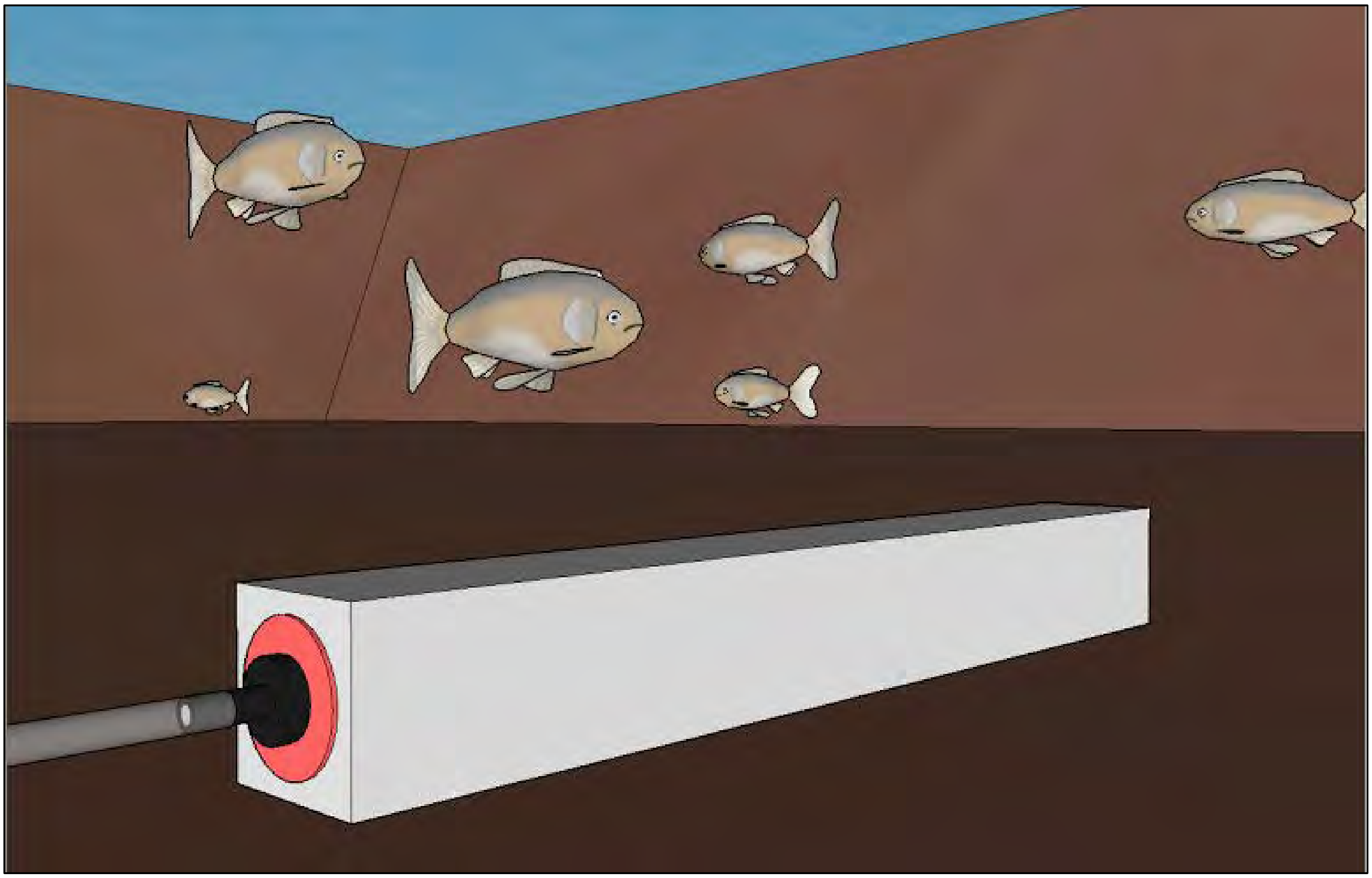
Tilapia Aquaculture Aeration: Solar Powered Diffusers



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Executive Summary

Aquaculture is an emerging international industry that cultivates fish under controlled conditions. Dr. Hillary Egna, a leading aquaculture expert, has requested the Biological and Ecological Engineering senior design class design an aeration system for tilapia aquaculture. This report provides a recommendation for a solar-powered diffuser aeration system for use in tilapia aquaculture in Eldoret, Kenya.

The primary design goals include meeting a $200 capital cost and maximizing net present value per oxygen delivered. As the system design developed, the feasibility and necessity of the $200 limit was reassessed to include creative funding sources and greater emphasis on maximizing oxygen delivery per dollar. Secondary goals consist of reliability, ease of use, appropriateness, and sustainability. Assumptions made for the aeration design include: fish density of 5 fish/m^3, fish harvest at 250 g, harvest cycles are 4 months long, tilapia smaller than 100 g do not require additional aeration, tilapia require 4 mg/L to survive, no evaporation takes place, the pond is well mixed, water is at 25 °C, peak sunlight (hours of 1000 W/m^2) occurs for 4 hours/day, electricity in the region is unreliable, the fish feed on algae and there is no supplemental feed, and the system will be run at night (when pond oxygen concentration is lowest due to algae respiration).

Four aeration technologies - paddlewheel, venturi, vertical pump and diffuser systems - were reviewed based on technical, economic, social, and environmental factors. The technologies were evaluated with an alternatives matrix with scores weighted according to the design goals. The outcome of this matrix indicated that venturi and diffusers were the top aeration technologies. However, this matrix did not include power sources, which were evaluated separately.

The design team reviewed four power sources but based on cost and size calculations only two of these power sources were deemed feasible for the project. Gasoline powered generators and solar with battery powered systems were the two power sources that passed the preliminary evaluation. The generator does not have a high capital cost, but annual costs are high. The inverse is true for a solar panel and battery. Ultimately, the lower annual cost for the battery and solar panel system made it more feasible.

The solar powered diffuser system was preferred over the solar powered venturi system because it scored slightly higher in an alternatives matrix and had a lower unit cost per mass of oxygen delivered. The design includes two 100 watt solar panels, a 100 amp hour battery, a charge controller, a 60 watt air pump, tubing and wires. It will be run 200 nights for two harvest cycles per year.

The system has a capital cost of $755 and for the 10 year design life, a NPV of -$1,110. It costs $0.28 per kg oxygen delivered. To overcome the capital cost associated with the solar powered diffuser design, farmers may need to apply for an agribusiness loan or some other source of micro-financing.

A smaller prototype of the system was tested in a 1 m^3 pool. The calculated standard oxygen transfer coefficient was 2.2 g/hr and the standard aeration efficiency was 0.035 kg/kWh. These values are lower than those cited in the literature, but the prototype was tested in a shallow pond which significantly reduces the oxygen transfer efficiency. The increased depth of the full-scale pond should increase oxygen transfer time and help manage this difference.
The experiment attempted to model fish, algae, diurnal variation, and sunlight. Although the test pool DO dropped below the 4 mg/L threshold for tilapia survival, when the prototype was run it drastically increased DO. Errors in the experiment, especially with charging the battery, caused the DO drops and would easily be corrected for the full-scale system.

1.0 Introduction

Aquaculture is the "breeding, rearing, and harvesting of plants and animals in all types of water environments including ponds, rivers, lakes and the ocean" (Oakes et. al., 2011). As the human population grows, food availability and security is a growing concern. Aquaculture is a potential solution, it has become so prevalent that, in 2007, 43% of the total aquatic food that humans consumed came from aquaculture (Bostock et. al., 2010). With current practices there is a limited number of fish per volume, also known as stocking density, which can be achieved due to oxygen demand. Fish consume oxygen during respiration and draw the dissolved oxygen (DO) concentration down; lack of oxygen leads to hypoxia, fish death, and a loss of profit for farmers.

Improving the effectiveness of these systems is important; one strategy is by increasing the dissolved oxygen in the pond via aeration. The addition of aeration to these aquaculture systems can lead to increased stocking densities, yields, and profits for farmers, as well as insurance that the fish will survive.

2.0 Design Statement

Dr. Hillary Egna, Director of the AquaFish Innovation Lab, commissioned the Ecological Engineering senior design class of 2014-2015 to design an aeration system for tilapia aquaculture. The primary goal was to maximize oxygen delivery per dollar. Originally a $200 capital cost goal was set, but as the system design developed, the necessity of the $200 limit was reassessed to include creative funding sources and greater emphasis on maximizing oxygen delivery/dollar. Secondary goals include reliability, ease of use, appropriateness, and sustainability. Reliability is understood as robustness with few expected breakdowns or required part replacements, functionality without an electric grid, consistent ability to operate at night, and few moving parts. The design should be easy to use as defined by portability, low maintenance, and ease of operation. Appropriateness includes socio-cultural considerations and economic viability. The sustainability goals of the system are met by renewable energy sources and materials and disposal plans.

The aeration system will be designed for a 400 m^3 rectangular pond (20m x 10m x 2m) located in Eldoret, Kenya. Assumptions for the calculations for the design include: fish density of 5 fish/m^3, fish harvest at 250 g, harvest cycles are 4 months long, tilapia smaller than 100 g do not require additional aeration, tilapia require 4 mg/L to survive, no evaporation takes place, the pond is well mixed, water is at 25 °C, peak sunlight (hours of 1000 watt/m^2) occurs for 4 hours/day, electricity in the region is unreliable, the fish feed on algae and there is no supplemental feed, and the system will be run at night (when pond oxygen concentration is lowest due to algae respiration).

3.0 Review of Alternative Aeration Systems

The four potential aerations technologies were chosen based on citation in literature, feasibility, and preliminary cost estimates; they are paddlewheels, vertical pumps, venturis, and diffusers. Each technology will be briefly discussed, focusing on technical, economic, social, and environmental aspects of consideration. For a more detailed assessment of the technologies, refer to Appendix C.

3.1 Paddlewheel Overview

Paddle wheels consist of a cylindrical 'wheel' with paddles attached that rotates to splash and aerate water. Examples of this system are 0.75-1.5 kW plastic Taiwanese paddle wheel aerators (Fig. 1) which are popular worldwide for small ponds due to availability, low cost, and high efficiency (Moore & Boyd, 1992). These systems are self-contained and easy to move. For aerator systems near this size (less than 1.5 kW), the standard aeration efficiency (SAE) ranges between 1.87 kg O_2 /kWh and 2.58 kg O_2 / kWh (Moore & Boyd, 1992). They are good at circulating water, sometimes to the point of erosion. Based on an internet search, small paddlewheel systems are for-sale for between \$620 to \$932 (aquaculture-com.net), not including a power source or implementation. The mechanical aeration depends on moving parts which increases the risk of breakage and maintenance and reduces reliability. Despite this risk, paddlewheel aerators are used worldwide so they are culturally appropriate. The potential environmental impact depends heavily on the power source.

Fig. 1: Self-contained, plastic paddlewheel aerator (Pentair, n.d.).

3.2 Vertical Pump Overview

Vertical pumps are self-contained units which expel water into the air for aeration purposes, similar to a fountain (Fig. 2). Aeration occurs in two locations: as the water droplet is exposed to the air and the disruption of the water's surface due to the cascading droplets. They come in two types: a submerged pump which draws water in and expels it through a nozzle, and a floating motor which spins a propeller just beneath the surface to lift water. Both must take precautions for fish protection to ensure that fish will not be harmed when these aerators are in operation. Vertical pumps have published SAE values ranging from 0.68 to 1.8 kg O_2 / kWh (Boyd, 1998) but are poor at mixing and aerating the entirety of the pond. Prices vary with power, but an average price range is \$300 to \$1,000. Engle and Hatch (1988) estimated an operation and maintenance cost equal to one third of the capital costs. Anchoring must be used to keep the aerator in a fixed location, but shore and bottom anchoring present theft and accessibility problems. The cultural acceptability of vertical pumps is unknown because they are not commonly used in aquaculture settings. The electric motor or electric pump requires no oil and is self-contained inside a protective float, making it an environmentally friendly option. Static water has been known to attract unwanted insects such as mosquitoes. A vertical pump can disrupt the surface water and provide gentle mixing to deter them.

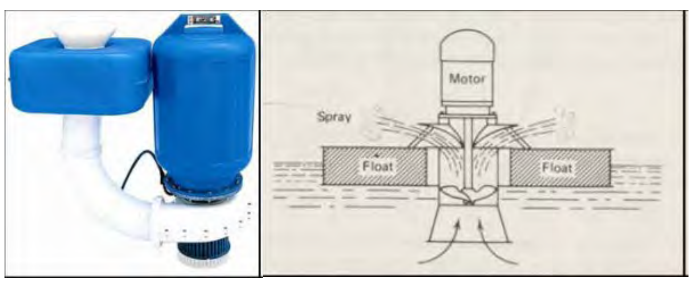


Fig. 2: Left: Spraying Aeration Floating Pump, Courtesy of Zhejiang Ford Machinery Co.; Right: Schematic for a vertical pump aeration system with motor, shaft, and propeller. Note that the only part below water is the propeller (Wheaton, 1977).

3.3 Venturi Overview

A venturi aeration system works by pumping water through a pipe at the pond bottom with a constricted diameter in the center (Fig. 3). An air tube is connected to this small diameter section of pipe and runs up to the surface of the pond. When the flowing water gets to the section of the pipe with a smaller diameter, the pressure drops. This drop is low enough to create a pressure differential which allows air at standard atmospheric pressure to be drawn into the tube from the water surface and mix with the water in the pipe.

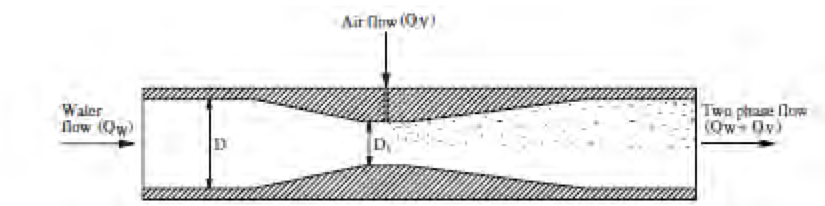


Fig. 3: Venturi aerator mechanics (Baylar and Ozkan, 2005).

Standard aeration efficiency (SAE) of venturi systems is usually between 1.4 – 3.0 kg O_2 / kWh (Lawson, 1995; Baylar et al. 2005). This range of SAE values is on the higher end compared to other aeration systems, and an added benefit of the venturi system is that it promotes mixing in the pond. Venturi systems have low capital costs since there are not many parts needed. The pump is the most expensive piece of the system, but these can be found for under $100. The rest of the system is piping and tubing, so without considering the power source a venturi aerator would cost less than $200.

3.4 Diffuser Overview

Diffused aeration systems work by pumping air through small, submerged openings into water, creating bubbles. Oxygen transfer occurs at the bubble-water interface assuming an oxygen gradient is present (Fig. 4). The amount of oxygen transferred depends on the depth of the diffuser, the number, size, and velocity of the rising bubbles, the type of diffuser, and the oxygen saturation deficit (EPA, 1989; Lawson, 1995). In general, the smaller the bubble, the more oxygen transfer occurs.

A diffused aeration system has three main components: an air pump, a diffuser, and connective tubing. There are many types of diffusers on the market, including coarse, medium and fine pore diffusers. It is estimated that coarse pore diffusers operate between 0.60 and 1.20 kg O2/kWhr, medium pore diffusers between 1.0 and 1.6 kg O2/kWhr and fine pore diffusers between 1.2 and 2.0 kg O2/kWhr (Colt & Orwicz, 1991). Fine pore diffusers produce tiny bubbles, whereas coarse pore diffusers produce larger bubbles. Diffusers are subject to fouling and scaling which are biological and chemical processes that impair diffuser functionality. This requires that diffusers be cleaned with hydrochloric acid as needed (Pentair, 2014).

Diffuser costs varies based on type and size and there are economic tradeoffs with each diffuser type related to upfront and annual costs. Fine pore diffusers are the most expensive to purchase at around $50, require larger pressures and frequent maintenance, while coarse pore diffusers are the least expensive to purchase at around $10, require less maintenance, but need larger flow rates. Medium pore diffusers operate in between fine and coarse diffusers with maintenance, flow, required pressures and cost. Medium pore diffusers cost between $0.50 and

$1.00 per cm length. They are economical because they do not need as large of flow or pressure so a smaller pump can be purchased and less energy used. Cost of air pumps that suit medium pore bubblers can be found for less than $100. Plastic tubing can be found for less than $2.00 per meter.

Fig. 4: Diffuser in operation (Jaeger Aeration).

3.5 Technical Alternatives Matrix & Conclusion

To assist in determining the best technology of the four alternatives, a technical alternatives matrix was created. The categories and weightages were chosen per the team's agreement on what aspects were considered the most important; because of this, the matrix is subjective. The ranking rubric for the Technical Alternatives Matrix can be found in Appendix A.

Table 1: Technical Alternatives Matrix.

TECHNOLOGY	Technical Alternative → Weightage	Paddlewheel	Diffuser	Venturi	Vertical Pumps
Technical					
Portability	4	3	4	5	5
Scalability	4	2	5	4	3
Efficiency	14	4	3	4	3
Installation	4	3	4	3	5
Reliability	6	2	3	3	3
O&M	8	4	4	4	4
Overall Technical Score	40	26.4	28.8	30.8	28.8
Environmental					
Protection of water/fish	5	3	5	4	4
Potential Bank errosion	3	3	5	4	4
Protection from unwanted insects	2	5	3	3	4
Overall Environmental Score	10	6.8	9.2	7.6	8
Social					
Culturally Acceptable	4	5	3	3	3
Theft	6	3	4	5	3
Overall Social Score	10	7.6	7.2	8.4	6
Economic					
Capital Cost	40	2	5	5	3
Overall Economic Score	40	16	40	40	24
Overall Score					
	100	**56.8**	**85.2**	**86.8**	**66.8**

As shown in the Technical Alternatives Matrix (Table 1), the diffuser and venturi systems scored significantly higher than the paddlewheel and vertical pump. The high capital cost and large number of moving parts, which reduces reliability, removed paddlewheels from consideration. Vertical pumps were eliminated because of moderate capital costs, risk to fish health, and poor mixing capability. The diffusers and venturi system's high performance across all considered categories (environmental, social, economic, and technical) shows the competitive nature of the systems, which lead to the preliminary selection of those two aeration technologies. Detailed justifications for each technology's scoring can be found in Appendix C.

4.0 Power

Since line power is assumed to be unreliable in the region of interest, methods for self-generation of electricity to power the aerator were investigated. The power sources considered here are gasoline, solar, wind, human, biofuel, and gravity. The two most feasible options are gasoline to power a generator and a solar panel/battery installation.

4.1 Gasoline

A small scale (~ 1 kWh) gasoline-powered system has low capital costs because the only investment necessary, generators, are $150 - $200. When comparing this to the capital costs of other power systems, generators are the best option. However, generators have a high annual cost due to the gasoline required for operation. For a 1 kW/d system, a generator was found that could provide power for 8 hours on 4.5 liters of gas (amazon.com). Over the course of a year, at $1.25 per liter (www.total.co.ke), running the system every day for 4 hours would cost the farmer $900/year. Even running the system for only 100 days/year would incur an annual cost of $250.

4.2 Solar

A solar-powered system is a promising alternative, if the capital costs can be overcome. Photovoltaic cells convert sunlight into direct current, which can be stored in a battery and discharged throughout the night. Eldoret, Kenya has relatively high average annual solar irradiance of about 6 $kW/m^2 \cdot d$, comparable to the Southwest United States (see Appendix H), which bodes well for solar powered systems. To generate 1 kW/day with solar panels and assuming 4 hours of direct sunlight/day (Messenger & Ventre, 2010), a 250 watt solar panel is required. Two 100 watt panels cost less than a 150 watt panel, $250, but will not need to be replaced for the 10-year lifetime of the system. Wet, deep cycle, lead acid batteries are a cheaper energy storage system than other battery technologies. These batteries are commonly used in conjunction with solar power. Battery life can be determined via a 'cycles v. depth of discharge' curve for each specific battery. The deeper the battery is discharged, the fewer cycles it will be able to run (See Appendix Q). A 100 Ahr battery was found for $150.

4.3 Human and Wind Power

The other two options considered were human power and wind power. A human-powered system would consist of a bicycle pedaling system that charges a battery or directly provides a pump with electricity. The average person can produce 100 W/hour when riding a stationary bike (Jansen, 1999). To provide 1,000 W/day someone would have to ride the bike 10 hours per day, not taking into account the efficiency of the bike, battery, or pump. Based on a minimum wage of $0.15 / hour (africapay.org) for unskilled manual labor, it would cost the farmer $1.50 per day to run the aeration system. To power the system 100 days per year, it would cost $150, which is reasonable compared to other power source annual costs. However, the capital costs for the systems, the work force required, and the hours of work needed make it an unreasonable power source.

Wind power was considered as mechanical power for an aeration system or battery storage. To generate 0.4 kW/day in Eldoret, Kenya, where monthly average wind speed varies from 2 to 5 m/s (Harries, 2005), a wind turbine with a radius of 8 meters is required to ensure constant monthly power generation (see Appendix G). That size of turbine would be excessive for a 200 m^2 pond. A brief search on Kenyan wind power found one complete wind-battery system (tower diameter of 8 ft) available for more than $10,000 (Kijito Wind Power). This may not be the only system available, but the company has been around for over 30 years and operates in Kenya so the prices are assumed to be competitive for the area. The price of the system and scale of power required makes wind power unreasonable for this design. Due to the time required and the size of the system, both of these options were determined to be unreasonable.

4.4 Other Power Options

Other power options considered were biofuel and gravity systems. Biofuel ranged broadly from the combustion of wood to compressed organic matter ‘pellets’ to ethanol. Biofuel was deemed not feasible due to its lack of availability in rural areas, high annual costs, inefficiency, and potential environmental damage. Gravity systems involved the pumping of water to a higher elevation and, like the vertical pumps, allowing droplets to aerate as they fall and as they disrupt the pond’s surface. To create 1000 W/day of potential energy, the volume or height of the water would be unreasonable (see Appendix G).

5.0 Alternative Finalists

To determine the best combination of technology and power source, a final design matrix was created to combine the most feasible aeration and power technologies. Based on the discussions above, the finalists considered were: generator powered diffuser, generator powered venturi, solar powered diffuser, and solar powered venturi. The ranking rubric for the Final Design Matrix can be found in Appendix D. The categories, weighting, and rubric were created based on the design goals; because of this, the matrix is subjective. Explanation of the matrix scores can be found in Appendix F.

5.1 Final Design Matrix & Conclusion

Table 2: Final Design Matrix.

FINAL TECHNOLOGY	Technical Alternative →	Venturi + Solar + Battery	Venturi + Generator	Diffuser + Solar + Battery	Diffuser + Generator
	Weightage				
Technical					
Portability	10	1	4	1	4
Scalability	5	4	3	4	3
Oxygen delivered	25	4	4	5	5
Efficiency	25	4	4	3	3
Installation	10	1	3	2	4
Reliability	15	3	4	3	4
O&M	10	3	1	2	1
Overall Technical Score	100	25.2	28.4	25.2	29.2
Environmental					
Protection of water/fish	20	4	2	5	3
Emissions	30	5	2	5	2
Disposal	30	1	2	1	2
Protection from unwanted insects	20	3	3	3	3
Overall Environmental Score	100	6.4	4.4	6.8	4.8
Social					
Culturally Acceptable	30	4	3	4	3
Lack of Noise	20	5	1	5	1
Theft	50	2	3	2	3
Overall Social Score	100	6.4	5.2	6.4	5.2
Economic					
Capital Cost	40	2	4	2	4
Annual Cost	20	5	0	4	0
NPV	40	4	1	5	3
Overall Economic Score	100	27.2	16	28.8	22.4
Overall Score					
		65.2	**54**	**67.2**	**61.6**

The generator systems both scored slightly higher in the technology section than the solar powered systems. However, in all other categories (environmental, social and economic) the solar powered systems received a higher score. Based on the competitive scores and significantly higher scoring in the economic section, the solar powered systems were selected for final consideration. This left the solar powered venturi and the solar powered diffuser system.

A solar powered diffuser system is recommended because it scored best in the Final Design matrix, was determined to meet the design criteria/objectives, provides more oxygen per day, and was the most economical. The solar powered venturi system had very similar scores and had lower annual cost. However, the venturi system uses more power and adds less oxygen to the pond per day. The net present value (NPV) per mass of oxygen added for the solar venturi system was over \$1.00 per kg of oxygen delivered, while the solar diffuser system cost \$0.45 per kg of oxygen delivered (see Appendix E). Over the lifetime of the solar diffuser system, 10 years, the farmer is paying roughly half as much as the solar venturi system per mass of oxygen introduced to the pond.

6.0 Recommended Design

The diffuser-battery-solar panel system was selected for Kenya aquaculture aeration. The technical specifications, operation plan, economic components, and social aspects of the design are considered below.

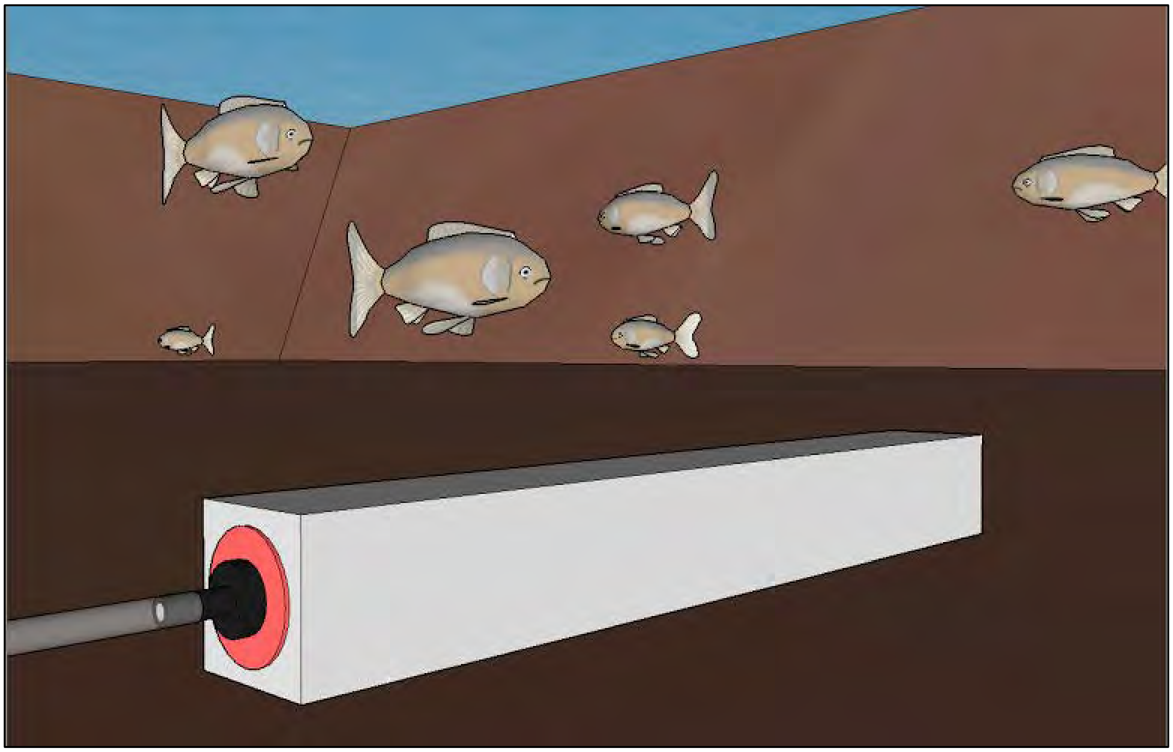


Fig. 5: Diffuser at the bottom of the pond.

6.1 Technical

The following section relies on calculations found in Appendix L. Table 3 outlines the components to be used in the final design.

Table 3: Final Design Components.

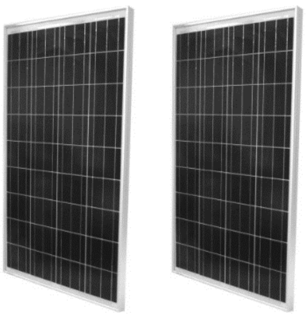
Components	Model	Quantity	Price per unit	Specs
Diffuser	Pentair Sweetwater AS30S	4	\$20	28.3 Lpm, 0.3m long, wetted pressure 17.3 kPa, medium pore
Pump	Boyu ACQ 906	1	\$80	12 V, 60 W, 120 Lpm, 120 kPa
Battery	Sollatek 100 Ahr Wet Lead Acid Battery	1	\$150	12 V, 100 amp hours, manufactured in Kenya
Solar Panel	WindyNation 100 W Polycrystalline PV Solar Panel	2	\$125	0.7 m^2, 100 W, 103 cm x 67 cm x 3 cm
Charge Controller	WindyNation P30L PWM 30 A Charge Controller	1	\$60	Built-in timer, 30 amp rating
Tubing	Readily Available	30 m	\$0.67 / m	6 mm ID
Wires	Readily Available	15 m	\$0.67 / m	10 gage

6.1.1 Battery

Wet Lead Acid Battery Sollatek (x1).

This 12 V battery is produced and sold in Kenya so shipping will not be a factor. Deep cycle batteries are difficult to ship because they are hazardous and heavy. The 100 Ahr rating was sized to ensure a 40% depth of discharge for regular run-time and provide a buffer for the system to operate for several cloudy days. A disposal procedure for lead acid batteries can be found in Appendix K.

6.1.2 Solar Panel



WindyNation 100 W Polycrystalline PV Solar Panel (x2).
It was assumed Eldoret, Kenya gets 4 hours of peak sun per day (Appendix H), this is assumed for the worst case scenario, most of the year peak sun will be higher. The panels will be mounted flat since Eldoret, Kenya is close to the equator. With the assumption of 4 hours of peak sun and no losses, the panels could produce 800 Whr/day. The system calculations show that 580Whr are required to recharge the battery every day (see Appendix L). The potential output is more than enough power needed to run the pump. These panels are also very cost effective and were less expensive than other panels and solar packages considered. Accumulation of dust is expected to occur on the panels; as such, regular cleaning is expected.

6.1.3 Charge Controller

WindyNation P30L PWM Charge Controller.
This charge controller was chosen because it includes a built-in timer, is rated for 30 A, and has a simplistic interface.

6.1.4 Pump

Boyu 906 ACQ Air compressor.
The air compressor has a low power draw and a small footprint so it has a long runtime and is easily stored.

6.1.5 Diffuser

Pentair Sweetwater AS30S diffuser.
These diffusers connect to ¼ inch tubing and have a dynamic wetted pressure of about 1.7 kPa. They produce a medium pore bubble (~3mm) that is optimal for economic aeration. The manufacturer states that they are very resistant to clogging which is necessary for an earthen pond (Pentair, 2014). The diffusers can be cleaned with hydrochloric acid as needed. Four diffusers will be centered in their own quadrants at the base of the pool (Fig. 6). The quadrant structure is selected to distribute aeration equally.

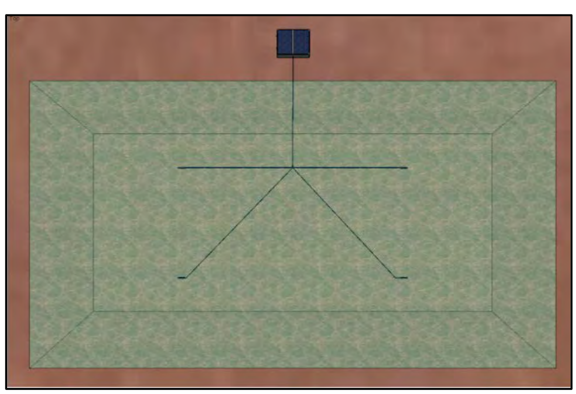


Fig. 6: Diffuser orientation within pond.

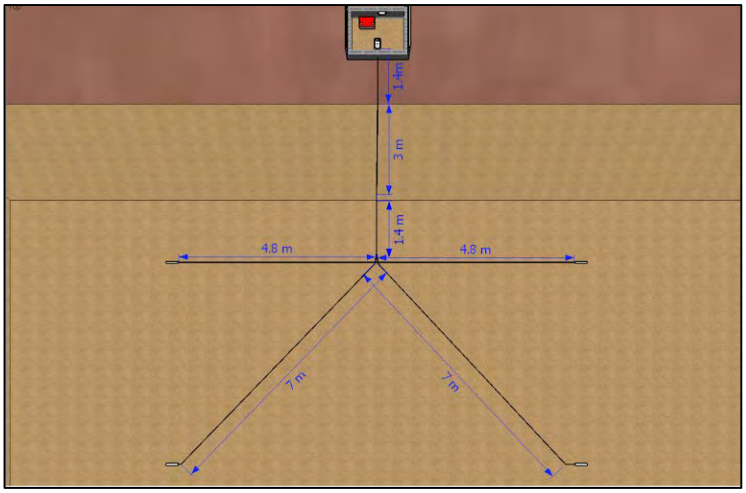
6.1.6 Wiring

15 meters of AWG 10 gage wire. The two solar panels have a maximum current of 5.75 amps in their wires, and the panels will be feeding power through one set of wires into the charge controller. The wires connecting the panels to the controller have the largest current, therefore the wires are sized based on these specs. Using a wire gauge design chart, 10 gauge wire will be best for the system (see Appendix J).

6.1.7 Tubing

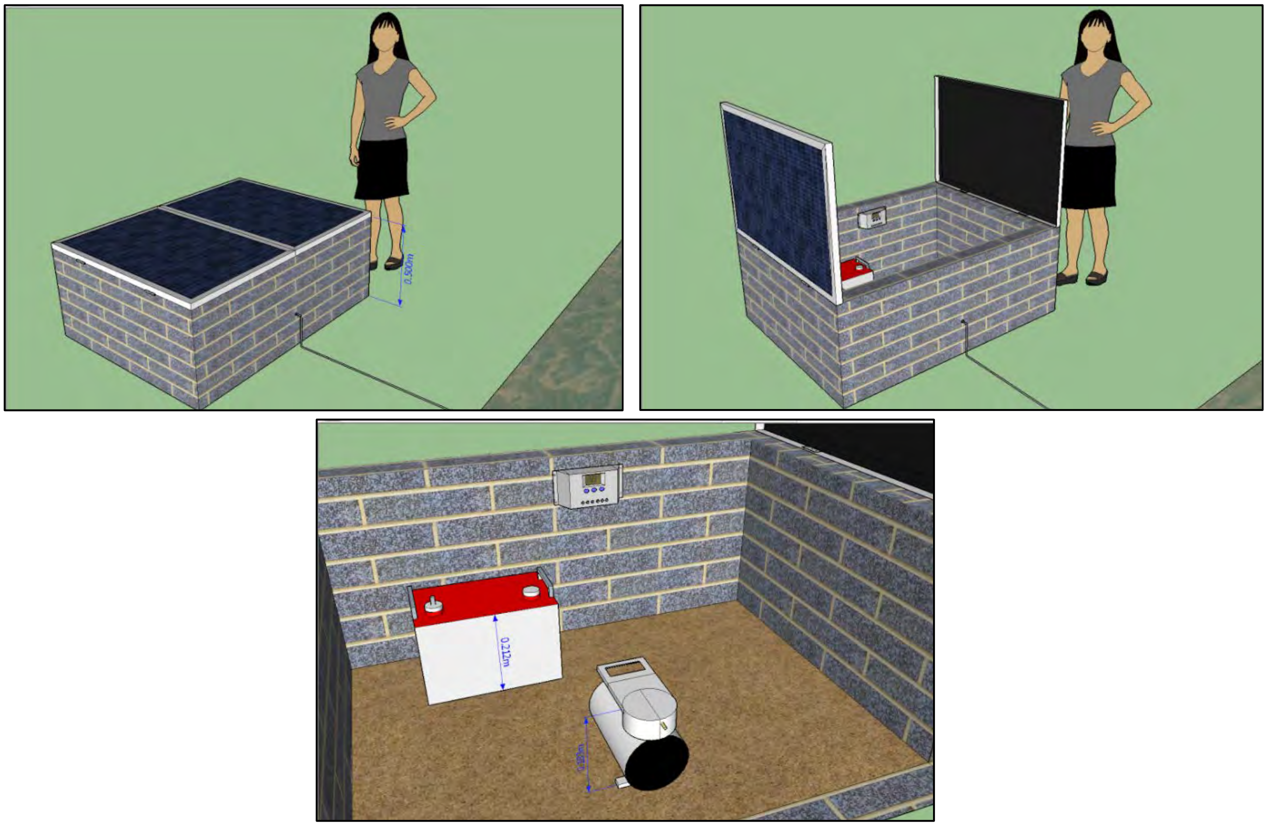
50 m of 6 mm inner diameter clear plastic tubing. The tubing is flexible, resistant to clogging and fouling, and easy to clean. It is available at most hardware stores and online. The tubing does float in the water, so weights will be added to the tubing line. Tubing layout and dimensions are shown below. A 4-way manifold will also be needed to split the tubing that leads to the diffusers (Fig. 7). This manifold will placed above the water level next to the pump (not shown below) with adjustable valves to control flow rate.

Fig. 7: Tubing lengths in pond.



6.1.8 Housing

The battery, pump, and charge controller will be stored inside a brick housing unit. On top of the brick walls, two solar panels will be hinged which allows access to its contents within. Not shown is the locking mechanism for the solar panels. A swinging clasp will be placed at the seam between the two panels and will be padlocked. Small holes will be built into the structure through spaced brick-laying (also not shown), to allow for adequate air for the pump. A hole will also be constructed to allow tubing to exit the housing. Mesh material will be placed around the bottom of the housing and covering structure holes to prevent snakes from nesting. This housing unit has extra space for storing additional materials (Fig. 8).



.Fig. 8: (Clockwise from upper left) Closed housing; open housing; pump, battery, and charge controller within housing.

6.2 Operation Plan

It is assumed that algae will photosynthesize during the day, helping aerate the fish pond, and respire at night, consuming oxygen. Therefore, the aerator was designed to run at night. It was also assumed that aeration would not be necessary at the beginning of the growth cycle, while the tilapia are 50-100 g, because they do not require as much oxygen as larger fish. Harvest cycles usually last 4 months (Dr. Egna, personal communication, 2014), so the aerator has been intended to run 100 days per harvest cycle. The system could run longer, but 200 days per year was estimated for the system's 10 year lifespan. Although these assumptions seem reasonable for an aeration system, the farmer is encouraged to monitor the fish and provide oxygen at any point that the fish are struggling to breathe. Examples of oxygen demand include grouping around the air stone or gulping air (Dr. Egna, personal communication, 2014).

6.3 Economic

The capital cost of the system is $755 and, using an internal rate of return of 8.5 percent (Central Bank of Kenya, 2015), net present value calculated over the 10 year design life is -$1,110. The price of oxygen over the lifetime of the system is $0.28 per kg oxygen. The air pump is expected to be bought three times over the design life. The battery is sized to a 40% depth of discharge which allows a 10 year lifespan. Annual maintenance cost was estimated to be 5 percent of capital costs ($38). This cost will include hydrochloric acid for diffusers and other unexpected maintenance costs including parts replacement. For detailed economic calculations refer to Appendix O.

The ability to reliably produce and sell fish will pay for the system over its lifetime and increase revenue. This was not included in the NPV analysis because cost of juvenile tilapia is unknown in Kenya. Even if the farmer is not purchasing the aerator to increase fish production, it provides insurance that the product will survive. Because the capital cost of the system is above $200, this aeration system's target audience is likely to be established fish farms. Smaller farms may need to invest in a microloan to purchase this system.

6.4 Social

This design would be quiet, with the only source of noise coming from the pump. The noise itself does not hinder conversations near it and ear protection is not required. Once the pump is placed in the housing, the noise will decrease significantly. Theft is an issue regarding large solar panels and a high quality battery. As mentioned above, the battery and pump will be housed in a brick structure, like a box, with the solar panel placed on top, acting as the lid. The solar panels will be hinged along the outer edge to allow the farmer to open the lid and provide easy access to the battery and pump inside. In addition to the hinge, a swinging clasp will be placed at the seam between the two panels and will be padlocked. Snakes are present in Kenya. The holes in the housing unit for air circulation and around the bottom of the housing will be covered with a mesh material to prevent snakes from entering.

7.0 Prototype

To test the system's oxygen transfer efficacy, a prototype was built and tested. The testing attempted to simulate diurnal variation, algae oxygen production, fish respiration, and aeration efficiency.

7.1 Methodology

In Kenya, the aerator will be operating during the night hours, when respiration exceeds oxygen supply due to algae respiration. To simplify testing and measurements during the peak oxygen-demand hours, day and night were flipped, with "day" occurring 6pm - 6am, and "night" occurring from 6am-6pm. "Night" was simulated with black tarp placed over the pond, and "day" was simulated with three 400 watt grow-lights. The experiment took place in a 50% shaded greenhouse.

Inflatable pools were used. The pool's volume was 1 m^3 (0.33 m deep and a surface area of 3 m^3). The pool contained a heater to keep the water at 25°C, a pump for water circulation, and a peristaltic pump which was to simulate fish oxygen demand by continuously pumping sodium sulfite, a chemical which consumes oxygen, at 1.3 mL/min. A solution of 1.5 liters of algae was added to the pool prior to testing. A fish stocking density of 5 fish/m^3 was chosen.

Over the course of the 5-day experiment, increasing fish weight was simulated each day to test the aerator's ability to provide ample oxygen to sustain fish growth in real-world scenarios (Table 4).

Table 4: Simulated fish weights for testing.

Day	1	2	3	4	5
Fish Weight (g)	50	100	150	200	250
Na_2SO_3 (g/L)	28.44	51.48	70.37	86.10	99.44

This method relies on the oxidation of Na_2SO_3 to Na_2SO_4 in the presence of oxygen to decrease DO concentrations. It effectively reduces the DO concentration based on a known ratio of Na_2SO_3 to oxygen.

7.2 Technical

7.2.1 Scaling

To scale down the large system to the prototype, the mass of oxygen delivered per volume of water per night (5 g oxygen /m^3) was held constant. With a diffused aeration system, pond dimensions are very important in determining efficiency and oxygen transfer rates. The large pond for the final design is 400 m^3 with a depth of 2 m, while the test pool for the prototype is 1 m^3 with a depth of 0.3 m. The standard oxygen transfer efficiency (SOTE) is the percentage of oxygen that actually dissolves in the water as the bubbles rise to the surface. In the large scale pond (at 2 m deep), SOTE = 15%. In the prototype pool (at 0.3 m deep), SOTE = 3% (see Appendix I). With these values, the airflow rate needed from the pump was found, and the prototype components were sized. Calculations for both the large and small scale systems can be found in Appendix M.

The pump (5.7 lpm, and 6.9 kPa pressure) used for the prototype had a current of 2.1 amps, and the required system run time varied from 3 - 12 hours, depending on fish size. The battery required capacity of at least 25 amp hours so it would have enough power to run the system all night (12 hours) when the fish were near harvest size and respiration rates were highest (see Appendix N). A 35 amp hour battery was used so that on the days of highest oxygen demand, the battery would not completely drain. It is important to oversize the battery so that it is not being fully drained every night and there is still power stored on cloudy days.

A 30 watt solar panel was purchased for the prototype so that each day under the grow lights (12 hours) the panel would provide 360 watt hours to the battery. The expected amount of power provided by the panel each day is greater than the power needed to run the system in the later stages of the harvest cycle. If the grow lights accurately mimic sunlight, the system will have excess power. A charge controller was used to prevent overcharging and control depth of discharge in the system. The same controller will be used in the large system. The power calculations can be found in Appendix N.

7.2.2 Wiring

The wiring for the smaller system is identical to the planned wiring for the larger system. Wire lengths on all components will not exceed 1 meter, keeping resistance minimal. 20 amp fuses will be used to prevent system malfunction.

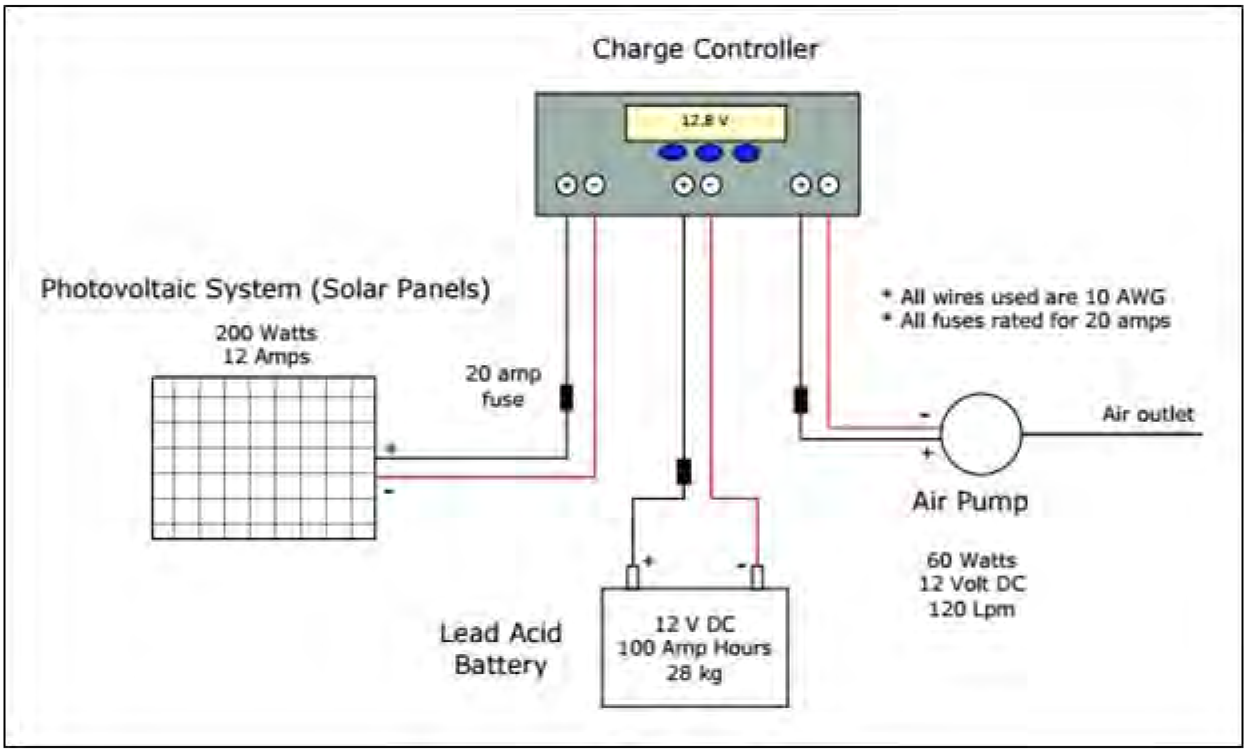


Fig. 9: Wiring Diagram.

7.2.3 Operation

The prototype was intended to be run longer as the simulated fish size was increased. Original intended operation is shown in Table 5.

Table 5: Intended operation schedule.

REAL TIME	POND TIME	Fish Size / Day				
		50 g	100 g	150 g	200 g	250 g
		Day 1	Day 2	Day 3	Day 4	Day 5
		Sun-Mon	Mon-Tues	Tues-Wed	Wed-Thurs	Thurs-Fri
18:00						
19:00						
20:00						
21:00						
22:00						
23:00						
0:00						
1:00						
2:00						
3:00						
4:00						
5:00						
6:00						
7:00						
8:00						
9:00						
10:00						
11:00						
12:00						
13:00						
14:00						
15:00						
16:00						
17:00						

7.2.4 Photos of Prototype System

Fig. 10: Prototype.

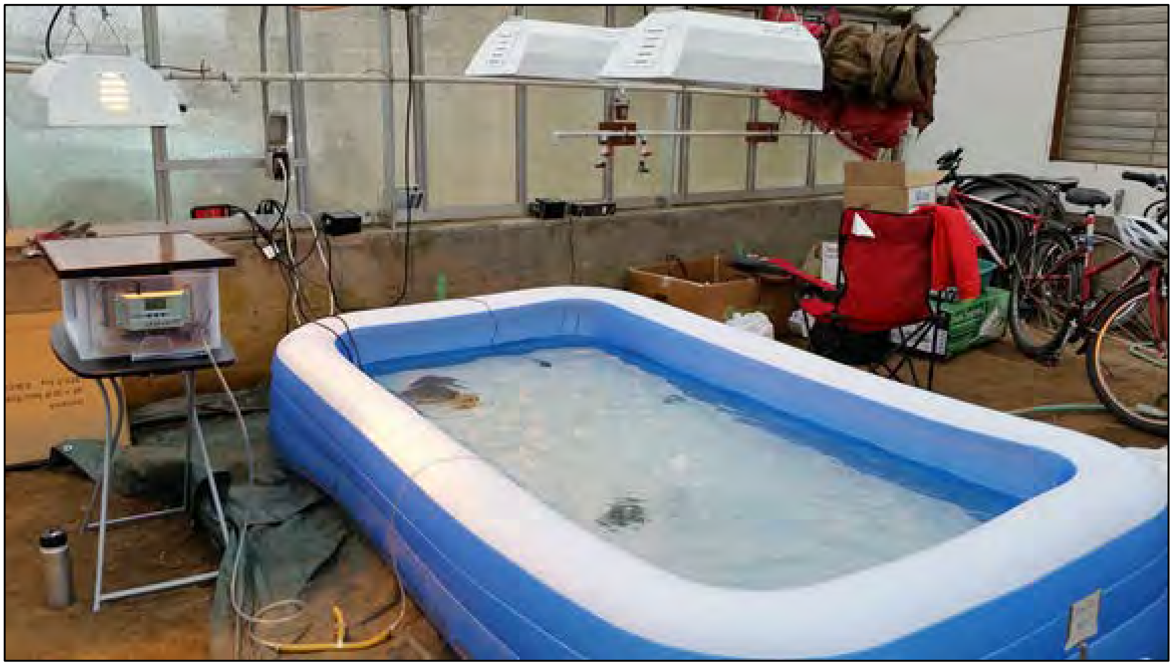


Fig. 11: Prototype aerating water.

7.3 Results & Discussion

Prior to the experiment, Kla, or the oxygen transfer coefficient, was determined. To test this, the pond's oxygen concentration was lowered to 3 mg/L with sodium sulfide and then the dissolved oxygen concentration was measured every 5 minutes while the aerator ran. The results from this are shown in Fig. 12. The oxygen transfer coefficient was then calculated (see Appendix P). It was found to be 0.65 hr^{-1}.

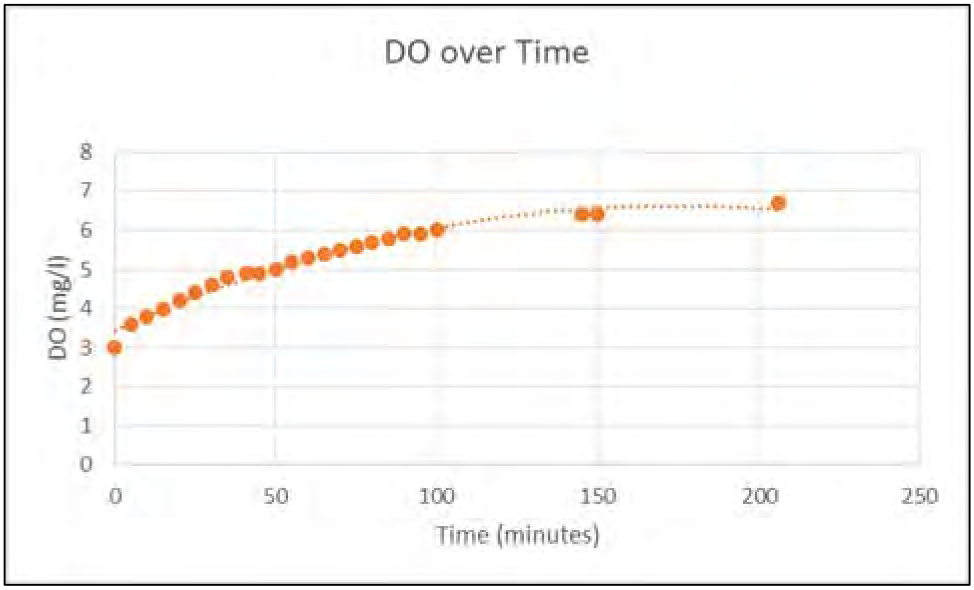


Fig. 12: Dissolved oxygen over time.

The expected standard oxygen transfer rate (SOTR) was then determined with the Kla, volume of the pond, and dissolved oxygen concentration. It was found to be 0.0022 kg/hr (Appendix P). The standard oxygen transfer efficiency (SOTE) of diffusers varies significantly by depth. As previously mentioned, the shallow pool resulted in a decrease from 15% SOTE to 3% SOTE (Appendix I). The reduced depth of the prototype pond significantly reduces the efficiency of diffusers, so it is expected that the full-sized system would have a higher SOTR.

Combining the SOTR and power consumption results in the standard aeration efficiency (SAE). Using the pump's draw of 2.1 amps at 12 V, the SAE was found to be 0.035 kg/kWh (see Appendix P). Again, this is lower than anticipated. Literature cites diffuser SAE between 0.6 kg/kWh and 2.2 kg/kWhr (Colt & Orwicz, 1991). The increased depth of the full-scale pond should increase oxygen transfer and help manage this difference.

The prototype results are shown in the figure below (Fig. 13). As the represented fish size increased, the respiration rate increased.

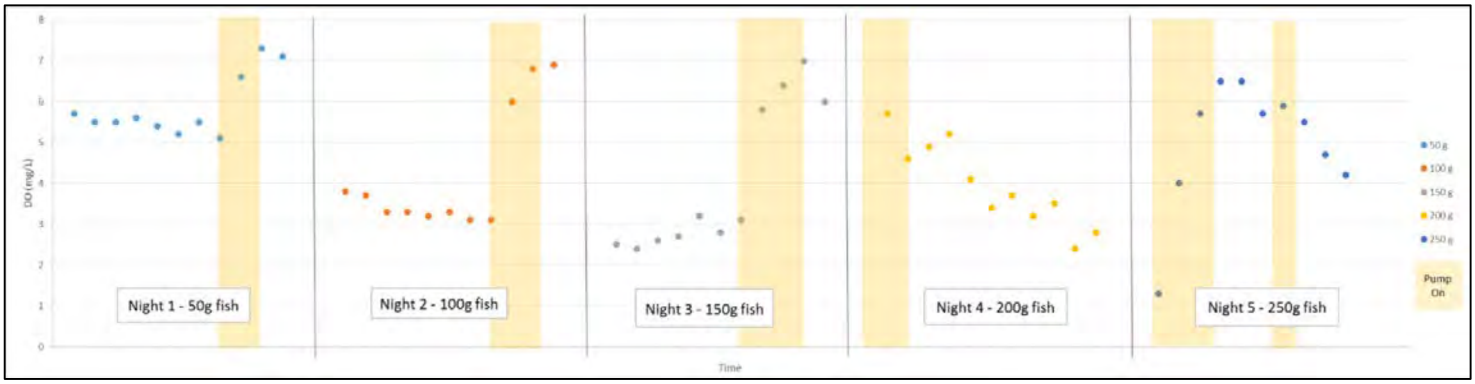


Fig. 13: Chart shows DO measurements taken between 8am - 6pm hours (during the simulated night) for each fish size. The yellow bands signify when aerator was run.

The experiment showed, especially in the first three fish weight simulations, that when the aerator was used, the DO in the water increased substantially. This was expected and demonstrates the efficacy of the diffuser aerator system. The chart does show that the DO dropped below the 4 mg/l threshold for tilapia, but this is believed to be based on errors in the experiment set-up and changes in operation timing.

The prototype experiment was plagued with errors such as an algae die-off, sodium sulfide that was unevenly mixed, and discrepancies in testing. The largest problem stemmed from the solar panel not being exposed to enough sunlight. It was unable to charge with the grow lights and the 50% shaded greenhouse reduced the ability to charge during the true-day. The inability to charge the battery resulted in an inability to reliably run the aerator, especially on the 4th and 5th days of testing. This is why the aerator was not run as the DO decreased in the pool on the 4th night.

The problems with testing were largely related to a tight timeline and non-comprehensive planning. In future tests, with the panel placed in a higher-sun environment and more time for the pond to equilibrate, it is expected the results will more accurately reflect the expected operating results. This experiment did prove that the aerator can significantly raise DO, and further tests would prove its ability to maintain oxygen above 4 mg/L for tilapia survival.

8.0 Conclusion

A solar powered diffuser system is the best design possible for aerating an aquaculture pond in Kenya. Given the specific location of Eldoret, the best technology (diffusers) and the best power source (solar) were combined to maximize the amount of oxygen delivered per dollar. The system is economical, robust, and aerates well. Considerations were given to environmental and social factors ensuring that the implementation of the system will be successful. The prototype was tested under Kenyan conditions and while the prototype saw many unanticipated errors, it also provided promising evidence for aeration capability. This design is capable of bulk production and will be able to function properly in regions with similar climatic conditions as Eldoret, Kenya.

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10.0 Appendices

List of Appendices

Appendix A: Technical Design Matrix Rubric

		Economic	Environmental			Social	
		Capital Costs (C.C)	Protect Water/Fish	Potential Bank Erosion	Protect Against Insects	Culturally Acceptable	Theft
0	Fail	> $1,000	Contaminated water and dead fish	Extreme bank erosion	Attracts excessive amount of insects	Technology has been used and already widely recieved negatiely	Attractive components are exposed with no security measures possible
1	Bad	$800 < C.C. < $1,000	Poor water and stressed fish	Heavy bank erosion	Attracts many insects	Technology has not been used but actively challenges social and cultural norms	Attractive components are exposed and impossible to secure
2	Poor	$600 < C.C. < $800	Substandard water and slightly stressed fish	Moderate bank erosion	Attracts moderate amount of insects	Technology has not been used in region, cultural and social norms is unknown	Attractive components exposed and difficult to secure
3	Acceptable	$400 < C.C. < $600	Moderately clean water and normal fish	Mild bank erosion	Attracts few insects	Technology has not been used in region, meeting cultural and social norms is expected to be positive	Attractive components are exposed and require moderate security
4	Good	$200 < C.C. < $400	Clean water and healthy fish	Slight bank erosion	Attracts no insects	Technology is occaasionally used in region, fits well with cultural and social norms	Attractive exposed components are easily secured
5	Excellent	C.C. < $200	Pristine water and thriving fish	No bank erosion	Facilitates the removal of insects	Technology is used widely in aera, fits well with cultural and social norms	No attractive components exposed

		Technical					
		Portability	Installation	Reliability	Scalability	O&M	Efficiency (kg O2 / kW*hr)
0	Fail	> 125 lbs	Intensive, multiday, multiperson setup	Multiple moving parts and requires weekly repairs	Impossible: will not work on a small scale	Cleaning/maintenance needed daily	SAE = 0
1	Bad	100 - 125 lbs	Intensive setup	Multiple moving parts and requires repairs per harvest	Difficult to scale: no previous history of scalable systems	Cleaning/maintenance needed once every week	SAE = 0 - 0.67
2	Poor	75 - 100 lbs	Difficult setup	Few moving parts and requires repairs per harvest	Scaling possible, but parts difficult to find	Cleaning/maintenance needed once every 2 weeks	SAE = 0.67 - 1.3
3	Acceptable	50 - 75 lbs	Moderate setup	Few moving parts and requires annual repairs	Scaling possilbe, parts avaliable	Cleaning/maintenance needed once every 8 weeks	SAE = 1.3 - 2.0
4	Good	25 - 50 lbs	Simple setup	Few moving parts and requires repairs every 2 years	Scaling common and parts avalialbe	Cleaning/maintenance at the end of each harvest cycle	SAE = 2.0 - 2.7
5	Excellent	0 - 25 lbs	Little to no setup	Few moving parts and few repairs expected over liifespan	Easy to scale and parts avaliable	Cleaning/maintenance at the end of each third harvest cycle	SAE > 2.7

Appendix B: Technical Design Matrix calculations

Paddlewheel:

Team 1 | PADDLE WHEEL AERATION | [redacted]

(It is difficult to calculate oxygen transfer from physical principles in this design (due to variability in turbulence, bubbles, splash, lift, ~~ect~~ etc) so empirical values will be utilized.)

OXYGEN TRANSFER

For a given system (below) how long will it take to transfer 2 kg O_2 into the pond?

Specifications
- paddle wheel length = 45cm
- paddle depth = 13 cm
- paddle size = 5 cm wide, 135° interior angle
- diameter = 61 cm
- rev/min = 85
- SORT = Ø.85 kg O_2/hr
- SAE = 2.19 kg O_2/kWhr
- Brake power = Ø.39 kw

(Moore, 1992)

These specs chosen b/c brake power ≈ Ø.5hp. Other specifications given in table or empirical calculations.

Calculate O_2 in pond with the SOTR corrected for water temp (because gas / liquid transfer decreases when gas content is closer to saturation)

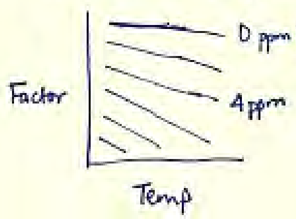


Figure 8 (Boyd, 1998)

initial DO assumed 4ppm (4mg/L)
temperature = 30 °C
correction factor = Ø.5

SOTR (at Øppm DO) = Ø.85 kg O_2/hr
SOTR' (at 4ppm & 30°C) = (Ø.85 kg O_2/hr)(Ø.5) = Ø.425 kg O_2/hr

Assuming needed O_2 / day = 2 kg O_2 (or 5 mg/L) ← rough potential estimate, will probably change

$$\frac{2 \text{ kg } O_2}{Ø.425 \text{ kg } O_2} = \boxed{4.7 \text{ hr}}$$

This would provide enough oxygen to the pond overnight, so it is feasible.

<u>Venturi:</u>

Venturi Design Calculations	BEE 469	[redacted]

Design Calculations for a Venturi Aeration System

First we need to calculate how much oxygen the system needs to deliver. Team One set the minimum DO level we would accept at 4 mg/L, and the saturated DO level at 9 mg/L. Our other known value is the dimensions of the pond ($20_m \times 10_m \times 2\ m$).

$DO_{min} = 4\ mg/L$

$DO_{sat} = 9\ mg/L$

$V_{pond} = 400\ m^3$ ($20 \times 10 \times 2$)

Our system needs to keep DO levels up during the night, when algae are using up oxygen and not photosynthesizing. Night time is assumed to be 8 hours. Therefore the system will need to run 8 hours per day.

$$DO_{sat} - DO_{min} = 9\ mg/L - 4\ mg/L = \underline{5\ mg/L \text{ of } O_2 \text{ per night}}$$

We have the concentration of oxygen needed per night, now we will convert the concentration to a mass of O_2 and finally a mass of air.

$$(\text{Vol pond})(\text{Conc. } O_2) = \text{Mass } O_2 \qquad (400\ m^3)\left(\frac{1000\ L}{1\ m^3}\right)\left(5\ mg/L\right) = \underline{2,000,000\ mg\ O_2}$$

$$2,000,000\ mg\ O_2 \ \frac{1\ kg}{1,000,000\ mg} = \boxed{2\ kg\ O_2}$$

↳ Oxygen is 21% of the atm

$$\text{↳ } 2\ kg\ O_2 \ \frac{5\ kg\ air}{1\ kg\ O_2} = \boxed{10\ kg \text{ air needed per night}}$$

We need 10 kg air to flow through our air tube each night (8 hrs). What is the flow rate needed in the air tube?

$$Q_{Air} = \frac{\text{Vol air}}{\text{time}} = \frac{(10\ kg\ air)\left(\frac{1\ m^3\ air}{1.2\ kg\ air}\right)}{(8\ hr)\left(\frac{3600\ s}{1\ hr}\right)} = \frac{8.33\ m^3}{28800\ sec} = \underline{2.9 \times 10^{-4}\ m^3/s}$$

$$\boxed{Q_{Air} = 2.9 \times 10^{-4}\ m^3/s}$$

Now we need to find the pressure differential in the venturi system that makes $Q_{air} = 2.9 \times 10^{-4}\ m^3/s$. The system will be run using a ½ hp pump, with a flow rate of 2600 GPH. (The group chose ½ hp as the pump size/power source to use unless our design calcs)

½ hp pump: $2600 \frac{gal}{hr} \cdot \frac{1\ hr}{3600\ sec} \cdot \frac{.00378\ m^3}{1\ gal} = \underline{.0027\ m^3/s = Q_{water}}$

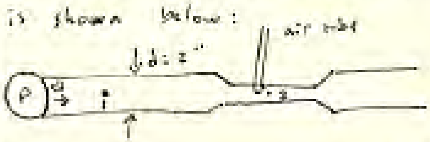
↑ flow rate of water exiting the pump.

Using the Power eqn. we can find the head provided by this setup.

$$P = \gamma Q h \qquad 375\ watt = \left(9800 \frac{kg}{m^2 s^2}\right)\left(.0027\ m^3/s\right)(h)$$

$$\underline{h = 14.17\ m}$$

With the head and flow rate at the pipe outlet, we can calculate pressure. A system diagram is shown below:



$$h_1 = \frac{P_1}{\gamma} + \frac{v_1^2}{2g} + z_1$$

$$h_1 = \frac{P_1}{\gamma} + \frac{\left(\frac{Q}{A}\right)^2}{2g} + \cancel{z_1}\ \emptyset$$

where $A = \frac{\pi (2")^2}{4}$

$A = 3.14\ in^2$
$\underline{A = .001\ m^2}$

$$14.17\,m = \frac{P_1}{9800 \frac{kg}{m^2 s^2}} + \frac{\left(\frac{.0027\ m^3/s}{.002\ m^2}\right)^2}{2\,(9.8\ m/s^2)}$$

$$14.07 = \frac{P_1}{9800} \Rightarrow \boxed{P_1 = 137.9\ kPa}$$

With the pressure at point 1, we can now calculate the pressure at point 2. I'll start by setting $P_2 = \emptyset$ since this is the threshold where air will start moving into the system. The venturi works by having a lower pressure in the pipe constriction than in the outside air, and $P_{air} = \emptyset\ Pa$. So the largest area the pipe constriction can have is where $P_2 = \emptyset$.

First, write Bernoulli from ① → ②

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + \cancel{z_1} = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + \cancel{z_2}$$

Cancel z since both points are at the same depth.

$$P_2 = \left(\frac{P_1}{\gamma} + \frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right)\gamma$$

Isolate P_2

$$P_2 = P_1 + \left(\frac{V_1^2 - V_2^2}{2\cancel{g}}\right)\rho\cancel{g}$$

Cancel gravity terms

$$P_2 = P_1 + \left(\frac{\left(\frac{Q}{A_1}\right)^2 - \left(\frac{Q}{A_2}\right)^2}{2}\right)\rho$$

rewrite V... $V = \frac{Q}{A}$

$$P_2 = P_1 + \frac{\rho Q^2}{2}\left(\frac{1}{A_1^2} - \frac{1}{A_2^2}\right)$$

Set $P_2 = \emptyset$, solve for A_2

Set = $\emptyset$ to find max A_2 for airflow

$$\emptyset = 137900 \text{ Pa} + \frac{(1000 \, kg/m^3)(.0027 \, m^3/s)^2}{2}\left(\frac{1}{.002 m^2} - \frac{1}{A_2^2}\right)$$

$$-137900 \text{ Pa} = .0036\left(\frac{1}{.002^2} - \frac{1}{A_2^2}\right)$$

$$-38305555 \text{ Pa} = 250{,}000 - \frac{1}{A_2^2}$$

$$\frac{1}{A_2^2} = 3.85 \times 10^7 \text{ Pa} \rightarrow \underline{A_2 = .00016 \, m^2} \rightarrow .00016 m^2 = \frac{\pi d^2}{4} \rightarrow d = .014 \, m = \underline{.56''}$$

Max diameter pipe in the constriction = .56"

Since the max possible diameter = .56", I'm going to plug in $A_2 = .0001 \, m^2$ (1 + 3/8")

$$P_2 = P_1 + \frac{\rho Q^2}{2}\left(\frac{1}{A_1^2} - \frac{1}{A_2^2}\right)$$

Solve for P_2

$$P_2 = 137900\ Pa + \frac{(1000\ kg/m^3)(.0027\ m^3/s)^2}{2}\left(\frac{1}{.002^2} - \frac{1}{.0002^2}\right)$$

$$P_2 = 137900\ Pa + -357024\ Pa$$

$\hookrightarrow \underline{P_2 = -225\ kPa}$ ← Now with this pressure at point 2, what airflow rate is achieved down the air tube.

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_L$$

$\hookrightarrow h_L = f\frac{L}{d}\frac{V_2^2}{2g}$

Everything on the left side cancels to $\emptyset$ since P, V, and z at the water surface $= \emptyset$

$$\emptyset = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + f\frac{L}{d}\frac{V_2^2}{2g}$$

Solve for V_2

- $z_2 = 2\ m$
- f_{PVC} is assumed to be 0.02
- Length of air tube = 2 m
- Diameter of air tube = 1/8" = .0032

$$\frac{-P_2}{\gamma} - z_2 = \frac{V_2^2}{2g}\left(1 + f\frac{L}{d}\right)$$

$$\frac{-(-225000\ Pa)}{9800\ \frac{kg}{m^2s^2}} - 2\ m = \frac{V_2^2}{2g}\left(1 + (.02)\left(\frac{2m}{.0032\ m}\right)\right)$$

$$20.95 = \frac{V_2^2}{2g}(13.5) \rightarrow \boxed{V_2 = 5.51\ m/s}$$

velocity of air down into system.

With V_{air} we can find Q_{air} of this setup.

$$Q_{air} = (V_{air})(A_{air}) = (5.51\ m/s)\left(\frac{\pi(.0032)^2}{4}\right)$$

$\underline{Q_{air} = 4.43\times10^{-5}\ m^3/s}$

$\hookrightarrow$ this is smaller than Q_{air} needed (pg 1 of design calc)

$$4.43\times10^{-5} < 2.9\times10^{-4}\ m^3/s$$

calculated needed

We can redo the calculations w/ smaller pipes to try and achieve this $2.9\times10^{-4}\ m^3/s$ flow rate.

The last calculation used 3/8" pipe as the constriction diameter and a 2" diameter for the larger pipe.

This next calculation will be for a 1/4" pipe at the constriction

$$P_2 = P_1 + \frac{\rho Q^2}{2}\left(\frac{1}{A_1^2} - \frac{1}{A_2^2}\right)$$

$$P_1 = 137900\ Pa + \frac{(1000\ kg/m^3)(.00027\ m^3/s)^2}{2}\left(\frac{1}{.002^2} - \frac{1}{3.16\times10^{-5}\ m^2}\right)$$

$$\underline{P_2 = -3495\ kPa}$$

↳ Now plug P_2 in to solve for V_{air} like before.

$$\cancel{0} = \frac{P_2}{\gamma} + \frac{v_2^2}{2g} + z_2 + h_L$$

$$\frac{-P_2}{\gamma} - z_2 = \frac{v_2^2}{2g}\left(1 + f\frac{L}{d}\right)$$

$$35.4\ m = \frac{v_2^2}{2g}(13.5)$$

$$V_2^2 = 515 \rightarrow \underline{V_{air} = 22.6\ m/s} \rightarrow Q_{air} = (22.6\ m/s)\left(\frac{\pi(.0032)^2}{4}\right)$$

$$\boxed{Q_{air} = 1.8\times10^{-4}\ m^3/s}$$

↳ Still too low, this setup would provide ...

$$1.8\times10^{-4}\ m^3/s \cdot \frac{1.2\ kg\ air}{1\ m^3\ air} \cdot \frac{28800\ s}{1\ cycle}$$

$$\boxed{\begin{array}{l} = 6.2\ kg\ \text{air per night} \\ = 1.25\ kg\ O_2\ \text{per night} \end{array}}$$

This setup falls short of our goal of providing 2 kg O_2 in 8 hours. We have a few options:

1) Purchase a pump with a higher flow rate

2) Run the system longer (13 hours would provide 2 kg O_2)

Vertical pump:

Vertical Pump Aerator

$\ast$ = assumptions

① Hypothetical Pond Turnover Time → how long would it take for a vertical pump to aerate all the water in the pond?

Online retail "AquaTech" lists a $\frac{1}{2}$ hp vertical pump to have a circulation rate $15 \frac{m^3}{hr}$

$\ast$ Nightly run time = 8hr
$\ast$ Volume of pond = 400 m^3
$\ast$ Water passing through aerator becomes saturated

$15 \frac{m^3}{hr} \cdot 8\,hr = 120\,m^3$ can be circulated by a $\frac{1}{2}$ hp vertical pump in 8 hrs

$\therefore \frac{400\,m^3}{15\frac{m^3}{hr}} = \boxed{26\,hrs}$ to aerate the entire pond

The entire pond cannot be mixed in 1 night - it requires 26 hrs of continuous pumping to circulate all the water in the pond, hypothetically. "Hypothetically" is used because vertical pumps draw water directly adjacent to them, thus not being likely to mix & aerate all water in the pond.

← Vertical Pump Sketch

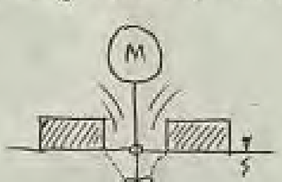
Online retail "AquaTech" lists a $\frac{1}{2}$ hp propeller aerator with float to have a circulation rate of $120 \frac{m^3}{hr}$

$\ast$ Nightly run time = 8hrs
$\ast$ Volume of pond = 400 m^3
$\ast$ Water passing through aerator becomes saturated

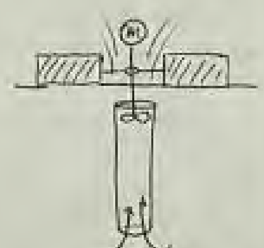
$120 \frac{m^3}{hr} \cdot 8\,hrs = 960\,m^3$ can be circulated by a $\frac{1}{2}$ hp propeller aerator in 8hrs

$\frac{400\,m^3}{120\frac{m^3}{hr}} = \boxed{3.3\,hrs}$ to aerate the entire pond

The entire pond can be mixed more than twice in 8hrs. But again, complete mixing of the pond unattainable.



← Propeller Aerator Sketch



? Could a pipe be fitted onto the propeller to draw water from the bottom of the pond?

(2) Hypothetical Time Required for Pond to deliver O_2 needs for $\frac{1}{2}$ hp system

* $DO_{initial} = 4\ \frac{mg}{L}$ * Respiration accounts for $5ppm = 5\ \frac{mg}{L}$ * Nightly run time = 8 hrs

→ Therefore, aerator must supply 5ppm oxygen to water.

Mass of O_2 delivered in 1 aeration period = (SAE)(P)(t)

* Average $SAE = 1\ \frac{kg\ O_2}{hp \cdot hr}$

$$M_{O_2} = \left(1\ \frac{kg\ O_2}{hp \cdot hr}\right)(0.5\ hp)(8\ hrs) = 4\ kg\ O_2$$ can be delivered in 1 night

* At T = 30°C & $DO_{initial}$ = 4ppm, actual SAE is half that of reported value (Boyd, 1998)

↳ actual $SAE = 0.5\ \frac{kg\ O_2}{hp \cdot hr}$

∴ 2 kg O_2 can be delivered in 8hrs to the pond water

→ So how long will the aerator take to put 5ppm into the water? What's the mass of 5ppm of oxygen?

$$5\ \frac{mg}{L} \cdot \frac{1000\ L}{1\ m^3} \cdot \frac{1\ kg}{10^6\ mg} \cdot 400\ m^3 = 2\ kg\ O_2$$ required to attain 5ppm in a $400m^3$ pond

* Assuming the oxygen is evenly distributed throughout pond

Since it is already known that the aerator can deliver 2 kg O_2 in 8hrs, to add 2kg O_2 to the pond water, it would mean that the aerator must run for $\boxed{8\ hrs}$.

Solar Power

* $\frac{1}{2}$ hp power requirement = 0.37 kW = 370 W * Run time = 8hrs

* Solar panels 20% efficient at turning photons into electricity

(3) What area of solar panels are required to power a 370W system for 8hrs?

"Electricity power solar energy" powerpoint on Blackboard has a world solar energy map on slide 7. Kenya's annual average solar irradiance ≈ $2000\ \frac{kWhr}{m^2 \cdot yr}$

$$2000\ \frac{kWhr}{m^2 \cdot yr} \cdot \frac{1\ yr}{365\ d} = 5.5\ \frac{kWhr}{m^2 \cdot d}$$ → A $1m^2$ solar panel can harness 5.5 kwhr in 1 day.

But because of efficiency of the solar cell,

$$5.5 \frac{kWhr}{m^2 \cdot d}(0.20) = 1.1 \frac{kWhr}{m^2 \cdot d}$$ can be transfered to the battery

* Battery overall efficiency = 75% (accounting for losses when inserting & withdrawing power)

$$1.1 \frac{kWhr}{m^2 \cdot d}(0.75) = 0.825 \frac{kWhr}{m^2 \cdot d} = 825 \frac{Whr}{m^2 \cdot d}$$ → "useable" power available

So how much power do we need?

$$(0.37\ kW)(8hrs) = 2.96\ kWhr = 2960\ Whr$$ ← need more than $1m^2$

How much area do we need? * Assume for 1day

$$\frac{2960\ Whrs}{825 \frac{Whrs}{m^2 \cdot d}} = 3.6 m^2$$ is the area necessary to store enough electricity in the battery to run a 0.37 kW aeration system for 8hrs

* Assuming we don't want the battery to drain 100% every time, insert factor of safety

Solar Panel Area Required = $\boxed{\sim 5 m^2}$

(4) Concentrating Photovoltaics (CPV) shine more sunlight onto a photovoltaic (PV) to yield more electricity generation. However, more sunlight on a solar cell can increase temperature & in turn, decrease efficiency.

* Assume fixed system (i.e. no tracking of the sun)

Kurtz & Geisz (2010) demonstrated that multijunction solar cells can attain efficiencies of ~40%, concentrating 500-1000 x more sunlight than conventional PV. Cost \$50,000/m^2. Area required for $\frac{1}{2}$ hp & 8hr run time?

* 500x sunlight
* \$50,000/m^2
* Solar Cell Efficiency = 30% ["Overview of Solar Cell Technology" by Mark McGehee]
* Optical Efficiency = 75%
* Overall Battery Efficiency = 75%

Recall that Kenya sun gives $5.5 \frac{kWhr}{m^2 \cdot d}(0.30)(0.75)(0.75) = 0.92 \frac{kWhr}{m^2 \cdot d}$ "useable power"

Recall the system needs 2.96 kWhr → $\frac{2.96\ kWhr}{0.92 \frac{kWhr}{m^2 \cdot d}} = 3.2\ m^2$

Round up to $\boxed{4m^2}$ to account for battery drainage

Diffuser:

Q: (1) How long will it take to fully aerate pond?
(2) How many diffusers are needed?
(3) Using best case, how much pressure must be overcome?
(4) What size pump meets pressure and flow rate requirements?

G: SOTE = 0.05 - 0.30, diffuser flow rates from 0.05 to 1 cfm per diffuser. DO levels must stay above 4 ppm, $DO_{SAT} \approx$ 8 ppm. Lowest DO occurs at night do to diurnal cycle, oxygen must be delivered in 8 hours or less. 200 m² by 2 m pond. DWP = 0.20 - 0.45 psi.

S:
First have to find how much O_2 needed to go from 4 mg/L to 8 mg/L. This difference is 4 mg/L, plus we will add 1 mg/L extra for buffer. So,:

$$5\,\frac{mg\,O_2}{L}\left(400\,m^3\right)\left(\frac{1000\,L}{1\,m^3}\right) = 2000\,g\,O_2$$

The standard oxygen transfer efficiency $\left(\frac{Kg\ dissolved}{Kg\ delivered}\right)$ varies per diffuser from 0.05 to 0.30.

If we need 2000 g O_2 dissolved, then it will require:

$$\frac{O_2\ dissolved}{SOTE} = O_2\ delivered$$

$$\frac{2000\,g}{0.05} = 40\,000\,g\,O_2 \quad \text{and} \quad \frac{2000\,g}{0.30} = 6667\,g\,O_2$$

Next we must find the volume of air put into the water to make this amount of O_2 enter the water.

It is known that air is about 21 percent O_2 and that 1 mol of air contains 22.4 L (At STP).

$$40\,000\,g\,O_2\left(\frac{1\,mol\,O_2}{32\,g\,O_2}\right)\left(\frac{100\,mol\,air}{21\,mol\,O_2}\right)\left(\frac{22.4\,L}{1\,mol\,air}\right)\left(\frac{1\,m^3}{1000\,L}\right) = 133.3\,m^3\,air$$

$$6667\,g\,O_2\left(\frac{1\,mol\,O_2}{32\,g\,O_2}\right)\left(\frac{100\,mol\,air}{21\,mol\,O_2}\right)\left(\frac{22.4\,L}{1\,mol\,air}\right)\left(\frac{1\,m^3}{1000\,L}\right) = 22.2\,m^3\,air$$

Between 22.2 and 133.3 m³ air actually needed

Most diffusers found in Pentair catalog range from 0.05 - 1 cfm in flow rate. To calculate time to aerate the pond with one diffuser:

$$time = \frac{volume\ air\ needed}{flow\ rate}$$

Convert flows to cubic meters per minute:

1 cfm = 0.0283 cmm

(1) Now find time to aerate the pond with one diffuser for the range of SOTE's and flow rates:

$$time_{High, High} = \frac{22.2\ m^3}{0.0283\ \frac{m^3}{min}} = 784\ min \text{ or } \boxed{13\ hours}$$

$$time_{Low, High} = \frac{133.3\ m^3}{0.0283\ m^3/min} = 4710\ min \text{ or } \boxed{79\ hours}$$

$$time_{High, Low} = \frac{22.2\ m^3}{0.00142\ m^3/min} = 15634\ min \text{ or } \boxed{260\ hours}$$

$$time_{Low, Low} = \frac{133.3\ m^3}{0.00142\ m^3/min} = 93873\ min \text{ or } \boxed{1565\ hours}$$

We see a huge range of values. It appears that flow rate is a large driving factor, as is the SOTE. Thus, it may be best to go with a fine or medium pore diffuser that has a high flow rate and SOTE. SOTE is also driven by depth, so the deeper the diffuser is placed, the better.

(2) The pond is to be aerated in 8 hours, how many diffusers are necessary?

$$\#\ diffusers_{High, High} = \frac{13\ hours}{8\ hours} = \boxed{2\ diffusers}$$

$$\#\ diffusers_{Low, High} = \frac{79\ hours}{8\ hours} = \boxed{10\ diffusers}$$

$$\#\ diffusers_{High, Low} = \frac{260\ hours}{8\ hours} = \boxed{33\ diffusers}$$

$$\#\ diffusers_{Low, Low} = \frac{1565\ hours}{8\ hours} = \boxed{196\ diffusers}$$

From this calculation we see that with a high flow rate we get a reasonable number of diffusers to place in the pond. Anything more than 15 diffusers may be cumbersome to manage. This also signals that coarse pore diffusers (low SOTE, high flow) may be reasonable. They would require about 10 diffusers in the pond, not unreasonable for a cheap product.

(3) In order to size the air pump, we need to find out how much pressure should be overcome. We must take into account hydrostatic pressure at diffuser depth, piping resistance and the dynamic wet pressure of the diffuser. For purposes of this order of magnitude calculation, we will neglect piping resistance.

If we place diffusers at 2m depth, the hydrostatic pressure is:

$$2m\ H_2O \left(\frac{1.42 \overset{\rightarrow \text{AT STP}}{\ } psi}{1m\ H_2O}\right) = 2.84\ psi$$

Each diffuser has a DWP between 0.20 psi and 0.45 psi depending on diffuser type. Because we are doing this for the best case scenario, which reflects fine pore diffusers, let's use a DWP of 0.35 psi, since fine pore diffusers have higher DWPs.

For 2 diffusers, total DWP is:

$2 \times 0.35\ psi = 0.70\ psi$

Just for fun let's take the 10 diffuser case with DWP of 0.25 psi (coarse pore).

$10 \times 0.25\ psi = 4\ psi$

We see that the number of diffusers greatly influences the total amount of pressure that must be overcome.

Neglecting piping, total pressure is:

$2.84\ psi + 0.70\ psi = \boxed{3.54\ psi}$ for 2 diffusers

(4) Pumps found on hydrogalaxy.com that can output 4 psi and covered 2 cfm are about 110 W.

110 W is approximately $\boxed{\text{1/7 of a horse power}}$

Appendix C: Technical Design Matrix justification

This appendix details the reasoning behind what values were inserted into the Technical Alternatives Matrix.

Justification for Paddlewheel Scores

In the technical section, the portability of the system was ranked low because it requires a large piece of equipment. It scored low on scalability because it was very difficult to find a scaled-down paddle wheel. The paddlewheel does score high with efficiency and SAE, ranking 2.0 kg O_2/kWh. The installation of the system is relatively simple and high-ranking because a paddle wheel requires placement and anchoring in the pond. The reliability of the system is low due to all of the moving parts, and operations and maintenance is scored high because there should not be significant maintenance.

In the environmental section the paddle well scored moderately on fish and water protection due to concern of oil contamination. There is potential bank erosion in paddle wheel systems, so that score was lower as well. The paddle wheel does move surface water around, so there is protection from unwanted insects such as mosquitos.

The paddle wheel scored well on social components because it is used worldwide (and culturally acceptable) and the system can be anchored to dissuade theft.

The economic component of paddle wheels was a low score because the capital cost for the system was greater than $500, without considering power.

The paddle wheel technology scored lowest in every category except social. It had the lowest score overall.

Justification for Vertical Pump Scores

Vertical pumps scored high on portability because they are lightweight. They are moderately scored in scaling because of difficulty of use in smaller sizes. A moderate SAE value gives vertical pumps a moderate score for efficiency. Installation is simple as long as it is anchored to the shore, so the pump scores high in installation. It is moderately reliable; vertical pumps have at least one moving part that can fail. Vertical pumps do not need heavy attention; routine operations and maintenance should be performed once per harvest, therefore they score well in this category. Vertical pumps neither contaminate water nor harm fish, provided a safety barrier is put in place, so it scores well. Because vertical pumps do a poor job at mixing the water, no bank erosion occurs and it scores well. That being said, vertical pumps move surface water and prevent stagnant water, the prime breeding grounds for mosquitos. Vertical pumps are not commonly used in aquaculture worldwide so cultural acceptability is unknown and a moderate score is assigned. Vertical pumps tend to be relatively expensive (over $300), less than a paddlewheel but more than a venturi or diffuser so another moderate score is given.

Vertical pumps do not have a high SAE, cannot mix the entire pond well, have more moving parts than diffusers/venturis, and have high capital costs. Because of this, vertical pumps are not a viable technology for this system with a $200 budget.

<u>Justification for Venturi Scores</u>

For the technical category, the venturi system scored high on portability, scalability, efficiency, and operations and maintenance. The venturi is portable because none of the individual parts are heavy (over 50 lbs). It's scalable because there are all different pump sizes and pipe sizes to be used for both small and large systems. The venturi is rated high in the operations and maintenance category since cleaning and general system maintenance is needed maybe once or twice per harvest cycle. Installation was rated as average, since the setup is more intensive than just putting something in the pond and turning it on. The farmer would be required to set up the venturi pipes, and make sure everything is sealed and working well under water, which may pose a challenge. The system was also average in the reliability section because there are few moving parts and only annual repairs are assumed to be needed.

The environmental category looked at water quality, erosion, and insect protection. The venturi has no parts that would degrade water quality, though a submersible pump is a mechanical component in the water which reduced the score. A venturi will not create a current in the pond, so there should be very minimal bank erosion. The only source could be the farmer getting in and out of the pond to check the pump and the pipes. The venturi has no effect on repelling insects since it doesn't agitate the water surface like other technologies. The venturi was rated as average in this category, since it neither increases nor decreases the amount of mosquitos and other insects around the pond.

The social category was rated based on cultural acceptability and theft. Since venturis aren't used as frequently in aquaculture settings worldwide, it was rated as average in the cultural acceptability section. It isn't used in the area, however there should be no reason locals would be against using a venturi system. The theft rating was excellent for venturis since there are no attractive system components exposed. The only part a thief might steal is the pump, and that will be underwater and not easily accessible.

The venturi was rated as excellent in the economic category, since the capital costs of the system are under $200. This doesn't take into account powering the system, the category is just rating and comparing the different technologies based on their capital costs.

Justification for Diffuser Scores

Diffusers were given an excellent score in portability because on a small scale the pump will weigh less than 25 pounds. They were given the same score in scalability because they can be implemented in large wastewater treatment facilities or in home fish tanks and there are a variety of diffuser types and sizes. Based on the SAE of medium pore diffusers, they rank moderately in efficiency. Installation is easy, but does require placing the diffuser in the pond and connecting the tubing; thus it scored well. It is estimated that repairs will be needed once per year with the system, earning the system a moderate reliability score. For operations and maintenance, because the design pond is earthen, it requires that diffusers be cleaned every few months, which corresponds to the harvest cycle in Kenya.

Diffusers and their pumps do not pose hazards to the water or fish. Pumps are oil-less and do not emit toxic chemicals. Unlike paddlewheel aerators, bank erosion is not an issue with diffusers, since the flow rates of the diffusers are not large enough to erode banks. Diffusers do not agitate the surface water directly like paddlewheels and vertical pumps, instead the surface water is indirectly agitated through rising bubbles. These bubbles should mix the surface water enough to deter insects.

The cultural acceptance of diffusers is unknown. That being said, it is expected to be positive based on its simple operation. Diffuser systems are not likely to be subject to theft. The air pumps, while exposed, can be housed and secured from theft easily.

The diffuser is an excellent economic choice. A pump, diffusers and tubing can be found for less than $200, giving this system an excellent capital cost.

Appendix D: Final Design Matrix Rubric

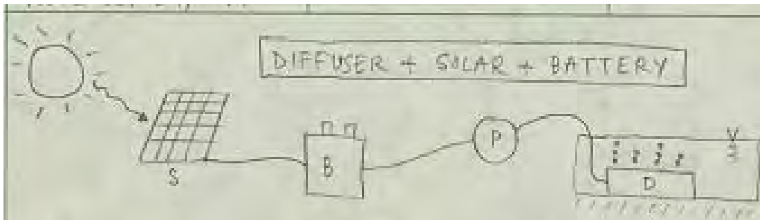
		Environmental				Social			Economic		
		Disposal	Protect Water/Fish	Emissions	Protect Against Insects	Culturally Acceptable	Theft	Noise	Capital Costs	Annual Cost	NPV per Oxygen
0	Fail	All components hazardous and dangerous disposal	Contaminated water and dead fish	Copious amounts of harmful emissions	Attracts excessive amount of insects	Technology has been used and already widely recieved negatiely	Attractive components are exposed with no security measures possible	90 - 100 db	> $1,000	> $500	$4.50 < NPV
1	Bad	Some components hazardous and dangerous disposal	Poor water and stressed fish	Large amount of harmful emissions	Attracts many insects	Technology has not been used but actively challenges social and cultural norms	Attractive components are exposed and impossible to secure	80 - 90 db	$800 < C.C. < $1,000	$200 < A.C. < $500	$3.50 < NPV < $4.50
2	Poor	Difficult to dispose of materials, but not hazardous	Substandard water and slightly stressed fish	Moderate amount of harmful emissions	Attracts moderate amount of insects	Technology has not been used in region, cultural and social norms is unknown	Attractive components exposed and difficult to secure	60 - 80 db	$600 < C.C. < $800	$100 < A.C. < $200	$2.50 < NPV < $3.50
3	Acceptable	Components are potentially recyclable or reusable	Moderately clean water and normal fish	Few harmful emissions	Attracts few insects	Technology has not been used in region, meeting cultural and social norms is expected to be positive	Attractive components are exposed and require moderate security	30 -60 db	$400 < C.C. < $600	$ 50 < A.C. < $100	$1.50 < NPV < $2.50
4	Good	Components are easily recyclable or reusable	Clean water and healthy fish	Little harmful emissions	Attracts no insects	Technology is occaasionally used in region, fits well with cultural and social norms	Attractive exposed components are easily secured	10 - 30 db	$200 < C.C. < $400	$ 20 < A.C. < $ 50	$ 0.50 < NPV < $ 1.50
5	Excellent	Biodegradable materials	Prestine water and thriving fish	No emissions	Facilitates the removal of insects	Technology is used widely in aera, fits well with cultural and social norms	No attractive components exposed	Operates silently - 0 - 10 db	C.C. < $200	A.C. < $ 20	NPV < $0.50

		Technical						
		Portability	Reliability	Installation	Scalability	Oxygen Delivered	O&M	Aeration Efficiency (kg O2 / kW*hr)
0	Fail	Largest Component > 125 lbs	System will not run	Intensive, multiday, multiperson setup	Impossible: will not work on a small scale	0.2 kg > O2 Delivered per 4 hours	Cleaning/maintenance twice a day	SAE = 0
1	Bad	100 < Largest Component < 125 lbs	System will not run on demand	Intensive setup	Difficult to scale: no previous history of scalable systems	0.2 kg < O2 Delivered per 4 hours < 0.4 kg	Cleaning/maintenance needed daily	SAE = 0 - 0.67
2	Poor	75 < Largest Component < 100 lbs	System runs on demand intermittently	Difficult setup	Scaling possible, but parts difficult to find	0.4 kg < O2 Delivered per 4 hours < 0.6 kg	Cleaning/maintenance needed once every week	SAE = 0.67 - 1.3
3	Acceptable	50 < Largest Component < 75 lbs	System will usually run on demand	Moderate setup	Scaling possilbe, parts avaliable	0.6 kg < O2 Delivered per 4 hours < 0.8 kg	Cleaning/maintenance needed once every 2 weeks	SAE = 1.3 - 2.0
4	Good	25 < Largest Component < 50 lbs	System will always run on demand at designed times	Simple setup	Scaling common and parts avalialbe	0.8 kg < O2 Delivered per 4 hours < 1 kg	Cleaning/maintenance needed once every 8 weeks	SAE = 2.0 - 2.7
5	Excellent	0 < Largest Component < 25 lbs	System will run on demand at any time	Little to no setup	Scaling possible at all sizes and parts readily avaliable	Greater than or equal to 1 kg O2 per 4 hours	Cleaning/maintenance at the end of each harvest cycle	SAE > 2.7

Appendix E: Final Design Matrix calculations

Solar Powered Diffuser:

DIFFUSER + SOLAR + BATTERY



① State tech specs & cost of parts

D: Diffuser ($20 each) x 2 [Pentair Sweetwater 12", 1 cfm air]

P: $\frac{1}{7}$ hp pump (12V), cost = $80 [Hydrofarm AAPA 112W, 110LPM Commercial Air Pump]

* Assume annual operation & maintenance = $20/yr

Tubing: ~$30

* Assume 10-yr life of diffuser & tubing; 5-yr life of pump

→ Total Costs = ($20) 2 + $80 (2) + ($20) 10 + $30 = $\boxed{\$430 \text{ over } 10\text{yrs}}$

② Power Requirement Calculation

Pump draws (112W)(4hrs) = 450 Whrs needed per night

S: Solar Cell [100W Monocrystaline Panel, 30A Charge Controller, MC4 Solar Adapter Cable] $170

* Assume Daily Irradiance in Eldoret, Kenya = 5.5 $\frac{kWhr}{m^2}$
* Solar cell efficiency = 20%

"Useable" Solar Energy = 5.5 $\frac{kWhr}{m^2}$ (0.20) = ~1000 $\frac{Whr}{m^2}$

* Assume 8hrs of sunlight hits the solar panel

(100W)(8hrs) = 800 $\frac{Whrs}{d}$ can be captured by solar cell

→ more than enough to meet the 450 Whr requirement

B: Batteries → Trojan T105-RE (6V) Deep-Cycle Lead-Acid Battery 225 A·hrs, $110 each

→ put 2 batteries in series to achieve 12V & retain 225 A·hrs

* Assume Battery ~70% efficient (overall)
* Assume depth of discharge = 40% → translates to 2000 cycles

225 A·hrs (0.70) = 157 useable A·hrs , Sizing = $\frac{450 \text{ Whrs req'd}}{12\text{ V}}$ = 37.5 A·hrs needed

LOOKS GOOD ☺

* Assume aerating 200 d/yr

At 40% Depth of Discharge (i.e. 2000 cycles), the batteries can last...

$$\frac{2000 \text{ cycles}}{200 \text{ d/yr}} = \boxed{10 \text{yrs}}$$

(3) Determine Power Costs

1x 100W Solar Cell = \$170
2x Trojan Battery = \$110 × 2 = \$220

$\boxed{\$390}$ → Power costs over 10-yr life

* Assume solar cell has design life 10 yrs

(4) Net Present Value & Cash Flow Chart

n	Cash Flow	Present Value
0	-560	-560
1	-20	-18.43
2	-20	-16.99
3	-20	-15.66
4	-20	-14.43
5	-100	-66.50
6	-20	-12.26
7	-20	-11.30
8	-20	-10.41
9	-20	-9.60
10	-20	-8.85

$\boxed{NPV = -\$744}$

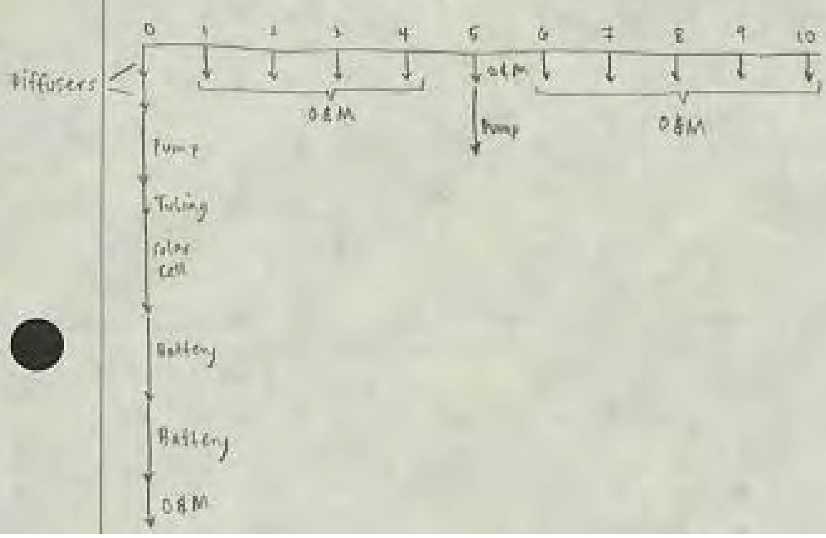
* Assume $i = 8.5\%$

$$NPV = \sum \frac{C_n}{(1+i)^n}$$

Example Calc:

Yr	
0	$\frac{-560}{(1+0.085)^0} = -560$
1	$\frac{-20}{(1+0.085)^1} = -18.43$
2	$\frac{-20}{(1+0.085)^2} = -16.99$
⋮	

Cash Flow: (costs only)



(5) O_2 Delivered

$$= 1\,\frac{ft^3}{min} \cdot \frac{60\,min}{1\,hr} \cdot 4\,hrs \cdot 2\text{ diffusers} \cdot \frac{0.20\,O_2}{1\text{ air}} \cdot \underbrace{\frac{O_2 \text{ diffused to water}}{O_2 \text{ delivered}}}_{\text{Standard Oxygen Transfer Efficiency (SOTE)} \approx 0.25}$$

* Assuming STP for gases

$$= \frac{24\,ft^3\,O_2}{night} \cdot \frac{28.3\,L\,O_2}{1\,ft^3\,O_2} \cdot \frac{1\,mole\,O_2}{22.4\,L\,O_2} \cdot \frac{32\,g\,O_2}{1\,mole\,O_2}$$

$$= \frac{970\,g\,O_2}{night} \approx \boxed{\frac{1\,kg\,O_2}{night} \text{ with run-time of 4 hrs}} \longrightarrow$$

In conclusion,

Capital costs = \$560

Annual costs = \$20 (with a new \$80 pump in yr 5)

NPV = \$744

O_2 delivered per night = 1 kg

<u>Generator Powered Diffuser:</u>

Diffused Aeration System with Generator

Q: What is the NPV for a diffused aeration system?

G:

Component	Price	Source
112 W Linear Air Pump	$80	Amazon.com
1000 W Portable Gas-Powered Generator	$130 (Found on sale for $100)	HarborFreight.com
2 Sweetwater 12" Diffusers	$20/DIF	Pentair Catalog 2014
3/8" Weighted Tubing	$1/Ft	Pentair Catalog 2014

Price of gas in Kenya is approximately $5/gal, from erc.go.ke (Energy Regulatory Commission of Kenya).

New pump to be purchased every 5 years - no information available regarding expected life - Note that the pump may have to be purchased more often than this.

System is designed for 10 year life.

Annual maintenance for the system requires $20 for purchase of hydrochloric acid to clean diffusers and/or replace diffuser.

System will provide 2 Kg O_2 for 8 hours run time.

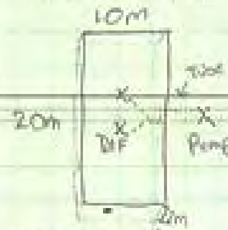
S: In finding the given parts, the goal was to minimize cost for maximum aeration. Note that the generator was also found on sale for $100. All of the prices listed above are likely overestimates if the system is to be mass-produced.

The generator given above seems grossly oversized for the amount of power that is needed (112W). This was the smallest <u>gas-powered</u> generator found for sale. It may be possible to have a smaller wattage generator made specifically for our system, but we are <u>not</u> assuming that. In addition, the generator can run at half-power so that it is not producing as much wasted energy.

We have also looked at gas-powered air compressors, essentially combining the pump and generator; however, none were found for better value than combined pump and generator.

To see justification of the 112 W pump and 2 12" diffusers system, please see NWO2 design calcs.

How much tubing is needed? If the diffusers are placed at the 2 m depth and placed in the middle of the pond, and the pump is placed 1 m from the pond, this equates to:



$$\underset{\text{Middle}}{5\text{m}} + \underset{\text{Depth}}{2\text{m}} + \underset{\text{To pump}}{1\text{m}} + \underset{\text{Between Dif.}}{1\text{m}} = 9\text{m tubing}$$

$$9\text{m}\left(\frac{3.24\text{ ft}}{1\text{m}}\right) = 29\text{ ft} \approx 30\text{ ft}$$

$$30\text{ ft}\left(\frac{\$1}{1\text{ ft tubing}}\right) = \boxed{\$30 \text{ for tubing.}}$$

Generator can last this long w/out refuel & this is operation time.

How much gas is required to run the system?
Based on generator specs, can provide 0.12 gal/hr at 1/2 load:

$$\frac{8\text{ hours}}{1\text{ cycle}}\left(\frac{0.12\text{ gal}}{1\text{ hr}}\right)\left(\frac{\$5}{1\text{ gal}}\right) = \frac{\$4.8}{\text{cycle}}$$

DAILY: \$4.8 (365 cycles) = \$1750 /Year

3/4 YEAR: \$4.8 (274 cycles) = \$1320 / Year

1/2 YEAR: \$4.8 (183 cycles) = \$880 / Year

1/4 YEAR: \$4.8 (92 cycles) = \$440 / Year

Calculate NPV for each of the run-times (irr=8.5%):

Total capital cost of the system is:

$$\underset{\$80}{\text{Pump}} + \underset{\$130}{\text{Generator}} + \underset{\$40}{\text{Diffusers}} + \underset{\$30}{\text{Tubing}} = \boxed{\$280}$$

Assume O&M costs in year 0. In order to compare with Venturi System, make run time 4 hours, halfing the O_2 delivered to 1 kg. This halves all of the gas costs computed above.

GENERATOR POWERED DIFFUSER

irr 0.085

kg O2 Delivered per 4 hours 1

DAILY

n	Cash Flow	Ci
0	-1155	-1155
1	-895	-824.885
2	-895	-760.262
3	-895	-700.703
4	-895	-645.809
5	-975	-648.419
6	-895	-548.586
7	-895	-505.609
8	-895	-465.999
9	-895	-429.492
10	-895	-395.845

-7080.6 NPV

-1.94 $ per kg O2

3/4 YEAR

n	Cash Flow	Ci
0	-940	-940
1	-680	-626.728
2	-680	-577.63
3	-680	-532.378
4	-680	-490.671
5	-760	-505.435
6	-680	-416.803
7	-680	-384.15
8	-680	-354.055
9	-680	-326.318
10	-680	-300.754

-5454.9 NPV

-1.99 $ per kg O2

1/2 YEAR

n	Cash Flow	Ci
0	-720	-720
1	-460	-423.963
2	-460	-390.749
3	-460	-360.138
4	-460	-331.924
5	-540	-359.125
6	-460	-281.955
7	-460	-259.866
8	-460	-239.508
9	-460	-220.745
10	-460	-203.451

-3791.4 NPV

-2.08 $ per kg O2

1/4 YEAR

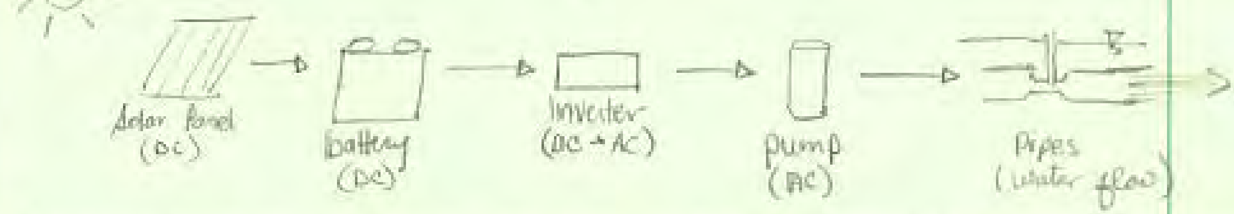
n	Cash Flow	Ci
0	-500	-500
1	-240	-221.198
2	-240	-203.869
3	-240	-187.898
4	-240	-173.178
5	-320	-212.815
6	-240	-147.107
7	-240	-135.582
8	-240	-124.961
9	-240	-115.171
10	-240	-106.148

-2127.9 NPV

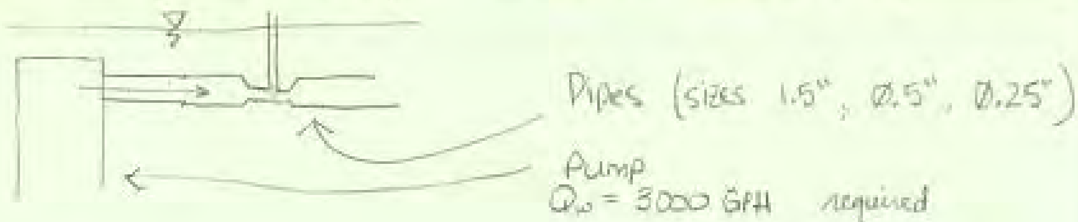
-2.33 $ per kg O2

Solar Powered Venturi:

VENTURI + BATTERY + SOLAR



Venturi : four hours of runtime, 0.8 kg oxygen/day



— Pipes → \$15
(\$5 /10 ft from Home Depot)

— Pump → \$45
(Wayne 58325-WYN1 Submersible Sump Pump from Amazon)
- 1/3 hp = 250 watts
- 120 volts
- 3060 GPH
- 1.5" discharge

— Inverter → \$30
(Go-Power 300 watt by Inverter Supply)
- 120 volts (AC) to 12 volts (DC)
- 300 watts

POWER DEMAND (from pump + inverter)

250 watts * 4 hr runtime = 1000 watt·hr ← pump draw

1000 watt·hr * 1.1 = 1100 watt·hr ← pump + inverter draw

inverter is 90% efficient

$\frac{1100 \text{ watt·hr}}{12 \text{ volts}}$ = 92 amp hr for pump + inverter

Power Demand (battery)

92 amp hour draw, 60% draw-down → 128 amp·hr

battery needed with 12 volts, 128 amps

— Battery → $ 250
(Trojan J185P-AC from altbatt)
- 12 volts
- 10 hr rate = 189 amps
- wet lead-acid battery
- 114 lbs, 52 kg
- 50% draw-down, 1200 cycles (100 days/yr 10 yrs)

POWER DEMAND (solar)

battery charge efficiency = 0.7

128 amps, 12 volts, 70%

P = IV = (128 amps)(12 volts)(1.3)

1997 watts delivered

240 watt panels * 8 hr (of sun/day) = 1920 watts
(close enough?)

— Solar Panel → $ 360
(Renology RNG-2400 from freeclean solar)
- 240 watts
- 12 volts

Total System Capital Costs

pipes + pump + inverter + battery + panel

$15 + $45 + $30 + $ 250 + $ 360 = $ 700

Variable Costs

pump = $45 / 5 yrs

annual maintenance = $20/yr

SOLAR POWERED VENTURI

irr	0.085
kg O2 Delivered per 4 hours	0.8

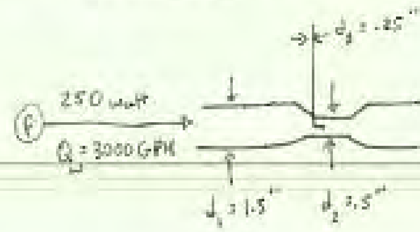
100 Days

n	Cash flow	Ci
0	-700	-700.00
1	-20	-18.43
2	-20	-16.99
3	-20	-15.66
4	-20	-14.43
5	-65	-43.23
6	-20	-12.26
7	-20	-11.30
8	-20	-10.41
9	-20	-9.60
10	-20	-8.85
		-861.15 NPV
		-1.08 $ per kg O2

Generator Powered Venturi:

Economic Calculations for a Venturi system powered by a generator

A venturi setup with the configuration shown below, powered by the Wayne RSP-130 - 1/5 Hp pump, delivers <u>0.8 kg O_2</u> per 4 hours of run time.



<u>Venturi Technology Cost:</u>

Pump: Wayne RSP-130 - \$45 (Amazon)

PVC Pipes: \$5.50/10ft - \$11 (Home Depot; Need two 10ft pipes)

Rubber Air Tube: \$5.20/20ft - \$5 (Home Depot)

PVC Connectors: \$2 each - \$10 (Home Depot; Need 5 connectors)

Total Capital Cost = \$71 for venturi technology

Annual costs are estimated at \$20/year for various cleaning and maintenance throughout the year. None of the pipes or tubing should need replacement, but we are planning on replacing the pump every 5th year.

So Annual costs will be \$20 each year, with year 5 being \$65 (pump price included)

<u>Power Requirement Calculation & Cost:</u>

For a 250 watt pump to run for 4 hours, we need a generator to provide 1 kwh.

The All Power America APG3004 provides 800 w continuous power, and runs for 8.5 hours at ½ load on 1.2 gallons of gas. This means one tank of gas (1.2 gallons) will provide power for 2 run cycles.

The All Power America APG3004 generator costs \$135 (Amazon)

Total capital cost of generator = \$135

Annual costs for the generator are estimated to be \$20/year for general operations/maintenance costs. Fuel costs will be the other annual cost, and the system uses 1.2 gallons of gas every 2 days. Running the system for 225 days each year means we would use 135 gallons of gas.

$$225 \text{ days} \cdot \frac{1.2 \text{ gallons}}{2 \text{ days}} = 135 \text{ gallons/year}$$

Gas is \$5/gallon in Kenya (Global Petrol Prices)

↳ (135 gal)(\$5/gal) = \$675/yr on gas.

Total Annual cost of generator = \$695

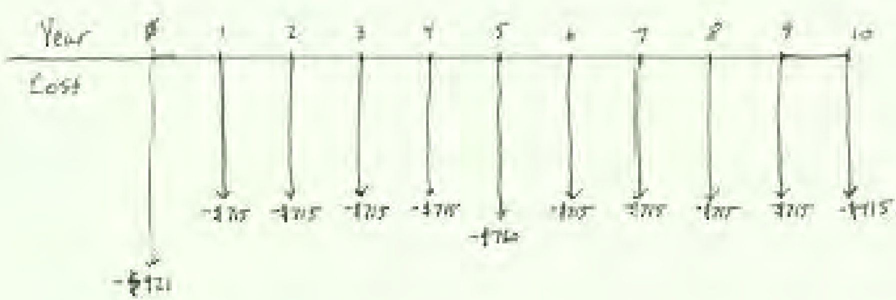
For a venturi system powered by a gas generator:

Total Capital Cost = \$206

Total Annual Cost : \$715 (5th yr annual cost = \$760 to replace pump)

The cash flow diagram below shows the investment made over 10 years.

Over 10 years, total cost of this system = \$7401



GENERATOR POWERED VENTURI

irr	0.085
Kg O2 Delivered per 4 hours	0.8

225 DAYS

n	Cash flow	Ci	
0	-921	-921	
1	-715	-658.986	
2	-715	-607.361	
3	-715	-559.779	
4	-715	-515.926	
5	-760	-505.435	
6	-715	-438.256	
7	-715	-403.922	
8	-715	-372.279	
9	-715	-343.114	
10	-715	-316.234	
		-5642.3	**NPV**
		-3.13	**$ per kg O2**

100 DAYS

n	Cash flow	Ci	
0	-520	-520	
1	-320	-294.931	
2	-320	-271.826	
3	-320	-250.531	
4	-320	-230.904	
5	-365	-242.742	
6	-320	-196.142	
7	-320	-180.776	
8	-320	-166.614	
9	-320	-153.561	
10	-320	-141.531	
		-2649.6	**NPV**
		-3.31	**$ per kg O2**

Appendix F: Final Design Matrix discussion

The four systems considered scored between 54 and 64 out of 100 in the final technology matrix. The generator systems both scored slightly higher in the technology section than the solar powered systems. However, in all other categories (environmental, social and economic) the solar powered systems received a higher score. Based on the competitive scores and significantly higher scoring in the economic section, the solar powered systems were selected for final consideration. This leaves the solar powered venturi alternative and the solar powered diffuser system.

The venturi/solar system ranked second due to high scores in the economic section on NPV and annual cost. The technical aspects of the venturi/solar system had the tied lowest score (with diffuser/solar). The portability of the system was ranked low due to the battery's weight. The system was moderately scalable because the venturi, battery, and solar panels can be configured for almost any size. The amount of oxygen delivered was based on the system's specification, 0.8 kg of O_2 delivered per four hour period (see Appendix 9.3 for design calculations). The system's efficiency was based on the SAE for venturis, 1.4 – 3.0 kg O_2 / kWh (Lawson, 1995; Baylar et al. 2005). The installation of the system was rated poorly because solar panels will require intensive set-up as will placing the venturi apparatus in the pond. The system's reliability was scored lower because solar panels are dependent on sun and the system will not able to run on-demand. The operation and maintenance for the system was ranked moderate because it will require cleaning the solar panels every two weeks.

The environmental score for the venturi/solar system came in second, close behind diffuser/solar. The fish protection score was moderately high because the power source will not add harmful components but the pump intake will need to have a fish-cover. The emissions were assumed to be zero because of solar power. Disposal scored poorly due to the battery containing hazardous lead that is difficult to dispose. Finally, the venturi will cause some surface disturbance, so the insect presence will be managed.

In the social category, the system tied with diffuser/solar for the highest score. The system was assumed to be culturally acceptable because there are not negative reports of venturis in Kenya and solar power is popular there. The system will be silent, so the noise score was high. Theft concern resulted in a lower score because solar panels are attractive.

Finally, in the economic section the venturi/solar system scored second highest. All of the detailed calculations are found in Appendix 9.4. The capital cost for the system includes pipes, pump, battery and panel resulting in a cost of $700, which corresponds to a low score. The annual cost for the system was assumed to be $20/year which resulted in a higher annual cost score. The net present value (NPV) score was determined by finding the NPV cost of the system over ten years per total kg oxygen delivered. It was found the NPV cost was $1.09/oxygen delivered which resulted in a high score.

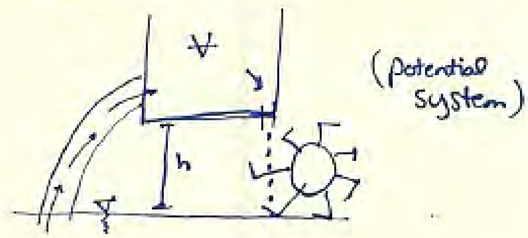
Based on our final design alternatives matrix and further discussion, Northwest Oxygen Solutions recommends a solar powered diffuser aeration system. A solar powered diffuser system was chosen because it scored the best in the Final Design matrix, was determined to best meet the design criteria/objectives, and it had the best NPV per amount of oxygen added to the pond. It is important to note that the solar powered venturi system had very similar scores and had lower annual costs. However, ultimately the venturi system uses more power and adds less oxygen to the pond per day. The NPV per mass of oxygen added for the solar venturi system was just over $1.00 per kg of oxygen delivered, while the solar diffuser system cost $0.45 per kg of oxygen added (see Appendix 9.4). With the solar powered diffuser system versus the solar venturi system, the farmer is paying much less per mass of oxygen introduced to the pond over the lifetime of the system.

Appendix G: Gravity and Wind power calculations

Team 1	POWER : GRAVITY & Water	[redacted]

Q: What specifications would it require to store Ø.5 hp of power (for 6 hr of runtime) in lifted water?

gravity = 9.8 m/s²
water density = 1000 kg/m³



$$\text{Power} = \frac{dE}{dt} = \frac{\text{potential energy}}{\text{time}} = \frac{mgh}{\text{time}}$$ (all power in gravity potential of water)

$$P = \frac{mgh}{t} \qquad m = \rho\forall \qquad P = \frac{\rho\forall h g}{t}$$

$$P = \frac{\rho \forall h g}{t}$$ specifications to change

$$\therefore \forall h = \frac{P \cdot t}{\rho g}$$

$$\forall h = \frac{(375\ \text{watts})(60\text{s} \cdot 60\text{min} \cdot 6\text{hr})}{(1000\ \text{kg/m}^3)(9.8\ \text{m/s}^2)} = 827$$

for Ø.5 hp (375 watts of power)

$$\boxed{h = 0.5\ m,\ \forall = 1650\ m^3 \quad \text{OR} \quad h = 1\ m,\ \forall = 827\ m^3 \quad \text{OR} \quad h = 8.2\ m,\ \forall = 100\ m^3}$$

For Ø.5 hp over 6 hrs gravity water power, the power alternative is NOT FEASIBLE due to the required volume of water or height of water.

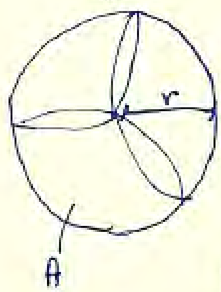
Team 1	POWER: WIND	[redacted]

①: What specifications would it require to generate 0.5 hp (375 watts) power with wind?

$$P = \frac{dE}{dt} = \frac{1}{2}\left(\frac{dm}{dt}\right)v^2$$

(assuming only kinetic energy and $KE = \frac{1}{2}mv^2$)

$$\frac{1}{2}\left(\frac{dm}{dt}\right)v^2 = \frac{1}{2}A\left(\frac{dx}{dt}\right)v^2\rho = \frac{1}{2}A\,v \cdot v^2 \cdot \rho = \frac{1}{2}\rho A v^3$$



efficiency of wind power < 0.59 (Betz Limit for max wind energy transfer)

assume efficiency = 0.4

$\rho(\text{at } T = 30°C) = 1.165\ kg/m^3$

for 0.5 hp = 375 watts

$$P = \frac{1}{2}\rho A v^3 \cdot eff \quad \therefore \quad A\vec{v}^3 = \frac{2P}{eff \cdot \rho}$$

$$A\vec{v}^3 = \frac{(2)(375\ w)}{(0.4)(1.165\ kg/m^3)} = 1609$$

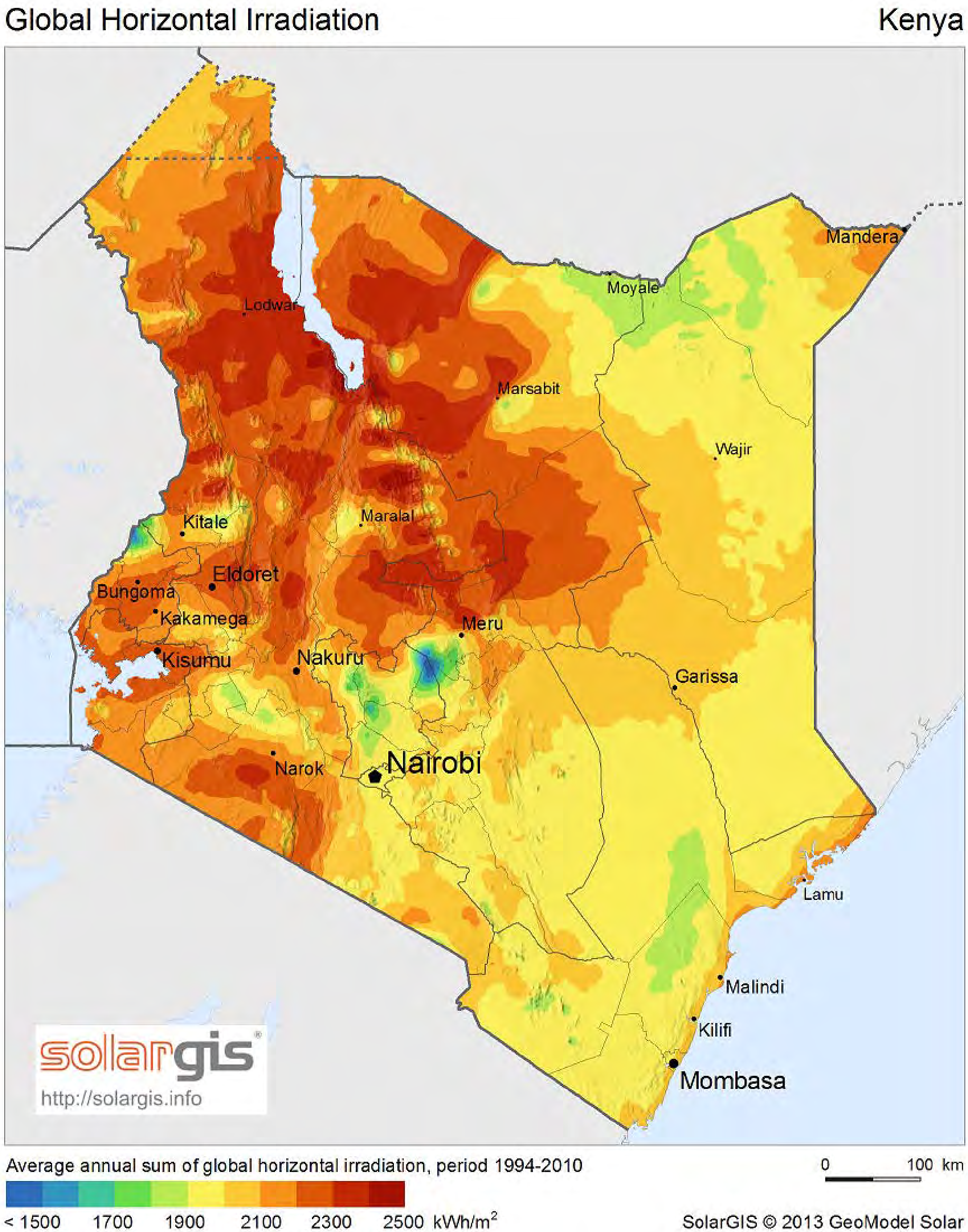
$$\boxed{\begin{aligned} A &= 3.14\ m^2 \\ r &= 1\ m \\ \vec{v} &= 8\ m/s \end{aligned}}$$

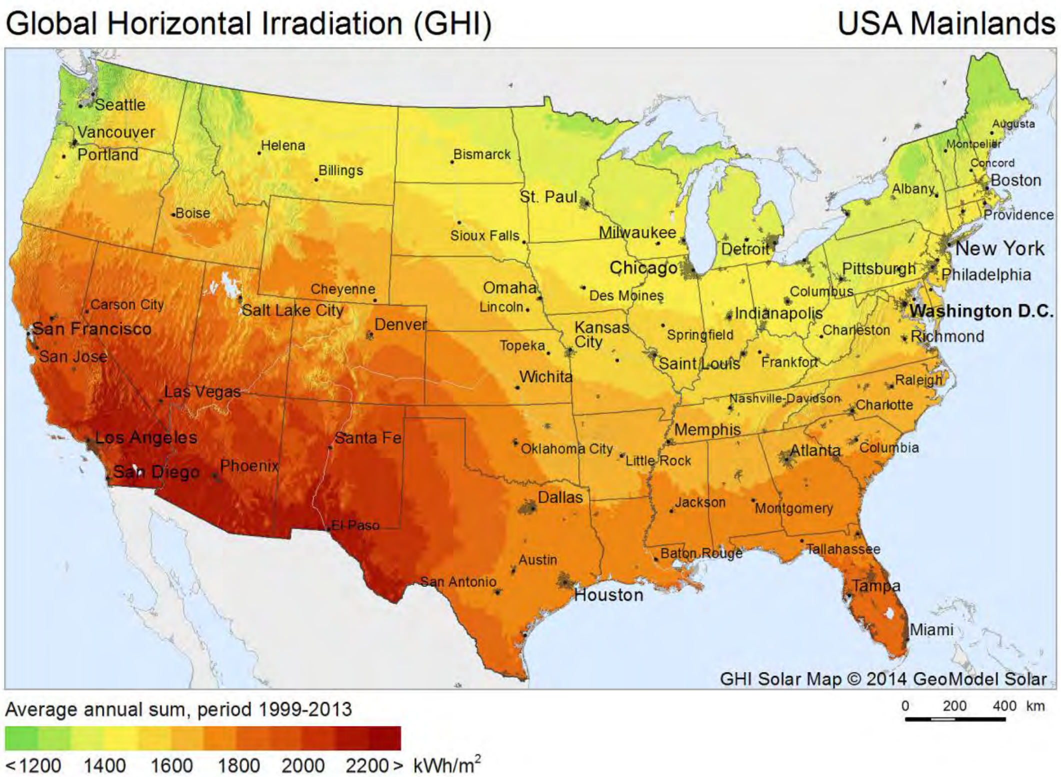
for Eldoret, Kenya AVERAGE max wind speed = 5 m/s, min wind speed = 2 m/s (Mike Harries, Kijito, 2005)

$\vec{v} = 2\ m/s$ $A = 201\ m^2$ $r = 8\ m$	OR	$\vec{v} = 5\ m/s$ $A = 12.8\ m^2$ $r = 2\ m$

This power source is semi feasible. It will depend on actual need power, ~~and~~ further ~~ideas~~ research on wind power & cost.

Appendix H: Solar Insulation in Kenya and the US



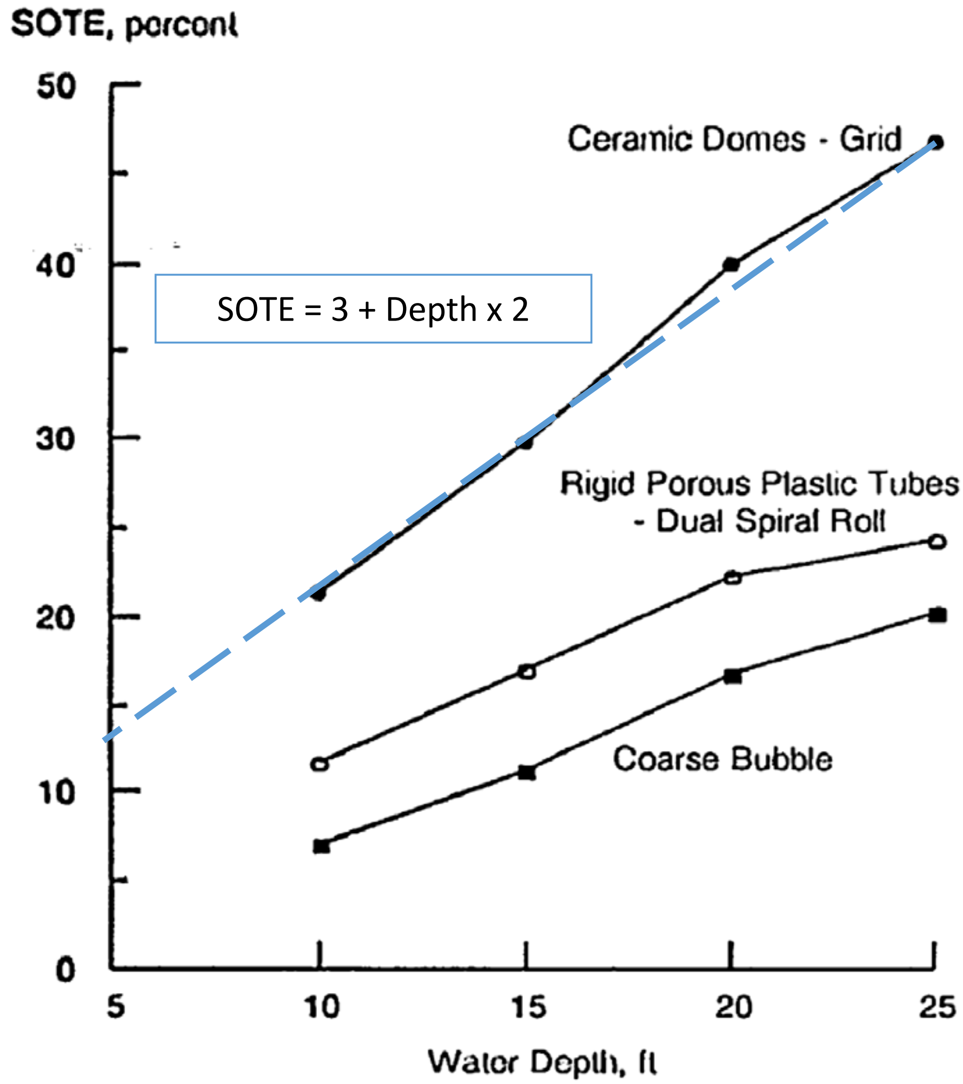


Nairobi, Kenya, Average Daily Peak Sun Hours, kWh/m², Latitude: 1°18′ S, Longitude: 36°45′ E

Month	Array Tilted at Latitude − 15° Fixed Array	Array Tilted at Latitude − 15° 1-Axis Tracker	Array Tilted at Latitude Fixed Array	Array Tilted at Latitude 1-Axis Tracker	Array Tilted at Latitude + 15° Fixed Array	Array Tilted at Latitude + 15° 1-Axis Tracker	2-Axis Tracking Array
Jan	6.93	8.57	6.46	8.08	5.67	7.02	8.62
Feb	7.14	8.95	6.89	8.73	6.29	7.92	8.96
Mar	6.41	8.17	6.49	8.35	6.26	7.98	8.37
Apr	5.32	6.78	5.65	7.29	5.75	7.36	7.40
May	4.40	5.51	4.86	6.21	5.13	6.55	6.57
Jun	4.13	5.09	4.66	5.88	5.02	6.34	6.41
Jul	3.46	4.37	3.81	4.98	4.02	5.32	5.35
Aug	4.02	5.19	4.30	5.68	4.42	5.83	5.84
Sep	5.26	6.80	5.42	7.08	5.33	6.91	7.09
Oct	5.80	7.44	5.69	7.37	5.32	6.81	7.48
Nov	5.93	7.49	5.60	7.12	5.01	6.26	7.52
Dec	6.52	8.06	6.03	7.52	5.24	6.44	8.15
Ann Avg	5.44	6.87	5.49	7.02	5.29	6.73	7.31

From: Photovoltaic Systems Engineering, Third Edition
By Roger A. Messenger, Jerry Ventre

Appendix I: SOTE chart



From: EPA, *Fine Pore Aeration Systems*, 1989 (p. 32)

Appendix J: Wire Sizing

The table below can be used to determine the combination of maximum current through a *12V* electrical wire, size (AWG) and length of cable.

American Wire Gauge (AWG)										
Length (feet)	Current (amps)									
	5	10	15	20	25	30	40	50	60	70
15	16	12	10	10	8	8	6	6	4	4
20	14	12	10	8	8	6	6	4	4	4
25	14	10	8	8	6	6	4	4	2	2
30	12	10	8	6	6	4	4	2	2	2
40	12	8	6	6	4	4	2	2	1	1/0
50	10	8	6	4	4	2	2	1	1/0	1/0
60	10	6	6	4	2	2	1	1/0	2/0	2/0
70	10	6	4	2	2	2	1/0	2/0	2/0	3/0
80	8	6	4	2	2	1	1/0	2/0	3/0	3/0
90	8	4	4	2	1	1/0	2/0	3/0	3/0	4/0

Note! Failure to use an adequate size may result in fire. Always secure a wire with a fuse.

- *1 ft (foot) = 0.3048 m*

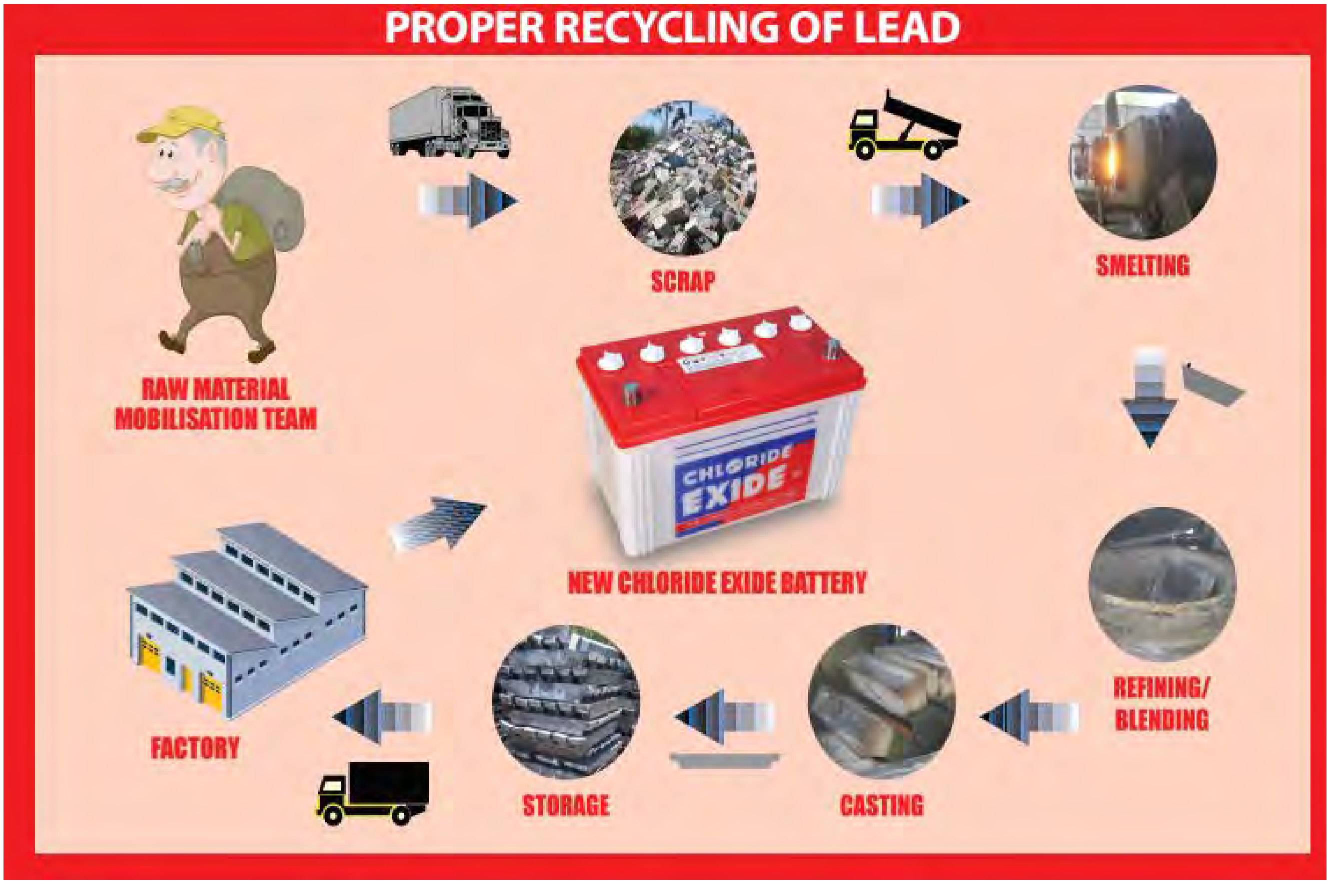
Wire Gauge Design Procedure

1. calculate the total length of the wire from the source to the device and back again
2. determine the amount of current in the wire
3. correct wire gauge is in the intersection of amps and feet

Note! The wire size is required for a *3%* voltage drop in *12 Volt* circuits. Oversize the wire if the voltage drop is critical.

From: engineeringtoolbox.com

Appendix K: Battery Recycling



From: www.cekl.co.ke

Appendix L: Full scale calculations

<u>Summary:</u>

To provide 4.4 cfm airflow and 3 psi of air pressure with the Boyu906 pump, 6.5 hours of runtime, and a battery depth-of-discharge of 40%, a 100 Ah 12 volt battery and 150 watt solar panel are required.

<u>Question:</u>

Based on oxygen/diffuser calculations, a dc system is needed to support 4.4 cfm airflow, 3psi, and 6.5 hours of runtime. What is the needed size of the parts of a solar panel and battery system?

<u>Assume:</u>

Charge controller 90% efficient
Charge controller used between solar panels, battery, and pump
Battery 90% efficient
Solar Panels 90% efficient (90% of energy absorbed is transferred to the system)
Ideal depth of discharge of battery is 40% for a 10 year lifespan
Solar Panels used to replace 1 night draw-down
Sunlight for solar panels is 4 hours

<u>Solve:</u>

The Boyu 906 pump outputs 4.3 cfm and 17 psi. It runs at 12 volts and 60 watts.

Pump (12 volts, 60 watts)
current = $I = \frac{P}{V}$ = 5 amps

Charge Controller (90% efficient)
including efficiency, amps needed = 5.5 amps

$$5\ amps * 1.1 = 5.5\ amps$$

Battery (90% efficient, runtime 6.5hrs)
including efficiency, amps needed = 6 amps

$$5.5\ amps * 1.1 = 6\ amps$$

required ampere-hours = 40 Ah

$$6\ amps * 6.5hrs = 40Ah$$

for 40% depth of discharge/run battery size = 100Ah

$$\frac{40\ Ah}{0.4\ depth\ of\ discharge} = 100\ Ah$$

BATTERY SIZE = 100Ah

Solar Panel only used to replace 1 night's draw down, so 40 Ah needed from panel/day

Charge Controller (90% efficient)
including efficiency, ampere-hours needed = 44 Ah

$$40\ Ah * 1.1 = 44\ Ah$$

Solar Panels (90% efficient)
including efficiency, ampere-hours needed = 48 Ah

$$44\ Ah * 1.1 = 48\ Ah$$

watts needed = 576 watts

$$power = IV = 48\ Ah * 12\ volts = 576\ watts * hours$$

solar panel wattage = 144 watts

$$\frac{576\ watt*hours}{4\ hrs} = 144\ W$$

Conservative estimate SOLAR PANEL SIZE = 150 watts

Conclusion:

Power requirements demand a 100Ah battery, and 150 watt solar panel.

Appendix M: Oxygen delivery calculations

Question:

What flow rate of air and system run time is needed to add 5 mg/L of oxygen to the pond per night?

Solve:

$5\ \frac{mg\ O_2}{l} = \mathbf{5\ \frac{g\ O_2}{m^3}}$ - We want to hold this constant to compare our large scale system to the prototype.

Large Scale System calculations:

$SOTE = \frac{Amount\ of\ O_2\ dissolved}{Amount\ of\ O_2\ delivered}$ - SOTE in a 2m deep pond = .15 (EPA, 1989)

$SOTE = .15 = \frac{5\frac{g\ O_2}{m^3}}{x}$

x = $\mathbf{33.3\ \frac{g\ O_2}{m^3}}$ - This amount of oxygen needs to be delivered per night to dissolve $5\ \frac{g\ O_2}{m^3}$

Now we need to convert the amount of oxygen delivered per night to a volume of air delivered per night.

$$33.3\ \frac{g\ O_2}{m^3} * \left(\frac{1\ mol\ O_2}{32\ g\ O_2}\right) * \left(\frac{100\ mol\ air}{21\ mol\ O_2}\right) * \left(\frac{22.4\ L\ air}{1\ mol\ air}\right) * \left(\frac{1\ m^3\ air}{1000\ L\ air}\right) * \left(\frac{35.3\ ft^3\ air}{1\ m^3\ air}\right)$$

$$= 3.92\ \frac{ft^3\ air}{m^3\ water * night} * (400\ m^3\ water) = \mathbf{1569\ \frac{ft^3\ air}{night}}$$

We need to deliver 1569 ft^3 air per night. The pond will be split into quadrants, with one 1cfm diffuser in the middle of each quadrant. We will be delivering 4 $\frac{ft^3}{min}$ total.

$4\ \frac{ft^3}{min} * x\ \text{min} = 1569\ ft^3$

X = 392.25 min = **6.53 hours of runtime per night**

To deliver 5 ppm of oxygen to the 400m^3 pond (with 2m depth), we need to run four, 1cfm diffusers for 6.5 hours.

<u>Small Scale System calculations</u>

For the small system, the goal is still to deliver 5 ppm to the pool, but the smaller volume and depth alters the SOTE and the rest of the calculations.

$$SOTE = .03\ (for\ a\ pool\ with\ 1\ ft\ depth) = \frac{5\ \frac{g\ O_2}{m^3}}{x}$$

x = $\boldsymbol{167\ \frac{g\ O_2}{m^3}}$ - This amount of oxygen needs to be delivered per night to dissolve $5\ \frac{g\ O_2}{m^3}$

Now we need to convert the amount of oxygen delivered per night to a volume of air delivered per night.

$$167\ \frac{g\ O_2}{m^3\ water} * \left(\frac{1\ mol\ O_2}{32\ g\ O_2}\right) * \left(\frac{100\ mol\ air}{21\ mol\ O_2}\right) * \left(\frac{22.4\ L\ air}{1\ mol\ air}\right) * \left(\frac{1\ m^3\ air}{1000\ L\ air}\right) * \left(\frac{35.3\ ft^3\ air}{1\ m^3\ air}\right)$$

$$= 19.6\ \frac{ft^3\ air}{m^3\ water * night} * (.946\ m^3\ water) = \mathbf{18.55}\ \boldsymbol{\frac{ft^3\ air}{night}}$$

We need to deliver 18.55 ft^3 air per night. For the prototype, we will use one, .2 cfm diffuser.

$0.2\ \frac{ft^3}{min} * x\ \text{min} = 18.55\ ft^3$

X = 92.75 min = **1.54 hours of runtime per night**

To deliver 5 ppm of oxygen to the .946m^3 pool (with 0.3m depth), we need to run one, .2 cfm diffuser for 1.5 hours.

Appendix N: Prototype sizing calculations

Summary:

To provide 6 hours of runtime, a battery depth-of-discharge of 40%, and 5.66 lpm and 6.9 kPa of air pressure with the DC 12V air compressor, the required components include at least a 25 Ah 12 volt battery and 50 watt solar panel.

Question:

Based on oxygen/diffuser calculations, a dc system is needed to support 0.2 cfm airflow, 1psi, and 6 hours of runtime. What is the needed size of the parts of a solar panel and battery system?

Assume:

Charge controller 90% efficient
Charge controller used between solar panels, battery, and pump
Battery 90% efficient
Solar Panels 90% efficient
Ideal depth of discharge of battery is 40% for a 10 year lifespan
Solar Panels used to replace 1 night draw-down
Natural Sunlight for solar panels is 4 hours / Greenhouse lights are equivalent to 7 hrs

Solve:

Pump (12 volts, 25 watts)
current = $I = \frac{P}{V}$ = 2.1 amps

Charge Controller (90% efficient)
including efficiency, amps needed = 2.3 amps
$2.1\ amps * 1.1 = 2.3\ amps$

Battery (90% efficient, runtime 6hrs)
including efficiency, amps needed = 6 amps

$$2.3\ amps * 1.1 = 2.5\ amps$$

required ampere-hours = 15 Ah

$$2.5\ amps * 6hrs = 15Ah$$

for 40% depth of discharge/run battery size = 25Ah

$$\frac{15\ Ah}{0.4\ depth\ of\ discharge} = 25\ Ah$$

MINIMUM BATTERY SIZE = 25 Ah

Solar Panel only used to replace 1 night's draw down, so 15 Ah needed from panel/day

Charge Controller (90% efficient)
including efficiency, ampere-hours needed = 16.5 Ah

$$15\ Ah * 1.1 = 16.5\ Ah$$

Solar Panels (90% efficient)
including efficiency, ampere-hours needed = 18 Ah

$$16.5\ Ah * 1.1 = 18\ Ah$$

watts needed = 216 watts

$$power = IV = 18\ Ah * 12\ volts = 216\ watts$$

solar panel wattage for natural light = 54 watts

$$\frac{216\ watt}{4\ hrs} = 54\ watt$$

solar panel wattage for greenhouse lights = 31 watts

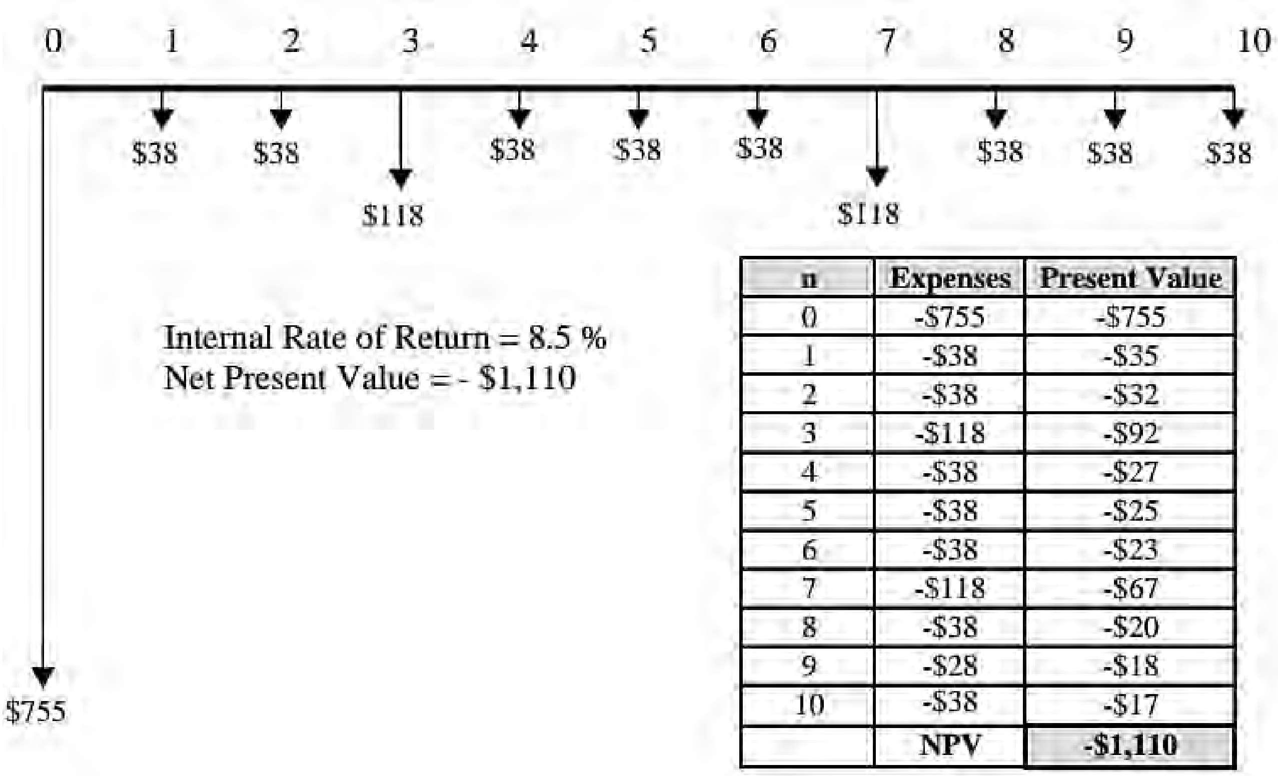
$$\frac{216\ watt}{7\ hrs} = 31\ watt$$

Conclusion:

Power requirements demand at minimum a 25 Ah battery and a 30-50 watt solar panel.

Appendix O: Final Design Economic Analysis

<u>Solar powered diffuser aeration system net present value (NPV) determination</u>



Internal Rate of Return = 8.5 %
Net Present Value = - $1,110

n	Expenses	Present Value
0	-$755	-$755
1	-$38	-$35
2	-$38	-$32
3	-$118	-$92
4	-$38	-$27
5	-$38	-$25
6	-$38	-$23
7	-$118	-$67
8	-$38	-$20
9	-$28	-$18
10	-$38	-$17
	NPV	**-$1,110**

Item	Cost Per Unit	Units	Total Cost	Expected Lifetime
Solar Panel (100 W)	-$125	2	-$250	10
Battery (100 Ahr/12 V)	-$150	1	-$150	10
Air Pump (60 W)	-$80	1	-$80	3.33
Diffuser (1 cfm)	-$20	4	-$80	10
Charge Controller (30 A)	-$60	1	-$60	10
Keyed Padlock	-$25	2	-$50	10
Brick	-$0.40	100	-$40	10
Tubing	-$0.40 / m	50 m	-$20	10
Latch	-$5	2	-$10	10
Hinge	-$2	4	-$8	10
Wiring	-$0.35 / ft	20 ft	-$7	10
	Capital Cost		-$755	
	Annual Maintenance Cost		-$38	5 % of Capital Cost

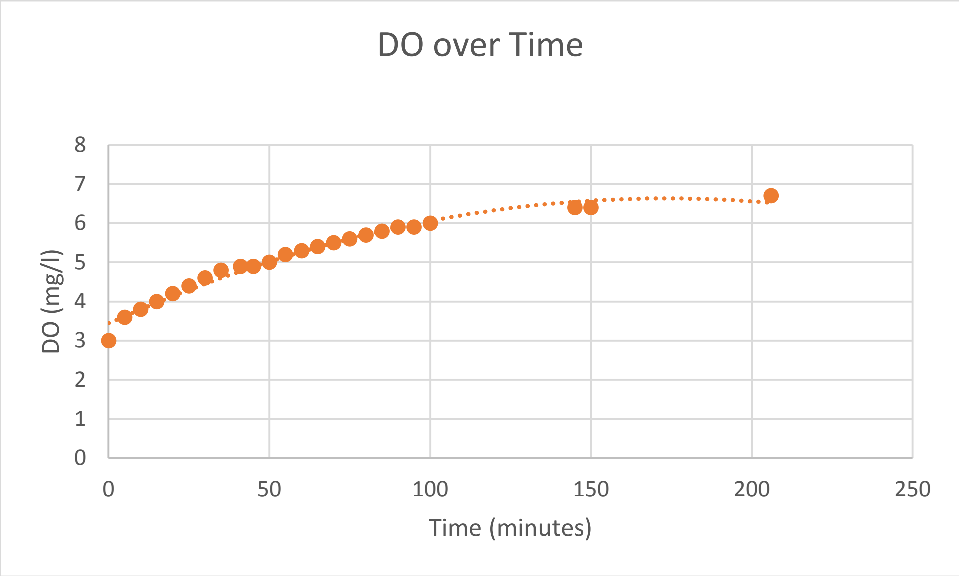
NPV per kg of oxygen added:

$$\frac{NPV}{kg\ O_2} = \frac{-\$1100}{\left(5\frac{g\ O_2}{m^3 * cycle}\right) * \left(\frac{1\ kg}{1000\ g}\right) * (400\ m^3) * \left(\frac{200\ cycles}{1\ year}\right) * (10\ year\ life)} = -\$0.28 \text{ Per kg of } O_2$$

Appendix P: Experimental calculations

Calculating Kla

K_La is the oxygen transfer coefficient



Variation of oxygen concentration in water

$$\frac{dC}{dt} = k_L a(C_\infty - C)$$

C = oxygen concentration in water (mg/L);
C_∞= point of stead DO concentration as time approaches infinity (mg/L);
t = time;
K_La = mass transfer coefficient (1/hr)

Integrating the above equation…

$$(k_L a)_T = \frac{\ln(C_\infty - C_0) - \ln(C_\infty - C_t)}{t}$$

C_0 = initial oxygen concentration (mg/L)
C_t = oxygen concentration at t

For collected data points (example of second KLA listed)

C_∞= 8.24 mg/L (oxygen saturation)

$$K_L a = \frac{\ln(8.24 - 3.0) - \ln(8.24 - 3.6)}{5} = 0.024$$

time (minutes)	DO (ppm)	KLA (1/min)
0.01	3	0.000
5	3.6	0.024
10	3.8	0.017
15	4	0.014
20	4.2	0.013
25	4.4	0.012
30	4.6	0.012
35	4.8	0.012
41	4.9	0.011
45	4.9	0.010
50	5	0.010
55	5.2	0.010
60	5.3	0.010
65	5.4	0.009
70	5.5	0.009
75	5.6	0.009
80	5.7	0.009
85	5.8	0.009
90	5.9	0.009
95	5.9	0.008
100	6	0.008
145	6.4	0.007
150	6.4	0.007
206	6.7	0.006
		0.011
	KLA (1/hr)	0.644

Calculating SOTR

$$= k_L a\,(DO - DO_{sat})\,V$$

SOTR = oxygen transfer rate (mg/hr)
KLA = oxygen transfer coefficient (1/hr)
DO = initial DO concentration (mg/L)
DO_{sat} = saturated DO (mg/L)
V= volume of water (L)

$$SOTR = (0.644\ hr^{-1})\left(3.0\frac{mg}{l} - 6.4\frac{mg}{l}\right)(1000l)\left(\frac{1mg}{1000g}\right) = \mathbf{2.20\ g/hr}$$

Calculating SAE

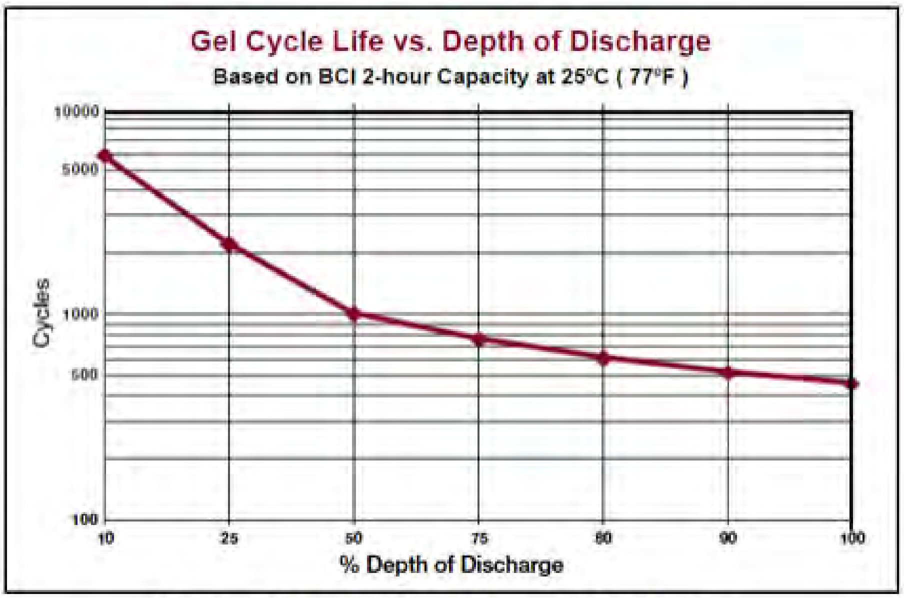
Standard aeration efficiency

$$SAE = \frac{SOTR}{power\ consumption}$$

Power consumption = 2.1 amps *12 volts * 2.5 hr runtime = 63 watt*hours = 0.063 kWh

$$SAE = \frac{2.20\,\frac{g}{hr}}{0.063\ kw} = 34.8\ g/hr = \mathbf{0.0348\ kg/kWh}$$

Appendix Q: Battery Discharge Curve



Effect of DOD on lifetime of Trojan Gel Cell battery

From trojanbattery.com