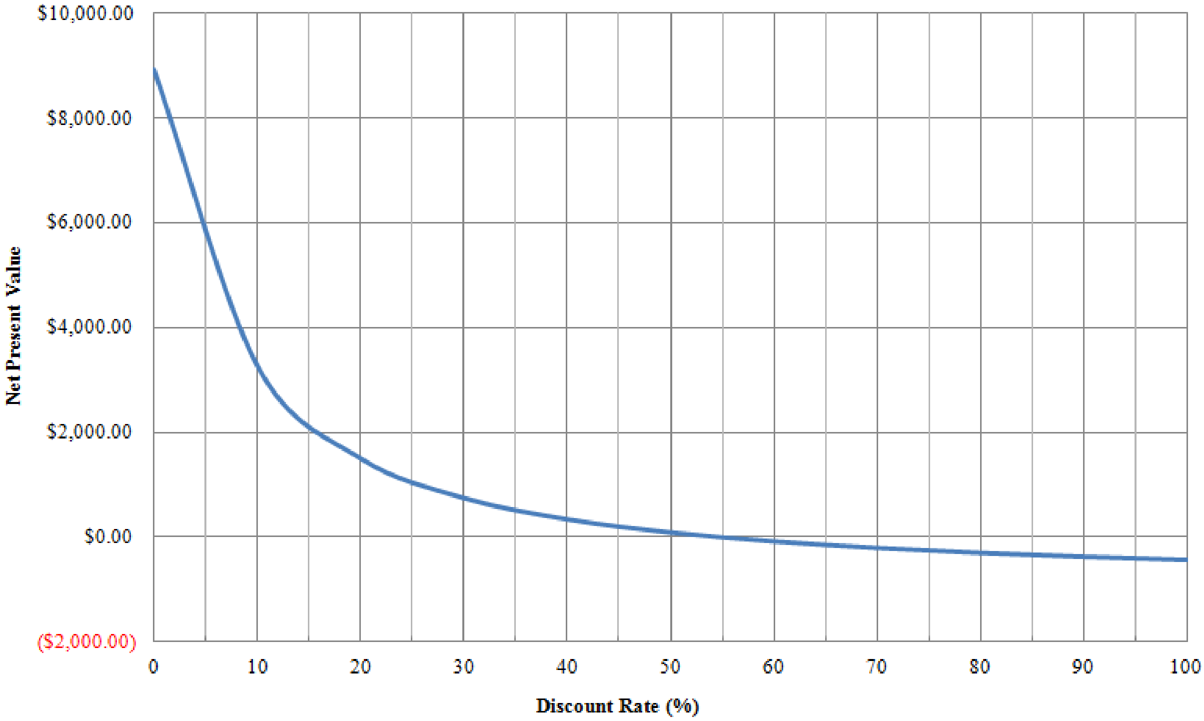


Figure 9: Plot used to determine IRR of approximately 55%.

15. Small Scale Testing

A small scale version of the system was built and tested in order to test sizing ratios and overall system feasibility. The scale version of the system was tested in a 12.5 cubic meter tank filled with river water. The testing lasted nine days, during which an oxygen demand was stimulated with bacteria and glucose. Battery voltage and DO levels were monitored throughout the testing period. The system was intentionally disabled on 2/21 in order to observe the effects of the glucose oxygen demand in the tank without aeration. During this period, DO dropped only slightly. The DO content never dropped below 90% of saturation, and remained above 100% for the majority of testing. The oxygen simulation system did not work as planned for the majority of the nine day testing period. Therefore the DO level is not very informative for the performance of the oxygenation by the diffuser. It is likely that the DO concentration in this tank maintains saturated levels regardless of aeration. The battery voltage data is the more meaningful of the data presented in Figure 9 below. The battery was at a lower voltage than desired for the first few days (around 12 V). This can be attributed to poor charging conditions (weather) and poor solar panel placement (shaded for a portion of the day). The last few days of testing experienced very sunny weather, and this is reflected in the increased charging of the battery. The solar panel was not sized to account for being shaded for a portion of the day, so ignoring the effects of that, the charging system ran as expected.

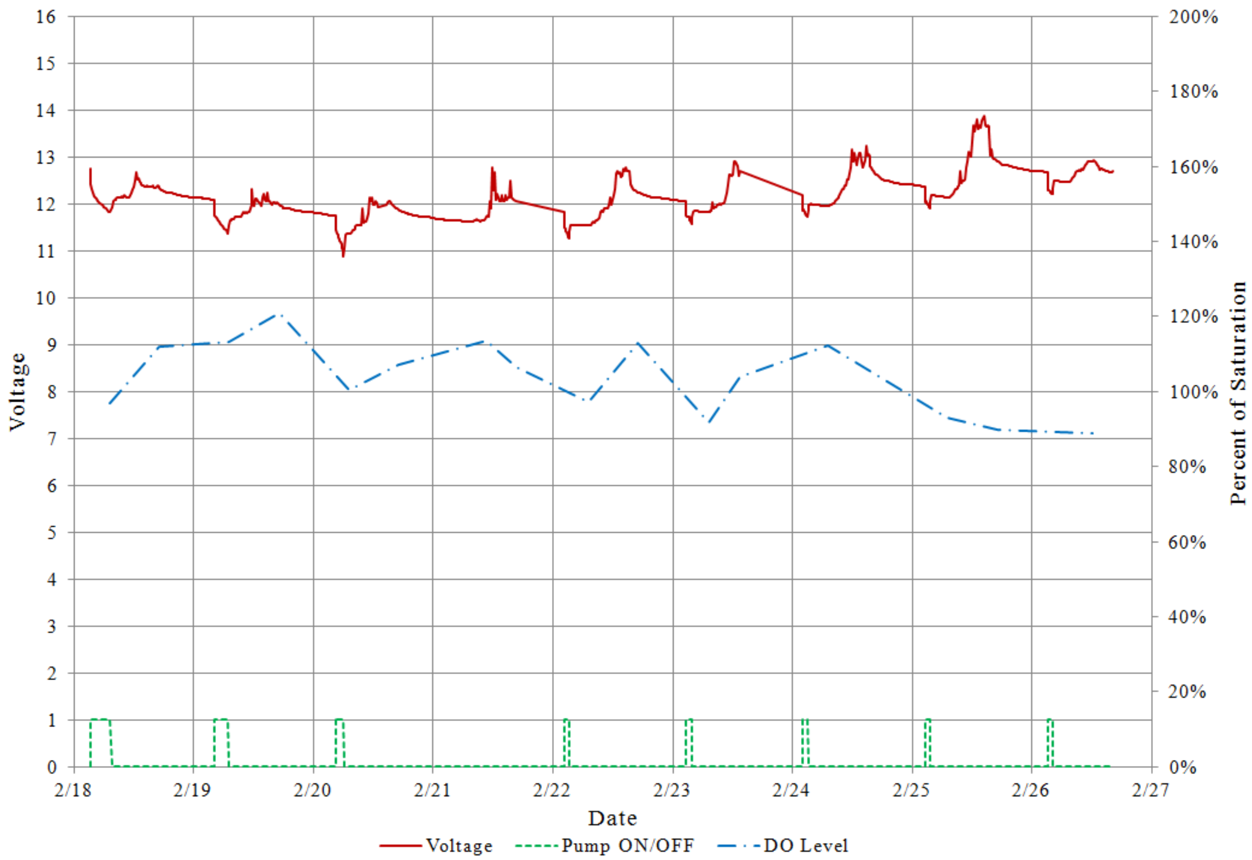


Figure 9: Recorded battery voltage, DO levels, and pump on/off status throughout the testing period. The pump's on/off status is shown as ON = 1 and OFF = 0. Voltage drops steadily through the night from the arduino, drops quickly when the pump turns on and rebounds when the pump turns off (typical when loading a battery), and then climbs during the day from the solar panel charging. The DO level stayed near or above 100% for the majority of the testing period, dropping to its lowest point of 90% at the end of the period. Note: the system was intentionally disabled on the 21st.

16. Conclusion

The goal of this system is to maintain dissolved oxygen levels in an earthen tilapia aquaculture pond high enough to increase fish harvest by 1 fish per square meter each crop cycle. This system is designed to be simple, reliable, easily operated, and inexpensive. These constraints were carefully considered throughout the design process that took place during Fall of 2015, this is reflected by the performance of the prototype built and tested this Winter. While small scale testing demonstrated reliable performance over a nine-day period, a system stress-test over a much longer period of time and in a less controlled environment is needed to make a better judgment of the system's durability. Such a test will occur in the Spring of 2016, and the results of that test will inform future design iterations and revisions.

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Appendix

A. Design Calculations

Table A1: Input parameters used in the Culberson and Piedrahita model. Values were selected to fit the problem statement and to represent typical conditions in existing ponds. The pond was modeled such that the only oxygen demand was from 1 fish/m2 (i.e. no algae or WCRR), which is the intended increase in density. Note: 0.667 fish/m3 = 1 fish/m2.

Input Parameters	Units	Value
Initial DO	mg/L	3.5
I_max	W/m2	1036
Algae cells	mg/m3	0
Kla	1/hr	20
Pond Area	m2	450
Depth	m	1.5
Wind Speed	m/s	0
Fish density	fish/m3	0.667
Individual fish mass	g	250
WCRR	mg/L/hr	0
WCRR Temperature	C	30

Table A2: Input values for sizing calculations.

Inputs	Units	Value
Mass O2 needed	g	500
O2 transfer eff.	O2/O2 pumped	0.1
Temperature	C	30
Depth	m	2
Head loss diffuser	m	1
Head loss pipes	m	1.5
Aeration time	hr	4
Pump upsize	-	2
Pump eff	-	0.25
Battery voltage	V	12
Battery upsize	-	3
Insolation time	hr	6
Solar panel upsize	-	1.5

Table A3: Intermediate calculation values for sizing calculations.

Calculations	Units	Value
Mass O2 pumped	g	5000
Mass air pumped	g	23810
Pump pressure	m	5.5

Volume air pumped	m3	13
Volume water displaced	m3	13
Work needed	J	718983
Pump power output	W	50
Pump power input	W	200
Current needed	A	17
Capacity needed	Ah	67
Battery size	Ah	212
Energy to charge battery	J	2875931
Solar panel power needed	W	133
Upsized panel wattage	W	200

Table A4: Output sizes from sizing calculations.

Outputs	Units	Value
Pump power input	W	200
Pump pressure	m	5.5
	psi	7.8
	kPa	53923
Pump flow rate	m3/hr	3.3
	lpm	56
	gpm	15
	cfm	2.0
Battery size	Ah	212
Solar panel power	W	200

B. Technology Selection Details

Qualitative assessment was done to narrow the number of technologies considered. The alternatives were dissected and compared according to social, economic, and technical constraints. Quantitative assessments involved the usage of decision matrices to compare technologies against important site and design considerations. The decision matrices consist of a weighted grading system used to tabulate scores for each alternative. The results were numerical values assigned to each technology that were used for comparison and selection.

Decision Matrix - Diffusers	**Weight**		**Diffusers**	
Team 5 - LEAF	**100 Total**	**Coarse Pore Metal**	**Fine Pore Ceramic Dome**	**Fine Pore EPDM Membrane**
Social				
Theft	10	2	2	2
Replacement Availability	5	3	3	4
Durability	10	5	3	4
Economic				
Capital	20	2	2	4
Operational	5	4	2	3
Technical				
SOTE (%)	10	2	3	4
SAE (kg O2/kWh)	15	2	3	3
Maintenance Method	10	4	2	4
Maintenance Interval/Fouling	15	4	2	3
Overall		28	22	31
Overall, Weighted		295	240	345

Point Rubric - Diffusers					
Team 5 - LEAF	1	2	3	4	5
Social					
Theft	Very easy to steal	Easy to steal	Difficult to steal	Very difficult to steal	Impossible to steal
Replacement Availability	Rare	Uncommon	Common	Quite common	Very common
Durability	Low (very fragile)	Low to medium	Medium	Medium to high	High (virtually indestructible)
Economic					
Capital	>$50	$40 - $50	$30 - $40	$20 - $30	$10 - $20
Operational	Very High	High	Medium	Low	No operational costs
Technical					
SOTE (%)	<15	15 to 25	25 to 35	35 to 45	>45
SAE (kg O2/kWh)	<1.0	1.0 to 3.0	3.0 to 5.0	5.0 to 7.0	>7.0
Maintenance Method	Acid required and cleaning	Acid possibly needed and cleaning	Hosing/scrubbing	Scrubbing	None
Maintenance Interval/Fouling	Very Often	Often	Occasionally	Rarely	Never

Decision Matrix - Pumps	**Weight**		**Pumps**	
Team 5 - LEAF		**Diaphragm**	**Rocking Pistons**	**Centrifugal**
Social				
Ease of use/understanding	12	5	5	5
Theft	5	2	2	2
Noise	5	5	5	5
Regulations	5	5	5	5
Replacement Availability	3	1	1	3
Economic				
Capital	25	2	2	3
Operational	5	4	4	4
Technical				
Lifetime	10	4	4	3
Total Efficiency (n)	20	2	3	3
Maintenance	5	4	4	3
Durability/Failure Chance	5	4	5	5
Overall		39	40	41
Overall, Weighted		318	338	354

Point Rubric - Pumps					
Team 5 - LEAF	1	2	3	4	5
Social					
Ease of use/understanding	Very complicated, expert level	Complicated, educated/trained adult level	Some instruction required	Simple, adult level	Very simple, child level
Theft	Very easy to steal	Easy to steal	Hard to steal	Very difficult to steal	Impossible to steal
Noise	>65 Decibels	50-65 Decibels	35-50 Decibels	20-35 Decibels	0-20 Decibels
Regulations	Use prohibited internationally	Major regulations in most countries	Restrictive regulations in some countries	Minor regulations in a few countries	No regulations
Replacement Availability	Not Available for Replacement.	Shipping cost exceeds benefit.	Shipping cost >50% of benefit	Shipping cost >25% of benefit	Shipping cost <25% of benefit
Economic					
Capital	>$300	$200-300	$150-200	$50-150	<$50
Operational	>35% of the capital cost annually	30-35% of the capital cost annually	25-30% of the capital cost annually	20-25% of the capital cost annually	15-20% of the capital cost annually
Technical					
Lifetime (years)	0 to 3	3 to 6	6 to 9	9 to 12	>12
Total Efficiency (n)	<30%	30-50%	50-70%	70-90%	>90%
Maintenance	Weekly	Monthly	Yearly	Rare	None
Durability/Failure Chance	Lifetime guaranteed to be reduced	Lifetime very easily reduced	Lifetime easily reduced	Lifetime difficult to reduce	Lifetime impossible to reduce

Decision Matrix Batteries	**Weight**	**Batteries**	
Team 5 - LEAF		**Wet Lead Acid Deep Cycle**	**AGM Lead Acid Deep Cycle**
Social			
Ease of use/understanding	5	3	5
*Theft**	0	2	2
Regulations	3	3	5
Replacement Availability	5	3	2
Environmental Impact	2	3	3
Economic			
Capital	25	4	2
Operational	5	3	5
Salvage	1	3	3
Technical			
Lifetime	20	3	2
Efficiency (%)[power in/power out]	4	3	3
Maintenance	15	2	5
Durability/Failure Chance	15	2	4
Overall		34	41
Overall, Weighted		295	321

*Theft had a no weight because all options were inherently identical for theft considerations

Point Rubric - Batteries					
Team 5 - LEAF	1	2	3	4	5
Social					
Ease of use/understanding	Very complicated, expert level	Complicated, educated/trained adult level	Some instruction required	Simple, adult level	Very simple, child level
Theft	Very easy to steal	Easy to steal	Hard to steal	Very difficult to steal	Impossible to steal
Regulations	Use prohibited internationally	Major regulations in most countries	Restrictive regulations in some countries	Minor regulations in a few countries	No regulations
Replacement Availability	Shipped with long lead time	Shipped with short lead time	Available in a few countries	Available in most countries	Easily available everywhere
Environmental Impact	Large impact		Moderate impact		No impact
Economic					
Capital ($)	>233	201 to 233	167 to 200	134 to 166	100 to 133
Operational	>20% of the capital cost annually		0-20% of the capital cost annually		No operational costs
Salvage	Pay to dispose of	No cost or gain	Recover 0-15% of capital cost	Recover 16-30% of capital cost	Recover >30% of capital cost
Technical					
Lifetime (years)	0 to 3	3 to 5	5 to 7	7 to 9	>9
Efficiency (%)	50 to 60	61 to 70	71 to 80	81 to 90	>90
Maintenance	Weekly	Monthly	Annually	Rare	None
Durability/Failure Chance	Lifetime guaranteed to be reduced	Lifetime very easily reduced	Lifetime easily reduced	Lifetime difficult to reduce	Lifetime impossible to reduce

C. Diffuser Efficiency

Because efficiency is a common basis of comparison of different aeration technologies, it is important to describe the manner in which efficiency is defined and the factors that influence it. Efficiency metrics are usually defined by the standard oxygen transfer efficiency (SOTE) and the standard aeration efficiency (SAE) [American Society of Civil Engineers, 2007]. SOTE is defined as the ratio of the mass of oxygen transferred into to the water (dissolved) per mass of oxygen supplied to the aerator, expressed as a percentage [American Society of Civil Engineers, 2007]. SAE is a measure of aerator energy expenditure and is defined as the ratio of the unit of oxygen transferred per unit time (the standard oxygen transfer rate, SOTR) and the power (P) required to achieve this rate [American Society of Civil Engineers, 2007].

The American Society of Civil Engineers (ASCE) has standardized the procedure and certain conditions under which these variables are determined to better normalize performance data and allow for better comparisons between aerator units to be made [American Society of Civil Engineers, 2007]. However, these standardized efficiency determinations can be as much as ten times the values experienced in field conditions [Deiters, 2005]. Therefore, to allow for more realistic determinations of operational efficiency, the standardized variables must be converted to the ex-situ equivalents (OTE, OTR, and AE) using conversion factors (Figure C1) or appropriate equations [Deiters, 2005].

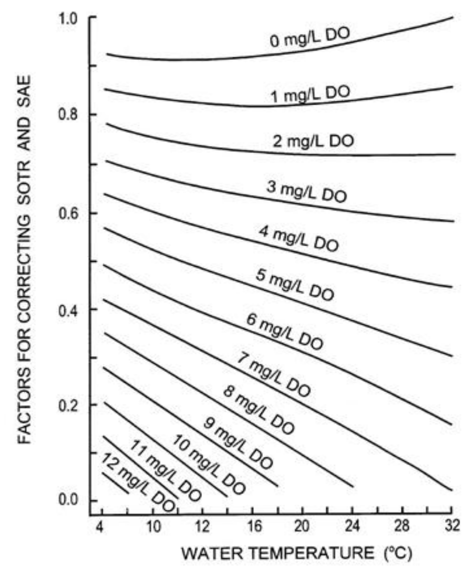

Figure C1: Approximate factors to convert SOTR and SAE to their in-field equivalents under different temperature and DO conditions. Source: [Boyd, (1998)]

D. Diffuser Background

Diffuser Materials

Diffusers are made using a variety of materials, the most common of which include steel (exclusively coarse-pore), ceramic, polyvinylchloride (PVC), high density polyethylene (HDPE), silicone, and ethylene propylene diene monomer rubber (EPDM). Of these materials, PVC diffusers experience shrinking and hardening issues and, as such, currently have a severely decreased presence in the market [Rosso, 2006]. Therefore, PVC diffusers were not considered for this project.

Diffuser Shapes

Diffusers are also made in a variety of shapes including domes (typically ceramic), disk (typically membrane), tubes (ceramic or membrane), and plates. However, it should be noted that many sources do not differentiate between disks and domes. Plates were commonly used historically in water treatment facilities, but are infrequently used currently (and are rarely used outside these facilities) due to low operational efficiency, high installation costs (they are generally cemented into a basin floor), and difficulty in cleaning [Rosso, 2006; Ovezea, 2009]. For these reasons, plate varieties will not be considered for this project.

Diffuser Bubble Size

Diffusers are generally classified as being coarse-pore (or coarse bubble) and fine-pore. These are distinguished based on the orifice diameter used to create the bubbles, with fine pore being within the 0-3 mm range and coarse pore being anything larger [Deiters, 2005]. Fine-pore diffusers create very small air bubbles which results in an overall greater total bubble surface area and greater oxygen transfer efficiencies [Deiters, 2005; Rosso, 2006; Wagner, 1998].

Diffuser Case Studies

Krampe (2006) compared the operational efficiency of typical EPDM, reduced plasticizer EPDM, and silicone diffusers in two wastewater treatment plants over a two and a half year period to determine the effects of clogging, biofouling, and ageing. In this study it was found that both types of EPDM experienced approximately a 25% loss in oxygen transfer rate within the first year of operation but remained steady for the rest of the study (2.5 years). Conversely, silicone diffusers increased in oxygen transfer rate over the same period by about 16%. However, silicone diffusers had a low initial SOTR and this increase only placed them equal with the other diffusers. This study initially intended to also investigate HDPE diffusers, but the aeration basins that were outfitted with these were no longer operational due to insufficient oxygen transfer rates. It was though this was due to the on/off operational regime of these particular basins which may have caused severe fouling.

One of the most common ways of measuring decreases in diffuser operational efficiency due to fouling is through the increase in backpressure required to maintain constant oxygen transfer rates over time [Environmental Dynamics International, 2012; Gehring, 2013; Mulinix; Stenstrom, 2010]. In comparing EPDM, polyurethane, and silicone diffusers, Rosso (2008), found that these diffusers vary in the change in backpressure, measured as the ratio (P) of used to new diffuser dynamic wet pressure (DWP) over different airflows. This study found that used silicone diffusers experienced a drastic increase (up to ~150%) in the DWP required compared to new diffusers over a range of airflow rates whereas EPDM diffusers experienced approximately a 50% increase in P. Conversely, polyurethane diffusers had a roughly constant P value (Figure D1). However, it should be noted that only one polyurethane diffuser was used to obtain data because the remainder had been severely damaged beyond operational ability due to hardening and shrinking over time, which indicates this may be an issue with this material of diffuser.

Krampe (2011) compared the pressure loss expected across new diffusers to that of used diffusers of varying ages, materials, and shapes based data from almost 100 wastewater treatment plants. This study showed that diffusers of almost all materials experienced dramatic increases in the pressure loss with age (Figure 5). In general, tube diffusers were found to have greater pressure increases (particularly silicone) compared to disc diffusers. And, aside from ceramic plate diffusers (which are not being considered), EPDM disc diffusers suffered the lowest increase in pressure when comparing new and used units and they experienced among the lowest pressure drop when new. However, these results may not be accurate as the sample size of plants using EPDM disc diffusers was very small.

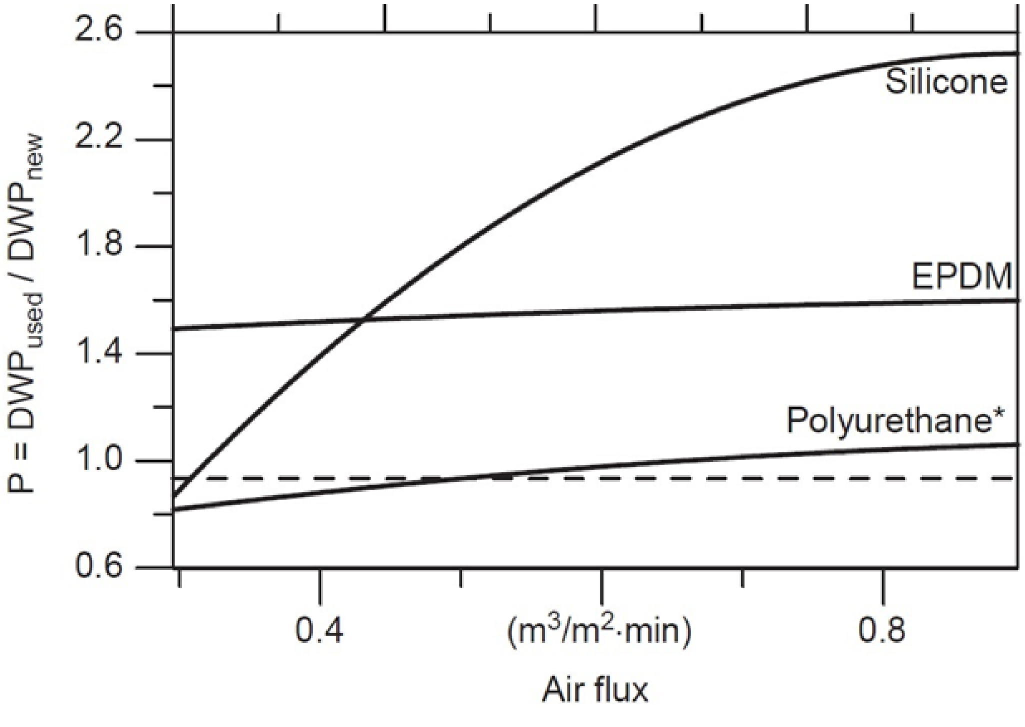

Figure D1: Comparison of new and used fine pore diffuser of various materials in terms of dynamic wet pressure (DWP) and airflow. * A single unit was tested for this material**.** Source: [Krampe, 2011]

E. Battery Background

A battery is needed to store energy generated from the solar panel during the day, and to power the pump for a few hours during the night, every night. The system will be in the tropics, where temperatures can reach 40°C or above. The battery should be able to run the pump for 3-5 nights without being recharged in case of a storm. A battery size of 12V, 100Ah will be used to compare different alternatives.

Survey of Current Battery Technologies

There are three major battery chemistries currently. They are nickel, lithium, and lead acid. Each of these chemistries has multiple types of batteries within them, where the different types within a chemistry all share similar characteristics.

Nickel Batteries

Nickel chemistries are widespread and have been around for a long time, but are being phased out in many applications. The two major types of nickel batteries are nickel-metal hydride (NiMH) and nickel cadmium (NiCd). The most common uses for both NiMH and NiCd batteries are cordless telephones and cordless tools. Nickel batteries tend to have a large number of charge cycles in their lifetime, generally up to 2000 cycles. Nickel batteries need to be fully discharged and then fully recharged on a regular basis to prevent the formation and buildup of crystals that reduce the capacity of the battery (commonly referred to as the memory effect).

While nickel batteries are great in some applications, they would not work in the proposed system. The system requires a battery that will typically only drain 20-30% before being recharged; this is not compatible with nickel batteries that need to be drained 100% on a regular basis.

Lithium Batteries

Lithium chemistries are much newer, and are replacing older chemistries in many applications. The major type of lithium batteries is lithium-ion (Li-ion). Common uses for Li-ion batteries include cell phones and laptops. Li-ion batteries are starting to replace nickel batteries in cordless devices and tools; they’re also replacing lead acid batteries in a few applications, such as golf carts and other small electric vehicles. Li-ion batteries have been gaining ground due to their discharging/charging characteristics and their weight. Li-ion batteries can be repeatedly discharged down to 20-40% of their capacity without damaging the battery, and experience little to no memory effect. A medium number of charge cycles can be expected for Li-ion batteries, up to 1200 cycles. In some cases, up to 5000 cycles can be expected [Smart Battery].

Li-ion batteries are ideal for the proposed system. They can handle a consistent shallow discharge, with occasional full discharge. They tend to have long cycle lives, and are resistant to extreme temperatures. The only downside is the cost of these batteries.

Li-ion batteries are lightweight at around 30lb for a 12V, 100Ah battery. This makes them easier to move around, which improves ease of use, but makes them easier to steal. The no maintenance aspect improves the ease of use. Large Li-ion batteries are difficult to find, and usually need to be purchased online and shipped, this would make replacing them difficult, and it would take several days to receive a replacement. Recycling would be a challenge as well, they would have to be shipped to a recycler in most cases, and at the cost of the farmer.

Li-ion batteries cost over $1000 for 12V, 100Ah. A 12V, 100Ah Li-ion battery would have 3000-5000 cycles in its lifetime [Smart Battery]. This would give 8-14 years of operation in the proposed system. A Li-ion battery would have no maintenance needs or costs associated with it. There are also potentially costs associated with proper disposal of Li-ion batteries.

Li-ion batteries have a large environmental impact from the manufacturing process. They require the mining of several metals, and the battery manufacturing process uses harmful chemicals. During use, there are no environmental impacts. Recycling processes for Li-ion batteries are new and expensive, these processes will have environmental impacts associated with them, but they could be an improvement over the impacts of mining new metals.

Lead Acid Batteries

Lead acid chemistries have been around for the longest time of the three chemistries mentioned. There are many types of lead acid batteries. Lead acid batteries are split into starting, light, and ignition (SLI), and deep cycle, which describe how the plates are built [Northern Arizona Wind & Sun]. They are also split into wet, gel, and absorbed glass mat (AGM), which describe the state of the acid [Northern Arizona Wind & Sun]. SLI batteries are designed to put out a high amount of energy in a short time period, and are damaged if drained more than 2-5% of their capacity consistently [Northern Arizona Wind & Sun]. Deep cycle batteries are designed to put out energy for an extended period of time, and can be drained down to 80% of their capacity consistently without being damaged [Northern Arizona Wind & Sun]. Wet lead acid batteries are not sealed, and the water in them can evaporate at high temperatures. Since they are not sealed, they can be refilled with DI water. Gel lead acid batteries do not have acid or water in an aqueous phase, they’re in a paste between the plates. Gel batteries are sealed, and are considered maintenance free since they lose little water to evaporation. AGM lead acid batteries have acid and water absorbed into a glass mat between the plates. These are also sealed and maintenance free. AGM batteries lose even less water than gel batteries, and are the most resistant to temperature extremes among lead acid batteries [Northern Arizona Wind & Sun]. Lead acid batteries vary widely in cycle life, and cycle life depends heavily on the typical depth of discharge (DOD). For the batteries described, and for a DOD of 20-30%, the cycle life is approximately between 750-3500 cycles [Northern Arizona Wind & Sun].

Of the lead acid batteries, only deep cycles will be considered for this system. Deep cycles are able to handle the proposed discharging behavior. Wet and AGM lead acid batteries will be considered further. Gel batteries will not be considered since AGM batteries have the same advantages, but lack several of the disadvantages that gel batteries have at similar costs.

F. Economic Calculations

Table F1 below shows the cost and replacement interval of each system component. These data were used in economic considerations to calculate the estimated system revenue, the IRR, and NPV estimations. Table F2 subsequently shows the determination of the IRR using various NPV and discount rate values.

Table F1: Determination of cashflow using component costs and replacement intervals.

Year	Solar Panel	Charge Controller	Battery	Pump	Diffuser	Plumbing	Fittings and Electronics	Revenue	Net Cashflow
0	-216	-46	-358	-140	-100	-72	-73		-1005
1								580.5	580.5
2								580.5	580.5
3								580.5	580.5
4								580.5	580.5
5			-358					580.5	222.5
6						-72		580.5	508.5
7								580.5	580.5
8				-140				580.5	440.5
9								580.5	580.5
10			-358			-72		580.5	150.5
11					-100			580.5	480.5
12								580.5	580.5
13								580.5	580.5
14								580.5	580.5
15			-358			-72		580.5	150.5
16				-140				580.5	440.5
17								580.5	580.5
18								580.5	580.5
19								580.5	580.5
20								580.5	580.5

Table F2: Data used to determine the internal rate of return (IRR).

Discount Rate (%)	NPV
0	$8,935.00
10	$3,274.64
20	$1,502.86
30	$744.04
40	$338.16
50	$86.92
60	($84.20)
70	($208.54)
80	($303.15)
90	($377.64)
100	($437.84)

NPV calculations depend upon the discount rate which varies by the risks and uncertainties associated with the entity making the investment (individual, company, etc.) and the venture (system) itself. As such, it is not possible to strictly determine an NPV for the system. However, there are a variety of methods used to estimate NPV, including using the discount rate set by the central bank of a given country. This method is used because this central bank discount rate is representative of the country's economy and, therefore, may be similar to discount rates used throughout the country. Since the system has the potential to be installed in Ghana it is reasonable to use this country as an example. Using the central Bank of Ghana's current (3/8/19) discount rate of 26%, the system revenue, a 20 year service life, and the system cost, a NPV of $988 is obtained. This NPV is appealing because it is positive despite the Bank of Ghana currently experiencing an unusually high discount rate (figure f1). This high rate is also illustrated by looking further back in the discount rates over the last ten years (figure f2), which shows that the Bank of Ghana is experiencing record high rates. Therefore, an NPV of $988 is likely a conservative estimate and actual values are likely to be significantly higher than this. For example, from figure f2, and average discount rate is closer to perhaps 16% which yields an NPV of about $2,000.

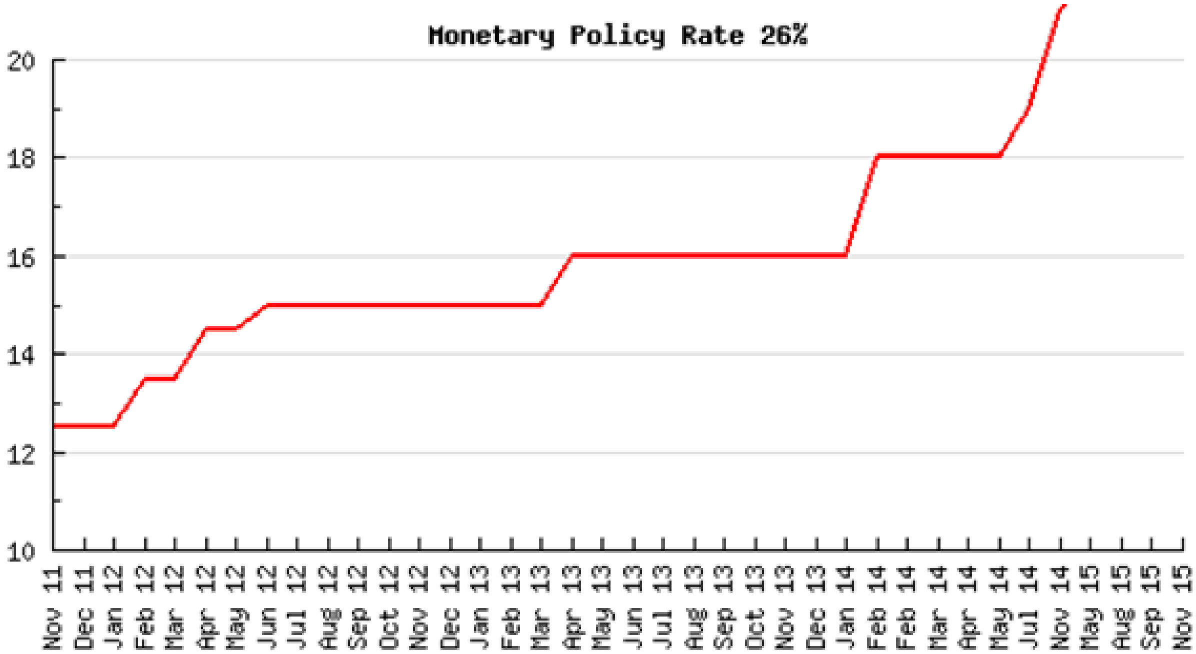

Figure F1: The central Bank of Ghana's discount rate over time, showing the gradual increase in the last few years and the current (3/8/16) discount rate of 26%. Note that the line only extends to approximately 22%, whereas it is actually significantly higher than this.

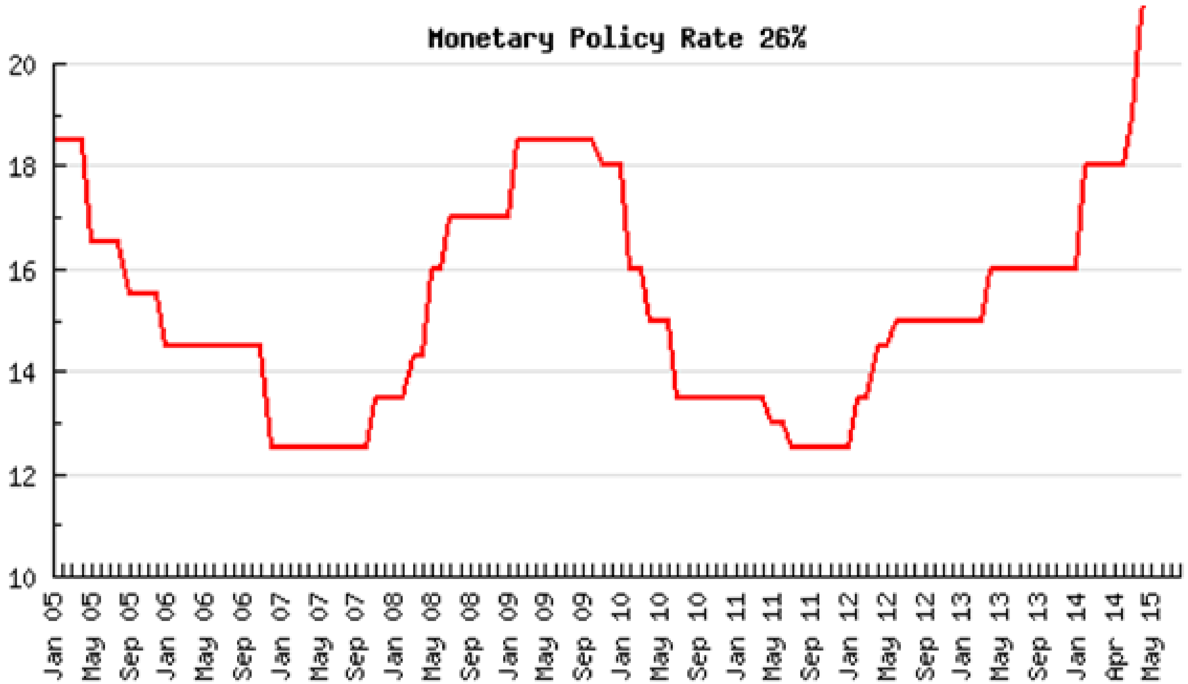

Figure F2: Bank of Ghana discount rate over approximately the last ten years, showing that it is currently experiencing record high rates during this interval.

G. Arduino Code

The following code was developed and used to control the small scale system. This code will be adapted to run the full scale system. Portions of the code were written by various people or websites all available online and considered public domain. This should run properly if pasted into the arduino code program (after downloading the indicated libraries). Comments are indicated by “//” at the start of a line, or any portions of text bounded by “/*” at the start and “*/” at the end.

```
/* UPDATED 3/12/2016 5:00 pm
LOW MEMORY USE - NO SERIAL MONITOR USE

 Libraries needed to run the code:
        Follow the links, download the ZIP file, then in this program:
        "Sketch" -> "Include Library" -> "Add .ZIP Library" -> Navigate to the ZIP file and select it

  Adafruit_DHT_Unified
    https://github.com/adafruit/Adafruit_DHT_Unified.git
  Adafruit_Sensor
    https://github.com/adafruit/Adafruit_Sensor.git
  Adafruit_TSL2591_Library
    https://github.com/adafruit/Adafruit_TSL2591_Library.git
  DHT-sensor-library
    https://github.com/adafruit/DHT-sensor-library.git
  RTClib
    https://learn.adafruit.com/adafruit-data-logger-shield/downloads
  SD
    https://learn.adafruit.com/adafruit-data-logger-shield/downloads

  ---------------------------------------------------------------------------------------------------------------

  This code works properly.
  Here’s what it does:

  Calculates battery voltage
  Determines how long to run the pump for
  Turns the pump on
  Goes into a loop for the calculated run duration
  Takes all sensor readings throughout the loop
  Exits the loop at end of duration
  Turns the pump off
  Goes into a loop until the next night
  Takes all sensor readings throughout the loop
  Exits the loop at end of duration
  Starts over
```

```
  Sensor readings currently taken and logged to SD card:

        Date & Time //From RTC
        millis  //Milliseconds since start up (just in case RTC fails)
        Vin  //Battery voltage
        TwC  //Water temp (*C) from thermistor
        TwF  //Water temp (*F) from thermistor
        h    //Humidity (%) from DHT
        t    //Air temp (*C) from DHT
        f    //Air temp (*F) from DHT
        hic  //Heat index (*C) from DHT
        hif  //Heat index (*F) from DHT
        *ir   //IR spectrum from lux sensor
        *full //Full spectrum from lux sensor
        *visible //Visible spectrum from lux sensor
        *lux  //Lux value from lux sensor
        ON/OFF  //Pump on (1) or off (0)

*Not working currently

  ------------------------------------------------------------------------------------------------------------
*/

//Defining Constants
const int R1 = 150; //Resistor in voltage divider, 150 k
const int R2 = 50;  //Resistor in voltage divider, 50 k
const float Vmin = 11.3;  // voltage at which pump doesn't run at all
const float Vmid = 12.0;   // Middle voltage value
const float Vmax = 12.5;   // voltage at which pump runs max duration
const float Tmax = 7200000; // 2 hours

//Defining Variables
int Q = 0;             // Q is the name chosen (randomly) to define the Analog Pin 0 (A0)
int sensorPin = A0;  // select input pin
int T = 0;             // variable to store run duration
int switchPin = 7;   // the pin sending power to the relay switch (7)

//Including libraries
#include "SD.h"
#include <Wire.h>
#include "RTClib.h"
#include "Adafruit_TSL2591.h"
#include <DHT.h>
RTC_DS1307 RTC;

//SD setup:
File dataFile;  //Create a file (similar to creating a variable)
```

```
const int chipSelect = 10;  //Set for the data logging shield
//SD card also communicates with pins 11, 12, and 13

//DHT setup:
#define DHTPIN 2            // Using digital pin 2
#define DHTTYPE DHT22   // DHT 22  (AM2302)
DHT dht(DHTPIN , DHTTYPE);   // Initialize DHT sensor.
// Connect pin 1 (on the left, red) of the sensor to +5V
// Connect pin 2 (yellow) of the sensor to Pin 2
// Connect pin 4 (on the right, black) of the sensor to GROUND

//Thermistor setup:
const int FixedR = 10000; //Fixed resistor value
#define THERMISTORPIN A1  //Define A1 as the pin used

//LUX setup:
// connect SCL to analog 5
// connect SDA to analog 4
// connect Vin to 3.3-5V DC
// connect GROUND to common ground
Adafruit_TSL2591 tsl = Adafruit_TSL2591(2591); // pass in a number for the sensor identifier (for your use later)//



void setup() {
  // put your setup code here, to run once:

  //Use this delay to delay the start of the enitre code
  //delay(34200000);  //Start up at 5pm, delays until 2am (9 hour delay). Only runs once

  Serial.begin(57600);
  Wire.begin();
  RTC.begin();

  //Define pin modes
  pinMode(switchPin, OUTPUT); // Defining "7" as an OUTPUT pin
  pinMode(sensorPin, INPUT);  // Defining A0 as an input pin

  //-----SD setup start-----//
  // initialize the SD card
  Serial.print("Initializing SD card...");
  // Make sure that the default chip select pin is set to
  // Output, even if you don't use it:
  pinMode(10, OUTPUT);

  // See if the card is present and can be initialized:
  if (!SD.begin(chipSelect))
  {
```

```
          Serial.println("Card failed, or not present");
  }
  else
  {
          Serial.println("Card initialized");
  }

  //Open csv file on SD card
  File dataFile = SD.open("data.csv", FILE_WRITE);
  if (dataFile) {
          //Write headers into the file, in same order that data is written later
    dataFile.println("Date&Time,Millis,Vin,TwC,TwF,h,t,f,hic,hif,IR,Full,Visible,Lux,ON/OFF");
          dataFile.close();
  }
  //-----SD setup end -----//

  //Real time clock check
  if (! RTC.isrunning()) {
          // following line sets the RTC to the date & time this sketch was compiled
          // uncomment it & upload to set the time, date and start run the RTC!
          RTC.adjust(DateTime(__DATE__, __TIME__));
  }


  //Configures the gain and integration time for the Lux sensor//
  // You can change the gain on the fly, to adapt to brighter/dimmer light situations
  //tsl.setGain(TSL2591_GAIN_LOW);          // 1x gain (bright light)
  tsl.setGain(TSL2591_GAIN_MED);           // 25x gain
  // tsl.setGain(TSL2591_GAIN_HIGH);   // 428x gain

  // Changing the integration time gives you a longer time over which to sense light
  // longer timelines are slower, but are good in very low light situations!
  tsl.setTiming(TSL2591_INTEGRATIONTIME_100MS);  // shortest integration time (bright light)
  // tsl.setTiming(TSL2591_INTEGRATIONTIME_200MS);
  // tsl.setTiming(TSL2591_INTEGRATIONTIME_300MS);
  // tsl.setTiming(TSL2591_INTEGRATIONTIME_400MS);
  // tsl.setTiming(TSL2591_INTEGRATIONTIME_500MS);
  // tsl.setTiming(TSL2591_INTEGRATIONTIME_600MS);  // longest integration time (dim light)
}


void SensorReadings() {
  //Put all sensor code here

  //-----------------------------------------Light Sensor START------------------------------------------//

  // More advanced data read example. Read 32 bits with top 16 bits IR, bottom 16 bits full spectrum
  // That way you can do whatever math and comparisons you want!
```

```
uint32_t lum = tsl.getFullLuminosity();
uint16_t ir, full, visible, lux;
ir = lum >> 16;
full = lum & 0xFFFF;
visible = full - ir;
lux = tsl.calculateLux(full, ir);

delay(1000);

//------------------------------------------Light Sensor END------------------------------------------//

//------------------------------------------DHT Sensor START------------------------------------------//

// Reading temperature or humidity takes about 250 milliseconds
// Sensor readings may also be up to 2 seconds 'old' (its a very slow sensor)
float h = dht.readHumidity();
// Read temperature as Celsius (the default)
float t = dht.readTemperature();
// Read temperature as Fahrenheit (isFahrenheit = true)
float f = dht.readTemperature(true);

// Compute heat index in Fahrenheit (the default)
float hif = dht.computeHeatIndex(f, h);
// Compute heat index in Celsius (isFahreheit = false)
float hic = dht.computeHeatIndex(t, h, false);

delay(1000);
//------------------------------------------DHT Sensor END------------------------------------------//

//------------------------------------------Thermistor START------------------------------------------//

//Takes multiple samples in a row to be averaged
uint8_t i;
int NumSamples = 5;
int Sample[NumSamples];

for (i = 0; i < NumSamples; i++)
{
	Sample[i] = analogRead(THERMISTORPIN);
	delay (10);
}

//Averages samples out
float avg = 0;

for (i = 0; i < NumSamples; i++)
{
	avg += Sample[i];
```

```
  }

  float AnalogReading = avg / NumSamples;

  //Thermistor resistance (voltage divider equation)
  float R = FixedR / ((1023 / AnalogReading) - 1);

  Serial.println(AnalogReading);
  Serial.println(R);

#define Ro 10000  // THERMISTORNOMINAL, resistance at 25 degrees C
#define To 298.15              // TEMPERATURENOMINAL, temp. for nominal resistance (almost always 25 C)
#define B 3950    // BCOEFFICIENT, The beta coefficient of the thermistor (usually 3000-4000)

  //Calculates water temp (Tw) in K
  float TwK = B / (log(R / (Ro * exp(-B / To))));

  //Convert to C
  float TwC = TwK - 273.15;

  //Convert to F
  float TwF = (TwC * 1.8) + 32;

  delay(1000);
  //-----------------------------------------Thermistor END------------------------------------------//

  //-----------------------------------------Battery Voltage START---------------------------------------//

  int SensorValue = analogRead(Q);
  //Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V): (Below)
  //Calculating battery voltage equivalent (calibrated)
  float Vin = SensorValue * (5.0 / 1023.0) * 4.1422 ; //(R1+R2)/R2;

  delay(1000);
  //-----------------------------------------Battery Voltage END------------------------------------------//

  //-----------------------------------------RTC START------------------------------------------//

  //Read the real time clock and print the date and time
  DateTime now = RTC.now();

  delay(1000);
  //-----------------------------------------RTC END------------------------------------------//

  //-----------------------------------------Write to SD START------------------------------------------//

  /*
```

```
        Things to write to SD, IN THIS ORDER:
        Date & Time //From RTC
        millis  //Milliseconds since start up (just in case RTC fails)
        Vin  //Battery voltage
        TwC  //Water temp (*C) from thermistor
        TwF  //Water temp (*F) from thermistor
        h    //Humidity (%) from DHT
        t    //Air temp (*C) from DHT
        f    //Air temp (*F) from DHT
        hic  //Heat index (*C) from DHT
        hif  //Heat index (*F) from DHT
        ir   //IR spectrum from lux sensor
        full //Full spectrum from lux sensor
        visible //Visible spectrum from lux sensor
        lux  //Lux value from lux sensor
        ON/OFF //Pump on (1) or off (0)
*/

//Open csv file on SD card
File dataFile = SD.open("data.csv", FILE_WRITE);

//Write to file if one opens
//Commas between every variable so that it can be read into excel
if (dataFile) {
        dataFile.print(now.year(), DEC); //Date & Time from RTC
        dataFile.print('/');
        dataFile.print(now.month(), DEC);
        dataFile.print('/');
        dataFile.print(now.day(), DEC);
        dataFile.print(' ');
        dataFile.print(now.hour(), DEC);
        dataFile.print(':');
        dataFile.print(now.minute(), DEC);
        dataFile.print(':');
        dataFile.print(now.second(), DEC);
        dataFile.print(",");
        dataFile.print(millis());  //Milliseconds since start up
        dataFile.print(",");
        dataFile.print(Vin);            //Battery voltage
        dataFile.print(",");
        dataFile.print(TwC);            //Water temp (*C) from thermistor
        dataFile.print(",");
        dataFile.print(TwF);            //Water temp (*F) from thermistor
        dataFile.print(",");
        dataFile.print(h);              //Humidity (%) from DHT
        dataFile.print(",");
        dataFile.print(t);              //Air temp (*C) from DHT
        dataFile.print(",");
```

```
            dataFile.print(f);                //Air temp (*F) from DHT
            dataFile.print(",");
            dataFile.print(hic);              //Heat index (*C) from DHT
            dataFile.print(",");
            dataFile.print(hif);              //Heat index (*F) from DHT
            dataFile.print(",");
            dataFile.print(ir);               //IR spectrum from lux sensor
            dataFile.print(",");
            dataFile.print(full);             //Full spectrum from lux sensor
            dataFile.print(",");
            dataFile.print(visible);   //Visible spectrum from lux sensor
            dataFile.print(",");
            dataFile.print(lux);              //Lux value from lux sensor
            dataFile.print(",");
            //Close file
            dataFile.close();
  }

  delay (1000);
  //-----------------------------------------Write to SD END------------------------------------------//
}


void loop() {
  // put your main code here, to run repeatedly:

  /*This section is what actually controls the pumps
            Things done here:
            Reads sensors throughout
            Decides how long to run the pump
            Turns the pump on
            Waits for calculated time
            Turns the pump off
            Waits until the next night
  */
  int ON = 1;
  int OFF = 0;

  //Read all sensors before running
  SensorReadings();

  //Open csv file on SD card
  File dataFile = SD.open("data.csv", FILE_WRITE);

  //Write to file if one opens
  if (dataFile) {
            //Last data point needs to include the "ln" so that the next set will be on a new line
            dataFile.println(OFF);
```

```
        //Close file
        dataFile.close();
}

//Calculate voltage
int SensorValue = analogRead(Q);
// Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V): (Below)
//Calculating battery voltage equivalent (calibrated)
float Vin = (SensorValue * (5.0 / 1023.0) * 4.1422); //(R1+R2)/R2;

//-----------------------------------------Vin > Vmax Loop Start-------------------------------------------//
if (Vin > Vmax)
{
        float T = Tmax;

        //Turn pump on
        digitalWrite(7, HIGH);

        int ON = 1;
        int OFF = 0;

        //Takes 10 readings during the time the pump is on
        for (float td = 0; td <= T; td = ( td + (T / 10))) {

        SensorReadings();

        //Open csv file on SD card
        File dataFile = SD.open("data.csv", FILE_WRITE);

        //Write to file if one opens
        if (dataFile) {
        //Last data point needs to include the "ln" so that the next set will be on a new line
        dataFile.println(ON);
        //Close file
        dataFile.close();
        }

        //Calculate voltage to decide to stay in the loop or not
        int SensorValue = analogRead(Q);
        // Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V): (Below)
        //Calculating battery voltage equivalent (calibrated)
        float Vin = (SensorValue * (5.0 / 1023.0) * 4.1422) ;

        //Breaks out of the loop if voltage is below 11V
        if (Vin < 10.7) {
        break;
        }
```

```
        delay (T / 10);
        }

        //Turn pump off
        digitalWrite(7, LOW);

        //24 hrs - run duration, makes code start at the same time everyday
        float Toff = 86400000 - T;

        //Takes 100 readings during the time the pump is off
        for (float tt = 0; tt <= Toff; tt = ( tt + (Toff / 100))) {

        SensorReadings();

        //Open csv file on SD card
        File dataFile = SD.open("data.csv", FILE_WRITE);

        //Write to file if one opens
        if (dataFile) {
        //Last data point needs to include the "ln" so that the next set will be on a new line
        dataFile.println(OFF);
        //Close file
        dataFile.close();
        }

         delay (Toff / 100);
        }
}
//-----------------------------------------Vin > Vmax Loop End----------------------------------------//


//-----------------------------------------Vmax > Vin > Vmid Loop Start-------------------------------//
else

        if (Vmid <= Vin <= Vmax)
        {
        //Calculating run duration
        //float T = (Tmax * ((Vin - Vmin) / (Vmax - Vmin)));
        float T = Tmax / 2;

        //Turn pump on
        digitalWrite(7, HIGH);

        int ON = 1;
        int OFF = 0;

        //Takes 10 readings during the time the pump is on
```

```
for (float td = 0; td <= T; td = ( td + (T / 10))) {

SensorReadings();

//Open csv file on SD card
File dataFile = SD.open("data.csv", FILE_WRITE);

//Write to file if one opens
if (dataFile) {
//Last data point needs to include the "ln" so that the next set will be on a new line
dataFile.println(ON);
//Close file
dataFile.close();
}

//Calculate voltage to decide to stay in the loop or not
int SensorValue = analogRead(Q);
// Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V): (Below)
//Calculating battery voltage equivalent (calibrated)
float Vin = (SensorValue * (5.0 / 1023.0) * 4.1422) ;

//Breaks out of the loop if voltage is below 11V
if (Vin < 10.7) {
break;
}

delay (T / 10);
}

//Turn pump off
digitalWrite(7, LOW);

//24 hrs - run duration, makes code start at the same time everyday
float Toff = 86400000 - T;

//Takes 100 readings during the time the pump is off
for (float tt = 0; tt <= Toff; tt = ( tt + (Toff / 100))) {

SensorReadings();

//Open csv file on SD card
File dataFile = SD.open("data.csv", FILE_WRITE);

//Write to file if one opens
if (dataFile) {
//Last data point needs to include the "ln" so that the next set will be on a new line
dataFile.println(OFF);
```

```
        //Close file
        dataFile.close();
        }

        delay (Toff / 100);
        }
        }
//-----------------------------------------Vmax > Vin > Vmid Loop End--------------------------------//


//-----------------------------------------Vmid > Vin > Vmin Loop Start--------------------------------//
        else

        if (Vmin <= Vin < Vmid)
        {
        //Calculating run duration
        //float T = (Tmax * ((Vin - Vmin) / (Vmax - Vmin)));
        float T = Tmax / 4;

        //Turn pump on
        digitalWrite(7, HIGH);

        int ON = 1;
        int OFF = 0;

    //Takes 10 readings during the time the pump is on
        for (float td = 0; td <= T; td = ( td + (T / 10))) {

        SensorReadings();

        //Open csv file on SD card
        File dataFile = SD.open("data.csv", FILE_WRITE);

        //Write to file if one opens
        if (dataFile) {
        //Last data point needs to include the "ln" so that the next set will be on a new line
        dataFile.println(ON);
        //Close file
        dataFile.close();
      }

        //Calculate voltage to decide to stay in the loop or not
        int SensorValue = analogRead(Q);
        // Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V): (Below)
        //Calculating battery voltage equivalent (calibrated)
        float Vin = (SensorValue * (5.0 / 1023.0) * 4.1422) ;
```

```
	//Breaks out of the loop if voltage is below 11V
	if (Vin < 10.7) {
	break;
	}

	delay (T / 10);
	}

	//Turn pump off
	digitalWrite(7, LOW);

	//24 hrs - run duration, makes code start at the same time everyday
	float Toff = 86400000 - T;

	//Takes 100 readings during the time the pump is off
	for (float tt = 0; tt <= Toff; tt = ( tt + (Toff / 100))) {

	SensorReadings();

	//Open csv file on SD card
	File dataFile = SD.open("data.csv", FILE_WRITE);

	//Write to file if one opens
	if (dataFile) {
	//Last data point needs to include the "ln" so that the next set will be on a new line
	dataFile.println(OFF);
	//Close file
	dataFile.close();
	}

	delay (Toff / 100);
	}
	}
//------------------------------------------Vmid > Vin > Vmin Loop End---------------------------------//



//------------------------------------------Vin < Vmin Loop Start------------------------------------------//
	else

	if (Vin < Vmin)
	{
	int T = 0;

	//24 hrs, makes code start at the same time everyday
	float Toff = 86400000;
	//Takes 100 readings during the time the pump is off
	for (float tt = 0; tt <= Toff; tt = ( tt + (Toff / 100))) {
```

```
            SensorReadings();

            //Open csv file on SD card
            File dataFile = SD.open("data.csv", FILE_WRITE);

            //Write to file if one opens
            if (dataFile) {
            //Last data point needs to include the "ln" so that the next set will be on a new line
            dataFile.println(OFF);
            //Close file
            dataFile.close();
            }

            delay (Toff / 100);
            }
            }
  //-----------------------------------Vin < Vmin Loop End------------------------------------//
}
```