Building a Solar-Powered Pump to Deliver Clean Water to Villagers in Ngomano, Kenya

Student Researchers: Rob Best (HMC ’10), Isabel Bush (HMC’12),
Evann Gonzales (HMC ’12), Ozzie Gooen (HMC '12)

Advisors: Professor Peter Saeta, Professor Susan Martonosi

Abstract

In pursuit of the goals of environmental, economic, and social sustainability, the Engineers for a Sustainable World (ESW) chapter at Harvey Mudd College completed a service project trip to Ngomano, Kenya during the summer of 2010. The purpose of the trip was to implement a solar-powered pump to deliver clean water to the Clay International Secondary School in Ngomano. The team designed a solar system that could pump water from an existing campus borehole and also provide the school with lighting and power. The students then travelled to Kenya to execute the design and build upon relationships established between Harvey Mudd students and Ngomano villagers during a water quality assessment trip to the village in January 2009.

Introduction

During the 2006-2007 school year, Andrea Leebron-Clay and her husband Jim Clay approached the Harvey Mudd College chapter of Engineers for a Sustainable World with an idea to form a partnership with the new Clay International Secondary School in Kenya. The Clay family saw an opportunity for Harvey Mudd students to have an abroad experience while solving challenging engineering problems in a developing nation and influencing the lives of less fortunate students. Their idea fit perfectly with the mission of Engineers for a Sustainable World--as a chapter of a national organization, ESW has a mission to promote sustainable practices at home and abroad through technical projects, education, and outreach. Since this initial meeting, the Harvey Mudd chapter has been diligently working with the Clays and members of the school in Kenya and Washington State to effect positive change on the campus and in the lives of the students and teachers. To date the club has successfully completed two service trips to the school and plans to continue the partnership in the future. This paper documents the process and lessons learned from the latest service trip to Ngomano, Kenya, during which members of the HMC ESW chapter designed and installed a solar-powered water pump and lighting system.

The Clay International Secondary School

The Clay International Secondary School is a private, fully-funded secondary school established by Project Education, Inc., a non-profit organization with offices in Seattle, Washington, and Kenya. The organization, the mission of which is to create a new model of education in developing nations, was founded in 2005 by Debra Akre and Jeanna King with financial support from James and Andrea Clay. The goal was to found schools which would provide free secondary education, a new concept at the time in impoverished regions of Kenya. The schools are meant to be self-sustaining economically and socially, which requires creating a steady stream of income for the campus to pay teachers and cover operating costs. It also requires support and participation from the community to maintain the campuses and provide for the students.

The Clay International Secondary School is the first campus born out of this model. The school was founded in 2005 by Benson Mutua and Project Education in an abandoned children’s home in Ngomano, Kenya. Ngomano is a small village seated atop a hill between two seasonal rivers which only flow during the rainy season. The rest of the year, these rivers are dry but water can be drawn from approximately one meter below the surface. Most villagers draw water from the river on the west side of the village as it is less brackish than the water from the river on the east side of the village.

Campus Layout and Operation

Since 2005, the school has purchased its own land on the eastward slope of the hill and built five classrooms, a laboratory, eight teachers' houses, an assembly hall, staff office, medical clinic, kitchen, Principal's office, and several guest houses. These facilities are divided into two areas—the upper campus which features the classrooms and offices and the lower campus which contains teacher and guest housing and the assembly hall. The housing in the lower campus encircles a communal kitchen and lounge which feature lighting, a television, and cooking and sitting areas. The upper and lower campuses are separated by the athletic fields. Figure 1 below shows an image of the classrooms and laboratory located at the upper campus. Figure 2 shows the lower campus with the assembly hall and housing.

Fig. 1. The upper campus classrooms and laboratory.

Fig. 2. The lower campus. The assembly hall is on the left while the teacher and guest housing are on the right.

Since its inception, the school has expanded from three teachers to eight and from one class of 27 students to four classes spanning Form 1 through Form 4 containing 128 students. Students learn eleven subjects: math, english, geography, kiswahili, history, humanities/religion, chemistry, biology, physics, agriculture, and business studies.

They also have extracurricular studies in physical education, music, and AIDS awareness and prevention. Many students stay after school to extend their studies and prepare for the next day's lessons because lighting is available in some of the classrooms on the campus, whereas no lighting is present in their homes. All teachers live on the campus during the school year but most return home for breaks.

Personnel

Project Education, Inc. is operated in the United States by Jeanna King and Debra Akre with financial support from James and Andrea Clay. The In-Country Director of the school is Benson Mutua, a native of Ngomano and a trained civil and computer engineer. The Principal of the school is Peter Okwiri, and the Vice Principal is Samuel Kheamba. The six other teachers are Mister Justus, Mister Kennedy, Madame Janet, Madame Veronica, Madame Dorcas, and Madame Sarah. There are two night watchman, a cook named Peter, and the Chairman, the caretaker of the grounds. A local gentleman named Mbithi David assists the school with construction projects. All other work is provided by either the students or community members when necessary.

Financial Operation

The school currently operates primarily on donations from the Clay Foundation but has a mandate to become financially sustainable. To achieve this, the school plans to cultivate land on the campus, using some of the crops to provide food for the teachers and students and selling the rest at market to pay the teachers' salaries and pay for supplies. Currently, there are crop fields located both by the classrooms, known as the upper fields, and between the assembly hall and the teachers' housing, known as the lower fields. There is also a fish pond by the staff office to provide the students with a source of protein in their meals. All of the fields are watered via a gravity fed network of pipes and tanks originating from a 75,000 L tank located uphill from the school in the village of Ngomano. The tank is fed by a 16 hp pump which draws water from a sunken pond in the river bed of the western river. The pump is typically operated once or twice per week to provide enough water for the students and crops. The Clay Foundation would eventually like to see this tank being used to provide water for the villagers. Under this scenario, villagers would pay a small amount to use the water which would then help pay for the gasoline to run the pump. Currently, however, villagers choose to fetch water themselves despite the labor intensive process to save money.

Cultivation in the fields is performed by both the students and their parents. Members of the community are very grateful for the school and the provision of free education for the students and thus volunteer their time on weekends and when called by the principal or director to help the campus. Through these efforts, the amount of land under cultivation has drastically increased in the last three years but currently does not provide enough income for the school to operate self-sufficiently. However the school is piloting a drip irrigation system which, by reducing the amount of work and water required while increasing the yield of the fields, can pay for itself within one to three growing seasons. Widespread implementation of drip irrigation could be one pathway to financial sustainability for the school.

Another pathway to financial independence that the school is exploring is renting out the assembly hall, which is due to be completed by the end of 2010. Benson envisions this space as being used by surrounding schools for plays and assemblies and by the community for meetings, functions, weddings, and other celebrations. The space will be the only indoor assembly hall in the district.

Summary of Previous Work

In January 2009, Professor Susan Martonosi and three students from Harvey Mudd traveled with the Clay Family and Don Mergens to Ngomano to explore options for future projects and demonstrate water purification by solar distillation. Provision of clean water at the campus is a constant problem. In 2006, a well was dug on the campus in the hope of providing clean drinking water for the students and teachers. However the water which was pumped was brackish and thus was underused. Two water tests have been performed on the well, and the results are given in Appendix A and B. Geologists have suggested that contaminants in the water may diminish over time as the well is used and flushed, but current use rates have not been substantial enough for clearing to be observed. The goal of the Harvey Mudd team therefore was to demonstrate a possible solution for removing the contaminants until the well clears.

The solution proposed by the team was solar distillation. In this process, a batch of dirty water is placed in a black-bottomed container covered in a clear film sloped toward an empty receptacle. Rays from the sun pass through the film, are absorbed by the bottom, and heat the dirty water. As this evaporates, it condenses on the clear film. When droplets reach a critical size, they run down the film and into the empty receptacle for collection. The process of evaporation leaves behind heavier-than-water molecules such as salts and sediments, the main contaminants of the well. Figure 3 shows a diagram of the solar distillation process.

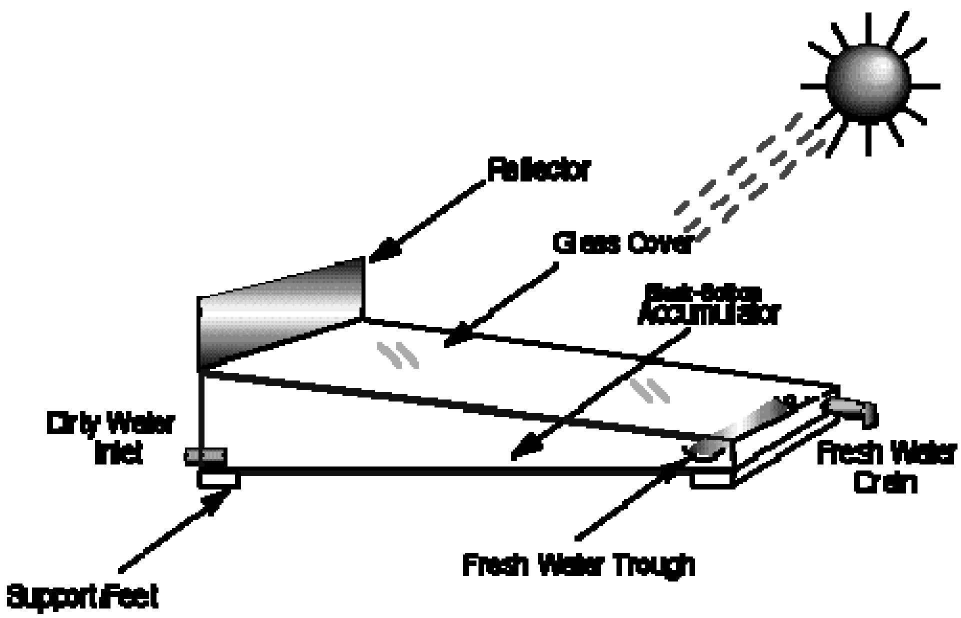

Fig. 3. A diagram of solar distillation (http://kanara-azaryahu.superbestfirst.in/10060517/solar-distillation/).

The team constructed a solar distillation unit at the Clay School and demonstrated its use to students and teachers. The team also instructed students at the school on the principle of operation and the importance of clean drinking water. The work provided a proof of concept but was not adopted on a large scale for the school during the visit. It was decided that provision of enough water for the students and crops was a more pressing concern, and that for the interim, the quality of water from the river bed was sufficient. However, should water quality from the well fail to improve, solar still technology has been proven on a large scale in tropical and subtropical areas by Aqua-Aero Water Systems and could provide a way of purifying water for the school (http://www.aaws.nl).

Project Preparation

Preparation for the second trip to Ngomano began in spring 2009. Following the first trip to the village, students decided that while water disinfection is still an issue for the village, the insufficient quantity of any water seemed to be the larger problem. Since Ngomano, Kenya is located near the equator and receives 6.5 -7 kWh/m2 of direct sunlight per day with only a short rainy season (by comparison Los Angeles receives 5-5.5 kWh/m2/day), the team determined that solar power would be the most feasible and sustainable power source for a new water pump. Thus the ESW team began work on providing the Clay school with a solar-powered water pump.

The first plan was to convert the school's diesel water pump to run on solar-electric power. This pump collects water from the dry riverbed every couple weeks and pumps it up 45 meters along an 850-meter run to fill the school's 75,000 liter tank. In the fall of 2009, the team calculated the electrical power that the solar panels would need to produce to run this pump, and then priced out the individual components. In order to run a pump once every two weeks, the solar energy from those two weeks would need to be stored in batteries. The students found that the solar energy requirement would be very great due to the significant energy losses through battery storage and running cables over such a great distance. The team determined that not only would this be a highly inefficient system, but the cost of such a massive solar array and battery bank would be far outside the planned budget, thus making it an unreasonable project.

After further conversations with Benson, the ESW team decided instead to improve the pump system in the borehole to help it flush and eventually provide usable water. This 100-meter-deep borehole was dug down into an aquifer located between 66 and 90 meters down, with the water level coming to 23 meters below the earth's surface. At the time it was dug, a hand pump was installed to allow access to the water. Unfortunately, although the aquifer had been found to produce clean, potable water in nearby areas, the water coming out at the Clay School was found to have very high mineral concentrations. When boreholes are first dug, much sediment is loosened and can contaminate the water. Thus the source must be pumped for some time before it is suitable for drinking. Benson indicated that in the years since the borehole was dug, the mineral content has decreased, making it suitable for cleaning and a few crops. However, due to infrequent use since the previous team had traveled to Kenya, Benson reported that there was little change in the taste of the water from the well and thus the school was using water from the river. The team therefore decided to install a new solar pump at the borehole capable of autonomously pumping water from the well, allowing it to flush and eventually be used for drinking and crop irrigation.

The next step for the team was to calculate the flow rate and pressure head that the pump would need to provide so that an appropriate pump could be purchased. The team decided to size the pump so that should the well-water flush, the pump would be able to provide enough water to become the school's primary water source, thus replacing the diesel pump. The pump thus needed to be able to provide about 80 meters of lift and have a flow rate of about 750 liters per hour, in order to provide 75,000 liters of water every two weeks, as is the school's current water demand. These calculations can be found in Appendix C. With this new system, the pump could run directly off the solar panels whenever the sun was shining, thus eliminating the losses and cost associated with a large battery bank.

Based on their calculations, the team members chose a Lorentz PS1200 series, HR-04H pump because it was an electrical pump that could provide the necessary pressure head and flow rate. The team purchased this pump in early May 2010, and tested it in Professor Peter Saeta's pool later that month to ensure it worked properly before leaving for Kenya.

During the 2009-2010 school year, the team also expanded the project to include the creation of an electrical system for the school. Since the team sized the pump and solar array to be able to provide all the school's water should the well-water become potable, until that happens, there will be many times when the pump would not running and thus the solar panels would be providing unused power. Benson expressed a desire for better lighting and power for the school, so the team decided to route the extra power from the solar panels to a battery-powered electrical system.

In the three weeks of summer prior to leaving for the trip, the team spent much of their time designing the electrical system. Since the Lorentz pump required a 72-volt solar array, batteries require 12-volts, and the school lighting could run on 12-volt DC or 240-volt AC, the team tried to design the simplest and most economic system to convert between these voltages. Some of their design alternatives can be found in Appendix D. After discussing the system with Harvey Mudd engineering professors and Claremont area solar installers, the team decided on the system detailed in the final results section of this report.

Pump System Process

Once in Kenya, the team spent a day in Nairobi and a day in Wote (a town of about 60,000 people located about 1.5 hours by car from Ngomano) purchasing supplies for the project. The students felt it was best to purchase supplies in country to allow for replacements should anything break down. Solar panels, batteries, charge controllers and other large system components were purchased in Nairobi, but most small hardware could be found in Wote.

The first day in Ngomano defined much of the rest of the trip. The plan was to remove the hand pump and associated galvanized iron piping from the borehole. Benson showed the team how to fashion a large tripod out of pipe and rope and then, with the help of some local citizens, a chain hoist was used to remove the hand pump. Although the system looked somewhat unstable and made us Americans feel uneasy, it was simply, as Benson put it, "engineering in the village." Unfortunately, this makeshift hoist system did not prove to work as well as hoped; the rope holding the chain hoist snapped, and the pump, pipe, and a pipe wrench went crashing to the bottom of the borehole.

Although the team could still put the new pump down 50 meters into the borehole before hitting the fallen pipe, this would mean the pump would be only 27 meters below the water surface, which would decrease the amount of water that could be pumped each day since the water would not recharge as fast as it was pumped. The team's project thus turned into an engineering design project – how to remove 50 meters of 1.5-inch piping from a 4.5-inch borehole when the top of the pipe is 50 meters below the surface.

The team came up with numerous "hook" possibilities, all of which were designed to drop below the first pipe segment coupling and then catch the coupling when pulled back up. The team faced many design problems such as how to funnel the hook either inside the pipe or around the outside when the pipe was likely resting along the borehole and how to design a mechanism that would be strong enough to catch and lift the estimated 600 lbs of pipe.

What proved to be most difficult, however, was designing a "hook" that could be fabricated in Wote. The team's original designs were drawn up with precise measurements and sharp angles, as if they were to be made in a machine shop with lathes, mills, and electronic drills. Instead, the blacksmiths in Wote were working with hand tools. Although they do have the ability to weld, all cuts are made with handsaws and all holes are burned rather than drilled and are thus large and uneven. The team's first couple designs proved to be too difficult to fabricate without losing much of the strength and functionality of the "hooks." Descriptions and photos of preliminary designs can be seen in Appendix E. After each unsuccessful attempt to retrieve the pipe using these designs, the team learned more about the types of materials that were available in Wote, the types of structures that could be easily fabricated by the blacksmiths, the difficulties associated with "fishing" for something that is out of sight and at great depths beneath the earth's surface, and lastly about the importance of creating a sturdy structure with backup attachments to avoid dropping more objects down the borehole.

The team's final hook design, shown in Fig. 4, resembled something of a rocket.

Fig. 4. Final pipe-retrieval design. The "rocket" is made to fit around the pipe. The curved structure at the right is designed to pull the top of the pipe away from the wall, and the dark portion is a funnel to guide the pipe into the rocket. The pawl on the side is designed to lock below the first pipe coupling.

The rocket body was constructed from a 2-inch pipe and consisted of four basic parts. At the top of the rocket, a section of threaded rod and a loop were welded to the 2-inch pipe. The rod would be used to lower and manipulate the rocket, while the loop would be attached to a length of chain that would serve as a fail-safe. At the base of the rocket, a piece of metal was bent into a cone and attached to the bottom of the 2-inch pipe. A rod and metal hook was attached below this cone. The idea of these bottom two parts was to funnel the pipe into the rocket. The base of the cone almost filled the borehole, thus it was expected to stop when it hit the top of the pipe. The rocket would then be twisted until the hook found its way behind the pipe against the wall of the borehole. With further twisting, the hook would pull the pipe off the wall and towards the center of the borehole, where it could then fall into the cone and be funneled into the 2-inch pipe of the rocket. The last part of the rocket was a pawl along the side of the rocket designed to actually catch the pipe. This hinged piece of metal was attached to the outside of the rocket and extended through a hole to the inside of the rocket. A compression spring held the pawl inside the rocket. The idea behind the pawl was that as the rocket slid down around the 1.5-inch pipe and over the first pipe coupling, the pawl would be pushed out of the way. Once the rocket passed the coupling, the spring would push the pawl back into its inward position, thus trapping the coupling and first pipe segment above the rocket. A picture of this pawl holding tight against the coupling can be seen in Figure 5.

Fig. 5. The rocket's pawl caught beneath the pipe coupling

Fig. 6. The tripod, chain hoist, and rocket holding the first pipe segment out of the borehole.

As can be gathered from Figures 5 and 6, this rocket design was finally successful in removing the original hand pump and piping. Although the rod holding the rocket somehow became unscrewed before all the piping was removed, the chain backup held and was used to remove the rest of the pipe. Once this was removed, the team set to work on installing the Lorentz electric pump. The pump was lowered on the same galvanized iron pipe, again using the makeshift tripod and chain hoist, but this time chain was used rather than rope to hold the chain hoist and more chain was attached to the pump as a backup. Metal zip-ties were used at 3-meter intervals to hold the pump wires against the pipe.

Once the 69 meters of pipe, chain, and wire had been lowered into the borehole, the pipe and chain were secured to a flange at the well's surface. Plastic piping was then used to run the 75 meters from the borehole to a water storage tank that the team installed above the teacher housing complex. The pump was wired through the pump controller to the solar panels, and the well was soon producing water.

Unfortunately, this success was short-lived. Just two days after water started flowing, the pump controller stopped working. The team discovered a burn mark on the controller's circuit board, which prompted the testing of the wires leading down to the pump. The low resistances between all wires indicated the existence of a short circuit, and thus the team decided to remove the pump one more time to find the cause of the short. Unfortunately, after much of the pipe was removed from the well, the pipe once again slipped, the chain snapped, and the new pump and remaining 25 meters of pipe fell back down to the bottom of the borehole. Although all the wires were removed, the source of the short could not be determined.

At this point, the team had only a couple days left in Ngomano. Although the students were confident that the rocket would work again to retrieve the pump, the top of the pipe now lay about 75 meters below the surface and thus there was not enough rod or chain to lower the rocket. The team also feared that with the available hoisting materials, there was too much of a risk that in a rushed retrieval effort, more rod, chain, or pipe would be dropped down the borehole. Thus the team decided that rather than retrieve the old pump, it would be safer to simply purchase a new pump, along with lighter-weight plastic pipe and polypropylene rope rather than chain. Since the pipe had fallen to 75 meters below the surface, it would not be in the way of lowering the new pump to the same 69-meter depth, and with the light-weight pipe and rope, the chain hoist should not be needed and there would be less risk of equipment failure. Unfortunately, the team did not have enough time to purchase and install a new pump before their return to the U.S., but the team was able to set up a plan for the installation. A new Lorentz pump was ordered from a distributor in Nairobi, wires were labeled, and instructions were left so that Benson and Mbithi would be able to easily and safely lower the new pump and attach it to the existing system. The team received confirmation from Benson on August 15 that the new pump had been lowered and was delivering water to the tank.

Electrical System Process

When not working on the water pump aspect of the project, team members were occupied with constructing the power house and electrical system. The power house, which is located beneath the water tank and holds the batteries and electrical equipment, was built out of bricks and concrete. The students learned how to shape the wire structure for the concrete pillars and then how mix, pour, and cure the concrete. Mbithi also showed them how to lay bricks and insert conduit into the walls. Once the structure was complete, the team was able to install the solar panels above the water tank and attach and wire the electrical components inside the power house. The power house, water tank, and solar panels can be seen in Figure 7. Wire was then laid underground from the power house down to the teacher's housing lounge and up to the school buildings for lighting and power outlets. The buildings were then wired as explained in the final results section.

Fig 7. Completed power house, water tank, and solar panel structure.

Final Results

Figure 8 describes the configuration of the whole system.

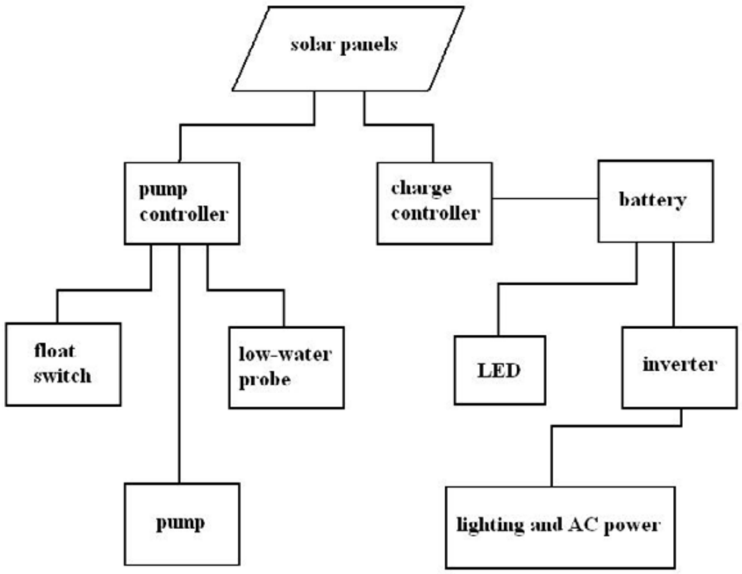

Fig 8. Whole system block diagram

The powerhouse contains a main disconnect switch which interrupts the positive wire from the solar panels, a Lorentz controller for the pump, a charge controller, an inverter, a solar battery, a power strip, a circuit breaker between the inverter and power strip, and an LED light attached to the ceiling. Figure 9 describes how components inside the powerhouse are connected. The powerhouse system is connected by wire running from the powerhouse to both the teacher's housing lounge and the borehole. Six wires go down the borehole to the pump and low-water probe. The pump requires four wires, including ground, and the low-water probe requires two.

The system has the pump controller and the charge controller running in parallel. This allows for the battery to charge during daylight hours when the pump is not running. The pump controller has eleven wires running into/out of it: four for the pump, two each for the float switch, low-water probe, and solar panels, and one for ground. The charge controller has five wires: two for the solar panels, two for the battery, and one for ground. The battery is connected to the LED and the inverter, each using two wires. The inverter, which is grounded, has three wires running to the power strip, with the red wire interrupted by the circuit breaker.

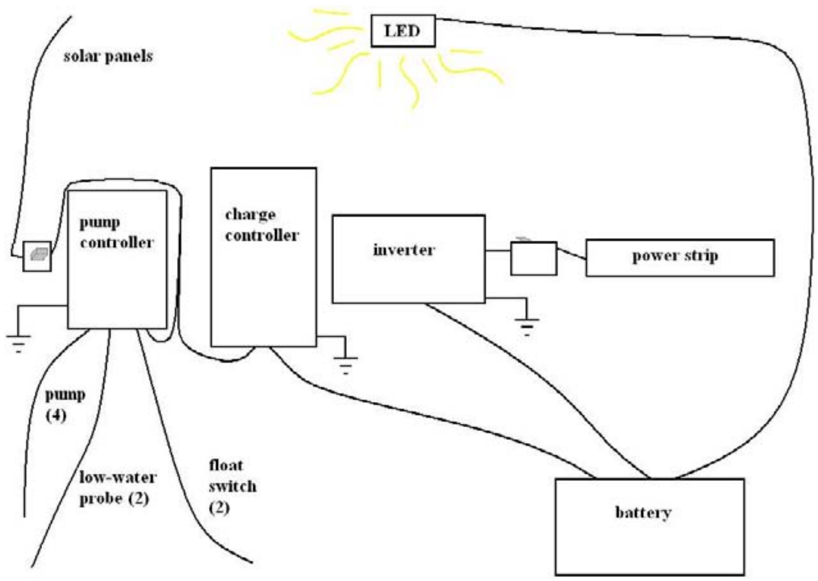

Fig 9. Powerhouse diagram

The powerhouse system powers the lab, the principal's office, and the power strip in the staff office via an underground wire running across the football pitch. The system in the staff office powers the classrooms for Forms one, two, three blue, and four. All of the connections were made such that the buildings are in parallel with one another. Figure 10 describes the wiring of the campus. The lab, principal's office, and staff office power strips were all grounded.

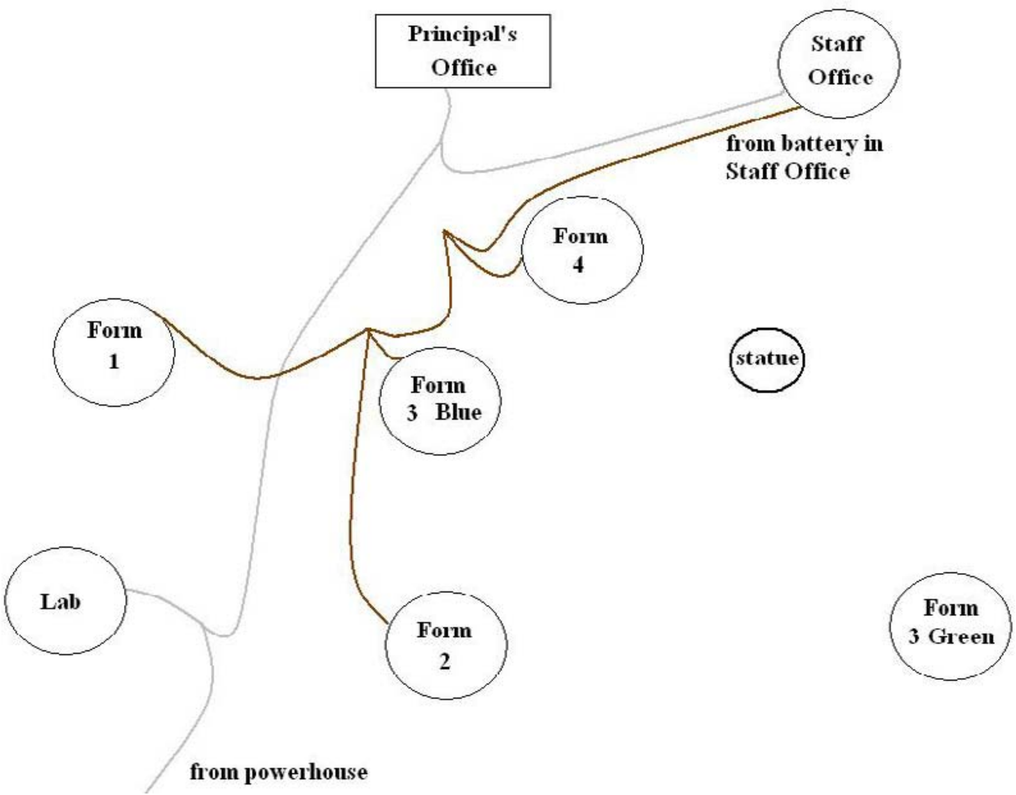

Fig 10. Wiring of the campus

The roof of the staff office holds eight 14-Watt solar panels and one 80-Watt panel. These panels connect in parallel to a charge controller obtained by the group. The charge controller connects to two parallel batteries. These batteries connect to a DC-to-AC inverter. The inverter then powers the classrooms and has an interrupt, or master switch, in the staff office. The classrooms are wired for AC power and have 14-Watt compact fluorescent bulbs. AC power was chosen to reduce power loss in the wire and to easily allow for expansion and modification, such as adding more power strips. Figure 11 describes the wiring of the classrooms and Figure 12 describes the wiring of the lab.

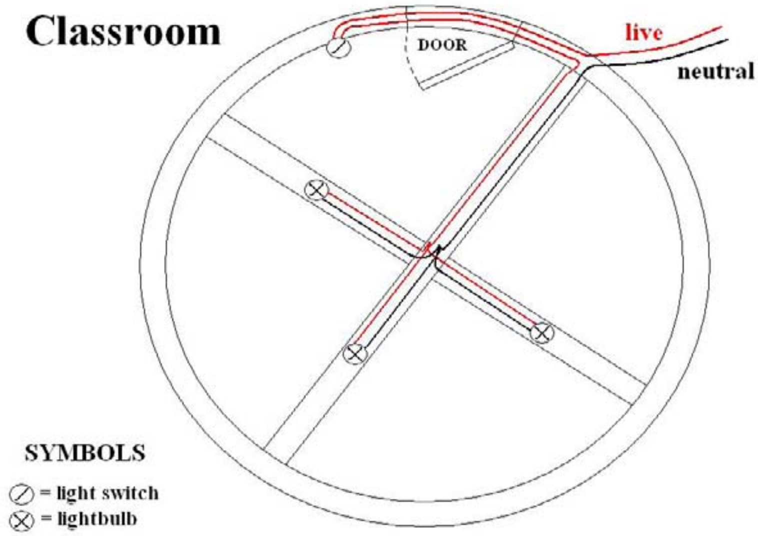

Fig 11. Completed wiring for the classrooms

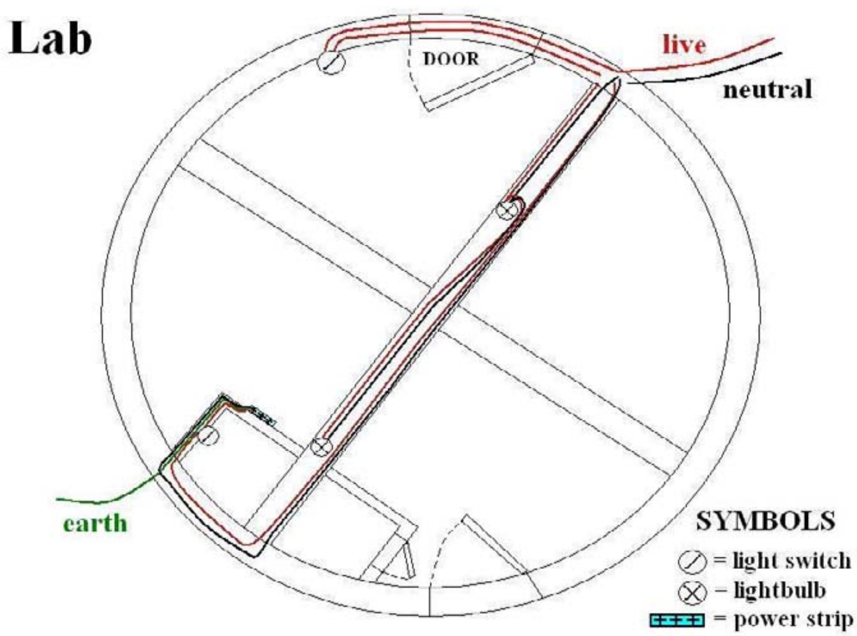

Fig 12. Completed wiring for the lab

Other Activities

When not working on the project, the Mudd students engaged in other activities with local students. The ESW team taught classes about engineering and sustainability to the Clay students. The team also provided some XO laptops and graphing calculators for the students and gave classes on their basic use. In addition, the team members taught a few short lectures to primary school children both in Ngomano and other villages around the country.

The team also had the opportunity to interact with the Clay students outside of the classroom through sports and music. Team members taught baseball, frisbee, and jump rope, as well as joined the local students in soccer and volleyball matches. The game "Sharks and Minnows" was played with the kids at dusk with glow sticks, and it was so well received that the school would love to find or be sent more glow sticks.

Ozzie brought a soprano saxophone to the school. After a demonstration, several students and faculty members became interested in learning how to play it. Three classes were given to the students to introduce them to both basic music theory and saxophone technique. Principal Peter also tried learning the saxophone with the help of a few private lessons. The hope is that with practice he can later teach the students. The saxophone is stored in his office, which is always open to the students.

One difficulty with music education in Kenya is that it is not commonly taught in schools, which means that music books are incredibly difficult to come by. It is advised that future students bring the school more instruments, as well as introductory music books.

Student Challenges

Upon leaving, three challenges were given to the students. Ozzie Gooen has agreed to send something to any student who completes one or more of them.

1. Complete the book, <u>Teach Yourself Electricity and Electronics,</u> by Stan Gibilisco.

Several students were interested in electronics, so this book was left with the school for them to further their interest. While this book is incredibly long (750 pages), it is hoped that some incredibly motivated student can get through it.

2. Learn to type over 25 words per minute on one of the XO computers.

It may be difficult to motivate the students to spend much time with the XO computers, mainly because they have relatively few programs. Developing adequate typing speeds, however, may prove to be incredibly useful to students. Currently many Kenyans learn to type in specialized 3 month programs, which can be expensive.

3. Develop a business plan or school project that gets implemented on campus.

The Clay International School is trying to become economically sustainable. It is hoped that community input will allow them to find new business ventures and campus plans.

Future Projects

The team has used its experiences abroad to develop the S.U.D.S. criterion. This is a set of four qualities that are important to keep in mind when creating and choosing future projects.

1. Sustainable.

Future projects should promote environmental and economic sustainability. This is the essential idea behind our organization and it should be followed as precisely as possible. Careful note should be kept of negative environmental consequences of possible projects; for example, the filth produced by a chicken coup next to the local drinking supply. Projects should be well understood by the local communities upon completion so that they can help long afterwards.

2. Useful.

Future projects should serve a vital need in a community. The project should be aimed at providing a resource that will serve a great number of people in need.

The best projects empower already dedicated individuals and organizations. At the Clay school, several incredibly motivated individuals have been instrumental in this project. These people should be able to keep the system running for a long time while maximizing their use of it. The team also met the teachers and faculty at an orphanage in Kisii that had a similarly dedicated community.

One of the most important things when coming up with projects is to have a lot of options. Typically local groups suggested one or two options that they thought would work for the ESW group; but it worked better when they provided more options to allow for further brainstorming. It is very easy to assume a very narrow set of possibilities, especially when one group is left out of the brainstorming (the students or parents, for example).

3. Difficult.

The projects must provide the Mudd students extensive and challenging problems so that they may gain relevant engineering experience. This means finding problems where the team's expertise is needed, not just money. For example, purchasing a used school bus to expand a school's reach may be great charity, but it would involve almost no team activity.

4. Safe.

The school and sponsors must feel secure with the locations and environments of possible projects. This is easiest to achieve when Mudd students have already visited the group with which we are working during a previous trip.

Because of this last point, it is important that future student groups traveling abroad try to contact and visit all possible places of future work. This year's team started seriously talking to the local Clay school faculty about expansion in the last few days. It came out that there were many nearby groups that could have used help, but by then it was too late to get in touch with them. Thus it is recommended that students start the planning process for future projects early on.

While this trip focused on one large project for one community, it is recommended that future teams attempt to work on a few smaller projects, or one large one with a few side projects. This would allow future groups to assist a greater number of people. Daily living expenses in Kenya cost relatively little in comparison to plane flights and materials. It could thus be relatively inexpensive for future groups to stay longer than six weeks to complete several inexpensive but technical problems.

Current Possibilities

So far there are several possibilities for future projects. The three main areas where we have made connections and discussed future work were the Clay International School, the Ngomano Primary School, and the Kisii Orphanage.

Projects for the Clay International School

1. Installation of a Drip Irrigation System.

The school currently uses drip irrigation for approximately one third of their crops. This process reduces water consumption, reduces farming time, and greatly increases crop yields, often paying for itself within one growing season. A larger drip irrigation system would be relatively simple and inexpensive, and may be installed before the next ESW team visit.

2. Lighting for the Teachers.

None of the teachers have lighting or power in their homes. One 9-watt light bulb in each of their homes could provide a large advantage in comfort and livability. Many of the teachers have come from urban environments and were used to having power before taking the sacrifice to come to the school. This would be very simple to wire because the homes are close to the power house. However, the solar and battery systems would need to be expanded for the extra power consumption.

3. Help create a business.

Some ideas discussed so far have been a bakery, a cell phone charging station, or a local Internet Cafe. Principal Peter is comfortable with getting the students and community involved in the business. While the school is making great progress with their agriculture, additional sources of revenue are important to hedge against fluctuations in the crop market. The students and local community were asked to help come up with business ideas.

Projects for the Primary School

1. A lighting system.

The school currently does not have working electricity and would like lights. It should be investigated how much time the students would spend using them. At the Clay Secondary School, a large fraction (about one half) of the students stay late studying. Most of these students leave at 9 p.m., but some stay long after. It is possible that at a Primary School, however, the students may not have as much of a need to study as much.

2. An electric pump system.

This could be useful to the school in similar ways that it has been to the Clay International School. However, as there is not a borehole drilled yet, it could be very expensive to create one and install an electric pump system.

Projects for the Kisii Orphanage

1. Biodigester.

Biodigestors convert organic waste into nutrient rich fertilizer and biogas. They can be created for as little as $300 and can be relatively simple to construct. However, according to the Clay For Earth foundation, they can require a lot of water to function, especially if they are used for chicken waste (http://www.clayforearth.org/solution.php?id=183).

2. Dormitory Construction.

Currently the school dormitories are donated by a local land owner. The space available is only enough to fit approximately forty out of the one hundred and fifty students who want to attend the orphanage. Many of the other students stay with distant relatives up to three miles away; others don't go to school at all. Also, the lack of official buildings means that the orphanage is ineligible for government funding. Small dormitory construction may require moderately little actual engineering, but would provide a huge advantage to the community.

2. Chicken Coup

The teachers and faculty at the Kisii Orphanage are all volunteers. While this seems to be working well, they would prefer a salary to help secure better teachers and keep the organization running. Nick, the school principal and also a part time veterinarian, suggested creating a chicken coup as a stable source of revenue. This would require the creation of a large chicken coup and the purchasing and feeding of five hundred chicks (according to his recommendation). After five months the chicks begin laying eggs, which can be sold at the local market. Approximately two years later, the chickens stop laying eggs and are sold off. This project would bring in a lot of revenue, but would require a high initial investment. Unless a future team could find a sponsor to donate the money for five months of chicken feed, the creation of a second business could be used to pay for this.

Chicken Coup Costs:
Poultry Structure: 58,000 Shillings.
Purchasing 500 Chicks: 36,000 Shillings
Chicken feed per day: 1,200 Shillings.
Chicken Coup Income:
Selling 400 eggs/day (on average) : 4,000 Shillings.

*Note: One dollar is approximately equal to 80 Shillings.

3. Cell Phone Charging.

Nick predicts that a cell phone charging station close to the school would be able to attract twenty customers per day. If other stations were set up in the local city, more sales would be possible. Each charge would cost the customers ten shillings. With a few small solar panels and a battery, one station may be relatively inexpensive to establish.

4. An Internet Cafe.

Currently citizens close to the orphanage need to pay over eighty shillings just for transportation to the closest Internet Cafe. An Internet Cafe could be in demand close to the Orphanage or further away at the more populated parts of the city. Cafes in nearby areas usually charge between one to three shillings per minute. This structure would require between three and five computers with Internet access. If this business became popular it may be able to host computer learning classes. Nick thinks it would take an Internet Cafe approximately two months to establish a customer base.

5. Other Businesses.

Many more business ideas must still be considered. It is preferred that a product idea would not be something commonly produced in the area, because a significant profit would be important. The orphanage has brainstormed a number of various solutions which are displayed on their website http://thrivingtalentscc.moonfruit.com/#.

Appendix A: Water Report 1

This list is not exhaustive.

Legend

- Passed guidelines; no expected health impact.
- Not known to pass guidelines or possible health impact.
- Negative non-health impact.
- Possibly positive health impact.

Parameter	Value	Units	Health Guidelines (WHO)	Notes
Colour	11	Colour unit		
pH	7.3	- log10([H+])	Not established.	[13]
Turbidity	6	NTU	Not established	[14]
Conductivity	924	mS/m		
Acidity (pH=8.3)	127	mg CaCO3		
Acidity (pH=10.8)	1431	mg CaCO3		
Alkalinity (phenolpthhalein)	0	mg CaCO3		
Alkalinity total (pH=4.5)	1178	mg CaCO3		
Hardness total	4872	mg CaCO3	Not established	[5,6]
Total solids (residue dried at 110C)	8094	mg/L		
Total dissolved solids (residue dried at 180C)	7403	mg/L	Not established	[12]
Settleable solids	<0.05	mg/L		
SAR (Sodium Absorption Ratio)	1.5	-		
RSC (Residual Sodium Carbonate)	-25.2	meq/L		
SI (Saturation index)	1.8	-		
Metals:				
Calcium (Ca++)	595	mg/L	Not established.	[4] [15]
Iron (Fe+++)	0.9	mg/L	Not established.	[8]
Magnesium (Mg++)	822	mg/L		[15]
Manganese (Mn++)	<0.1	mg/L	<0.4 mg/L	[9]
Potassium (K+)	9	mg/L		
Sodium (Na+)	467	mg/L	Not established.	[10]
Arsenic	Not tested	mg/L	<0.01 mg/L	
Barium	Not tested	mg/L	<0.7 mg/L	
Boron	Not tested	mg/L	<0.5 mg/L	
Chromium	Not tested	mg/L	<0.05 mg/L	
Molybdenum	Not tested	mg/L	<0.07 mg/L	
Selenium	Not tested	mg/L	<0.01 mg/L	
Uranium	Not tested	mg/L	<0.015 mg/L	
Inorganic Nonmetallic constituents:				
Carbon dioxide (CO2)	112.4	mg/L		
Bicarbonate (HCO3-)	1434	mg/L		
Carbonate (CO3--)	1.4	mg/L		
Chlorine (Cl)	<0.05	mg/L	<5 mg/L	[1,3]

Nitrate + Nitrite (NO3-, NO2-)	34	mg/L	<50 mg/L (NO3-), <0.2 mg/L (NO2-)	
Total Reactive Phosphorous (P)	0.8	mg/L	Not established.	[16]
Chloride (Cl-)	2813	mg/L	Not established.	[2]
Fluoride (F-)	1.1	mg/L	<1.5 mg/L	
Silica (SiO2)	106	mg/L	Not established.	[17]
Sulfate (SO4-)	1573	mg/L	Not established	[11]
Others				
Hydrogen sulfide	Not tested	mg/L	Not established	[7]

Note [1]: For effective disinfection, residual Chlorine concentration should be >=0.5 mg/L after 30 min contact time at pH<8.0.
Note [2]: Taste threshold about 200-300 mg/L.
Note [3]: Taste threshold 0.3-5 mg/L. Typical values for safe chlorination are at or above taste threshold but taste is not a reliable indicator of chlorine levels.
Note [4]: Taste threshold for calcium is 100-300 mg/L.
Note [5]: GDWQ p. 215 "in some instances, consumers tolerate ware hardness in excess of 500 mg/L"
Note [6]" GDWQ p. 215 "a hardness above ~ 200 mg/L may cause scale deposition in the treatment works...pipework and tanks..."
Note [7]: GDWG p. 216 Taste and odor threshold of 0.05-0.1 mg/L (rotton egg smell due to oxygen depletion and bacterial activity).
Note [8]: Ferrous iron > 0.3 mg/L stains laundry and plumbing fixtures. Taste threshold ~0.3 mg/L. Promotes "iron bacteria" growth.
Note [9]: Manganese > 0.1 mg/L causes undesirable tastes and stains sanitary ware and laundry.
Note [10]: Taste threshold ~ 200 mg/L.
Note [11]: Taste threshold 250-1000 mg/L. High levels (>500 mg/L) may cause laxitive effect in unaccustomed consumers.
Note [12]: TDS < 600 mg/L considered good; water increasingly unpalatable at TDS > 1000 mg/L. High levels produce excessive scaling in pipes, heaters, boilers, and appliances.
Note [13]: pH of 6.5-8 desirable. GDWQ p. 217.
Note [14]: Turbidity < 5 NTU usually acceptable to consumers; turbidity can protect microorganisms; <0.1 NTU desirable for effective disinfection.
Note [15]: High levels of calcium and magnesium can be good by providing a significant source of these important metals in the diet.
Note [16]: Total phosphorus recommended not to exceed 0.1 mg/L in streams. High phosphorus can produce degradation in rivers, lakes, and streams.
Note [17]: High silica can cause scaling in pipes and can interfere with iron and manganese removal. Can often be removed by settling.

Appendix B: Water Report 2

		Our ref.:	*080401NWG T606*
Test type:	*Standard Chemical Water Analysis*		
Submitted by:	*Benson Mutua*	Date received:	*3/17/2008*
Source:	*Makueni Project Education project Shallow well*	Date taken:	*3/15/2008*

Physical and Aggregate Properties:	***Results***	***Units***
Temperature		°C
Colour (true)	*7*	Colour units/l
pH	*7.2*	
Turbidity	*9*	NTU
Conductivity	*944*	mS/m
Acidity (pH=8.3)	*55*	mg $CaCO_3$/l
Acidity (pH=10.8)	*464*	mg CaCO3/l
Alkalinity (phenolpthhalein)	*0*	mg $CaCO_3$/l
Alkalinity total (pH=4.5)	*353*	mg $CaCO_3$/l
Hardness total	*7105*	mg $CaCO_3$/l
Total solids (residue dried at 110C)	*8290*	mg/l
Total dissolved solids (residue dried at 180C)	*7384*	mg/l
Settleable solids	*Less than 0.05*	ml/l
SAR (Sodium Absorption Ratio)	*0.9*	-
RSC (Residual Sodium Carbonate)	*0.0*	meq/l
SI (Saturation index)	*1.5*	
Metals:		
Calcium (Ca^{++})	*1627*	mg/l
Iron (Fe^{+++})	*0.2*	mg/l
Magnesium (Mg^{++})	*738*	mg/l
Manganese (Mn^{++})	*Less than 0.1*	mg/l
Sodium (Na^{+})	*354*	mg/l
Inorganic Nonmetallic constituents:		
Carbon dioxide (CO_2)	*48.9*	mg/l
Bicarbonate (HCO_3^-)	*431*	mg/l
Carbonate (CO_3^{--})	*0.3*	mg/l
Chlorine (Cl)	*Less than 0.05*	mg/l

Nitrate + Nitrite (NO_3^- -N)	*2.4*	mg/l
Total Reactive Phosphorous (P)	*Less than 0.1*	mg/l
Chloride (Cl^-)	*2487*	mg/l
Fluoride (F^-)	*1.50*	mg/l
Silica (SiO_2)	*89*	mg/l
Sulfate ($SO_4^{=}$)	*3472*	mg/l

Conclusions:

The water is slightly turbid, however with no colour.
The water is very hard (this may lead to high soap consumption when washing), with high alkalinity.
The Sodium content is above the Guidelive Value of 200mg/l and this may give the water an unpleasant taste.
The Chloride and Sulfate contents are above the Guideline Value of 250mg/l respectively and this may also give the water an unpleasant taste.
Generally the water has high mineral content and this makes it less suitable for irrigation.
Based on the measured parameters the water can be used for other domestic purposes.

General Remarks:

The conclusions and recommendations follows World Health Organization (WHO) guidelines (1994). The conclusions are based only of the parameters measured.
Shallow wells, springs, surface water: *The chemical components of the water is likely to change during a season.*
Deep wells: *The chemical components of the water is likely to change in the first period after drilling the borehole, it is therefore recommended to retest the water after e.g. 6 months.*
Test Methods: *the test methods follows the "Standard Methods for the examination of Water and Wastewater" published by American Public Health Association and American Water Works Association.*
Further information *on the individual test is available in the folder "Interpretation of Water Test Results" from CDN Water Quality.*

3-Apr-08

CDN Water Quality Laboratory Date

Appendix C: Sizing the Pump

After reviewing the market for Lorentz submersible pumps, the team identified two key parameters for choosing the correct pump: total head and flow rate. To find the desired flow rate, the team assumed that in the optimal scenario the submersible pump would provide the entirety of the school's water needs. With the planned installation of drip irrigation, Benson expected the water demand to drop to 75,000 L every two weeks. This corresponds to 5,357 L per day. Since the pump is solar powered, it can only run when there is enough sunlight to power it. Assuming a 7 hour solar day, the pump would be required to provide 765 L of water per hour, or 0.2125 L/s. The team therefore decided to find a pump capable of delivering at least 750 L of water per hour.

The total head refers to the distance between the top of the pump and the inlet to the tank and is a proxy for the force which the pump must overcome. Total head serves as a single proxy measurement for the force due to the weight of the water above the pump and the force due to losses in the piping from friction and sudden changes in the flow of water due to bends, elbows, valves, or other impediments. This can be represented as

$$h_{total} = h_{grav} + h_{loss}$$

In the above equation, h_{total} represents the total head, h_{grav} is the gravitational head and h_{loss} is the head loss, or contribution to total head resulting from friction. In conversations with Benson, the team learned that the current pump was installed at 50 m but previously had resided at 70 m. From there, it was another 9 meters to the where the inlet of the tank would be. Thus, the pump must overcome 79 meters of gravitational head. To calculate the head loss, the material of the pipe and its diameter must be known. Based on the material, a roughness factor, ε, can be retrieved from a table, such as that in Figure 13. This roughness factor is then divided by the diameter of the pipe, D, to get the relative roughness, r

$$r = \frac{\varepsilon}{D}$$

Using a Moody chart, such as the one shown in Figure 13 below, this roughness factor and the Reynolds number, Re, for the water in the pipe can be used to find the experimentally determined friction factor, f.

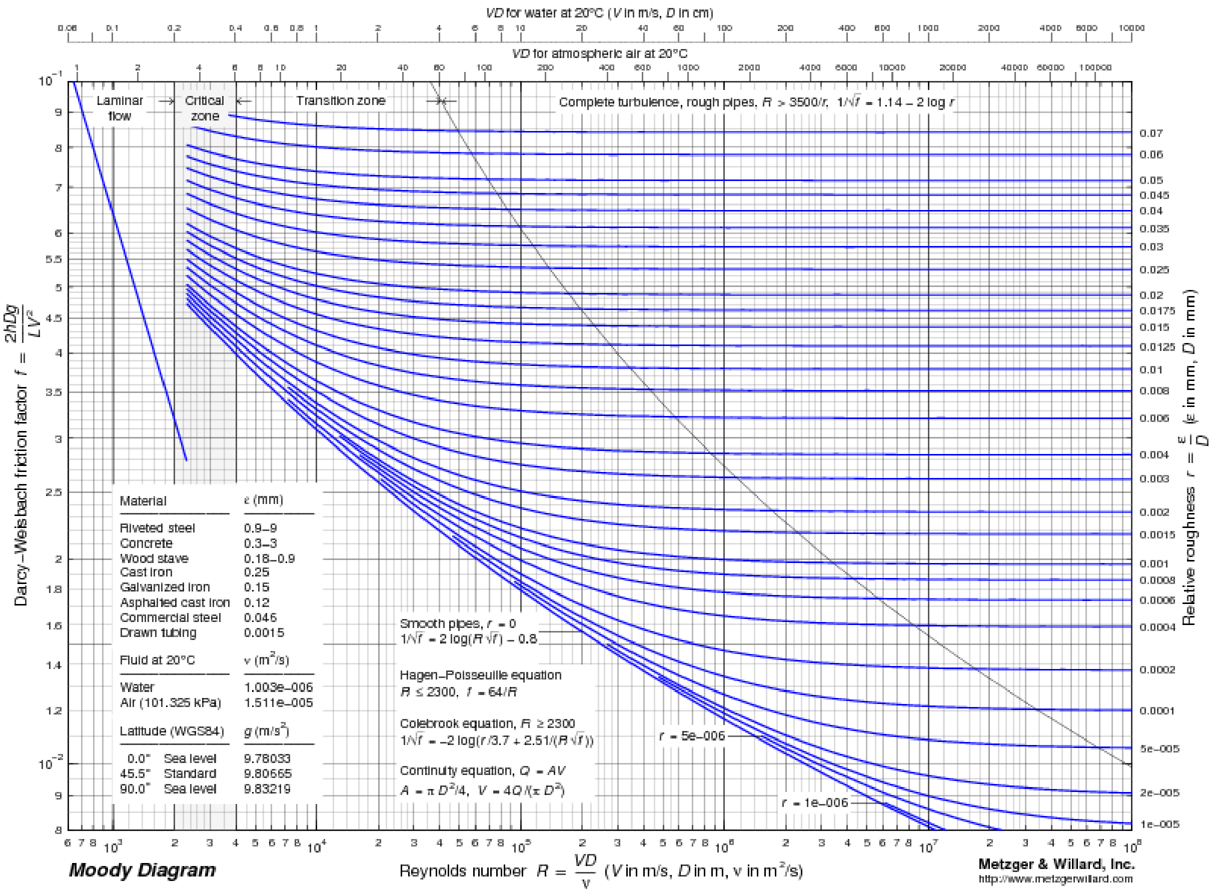

Fig. 13. The Moody Chart used for finding friction factors (left axis) based on experimental fits from the Reynolds number (bottom axis) and the relative roughness (right axis).

The Reynolds number is a dimensionless quantity which, as indicated in the Moody Chart, describes the nature of the flow as either laminar (Re<2300), transitional (2300<Re<10^5), or turbulent (Re>10^5). Note that the boundaries given in the parentheses are valid only for water in a round pipe. To find the Reynolds number requires knowing the density of the fluid, ρ, the average velocity, V_{avg}, the diameter of the pipe, D, and the kinematic visocity of the fluid, μ. The Reynolds number is then given by

$$Re = \frac{\rho V_{avg} D}{\mu}$$

The average velocity of the pipe is simply the volumetric flow rate, Q, divided by the cross sectional area of the pipe. Given a round pipe, this equates to

$$V_{avg} = \frac{Q}{\frac{\pi D^2}{4}}$$

Once Reynolds number is found, the Moody Chart can be used to find the friction factor. The friction factor is then used to find the head loss due to friction by the formula

$$h_{loss} = \frac{fLV^2}{2Dg}$$

Here, L is the total length of the pipe and g is the gravitational constant. For this project, the length of pipe was 70 m below ground and 75 meters above ground for a total length of 145 m.

For the project in Ngomano, two possible scenarios were given to the team. The 1.5" diameter galvanized iron pipe which currently supported the pump could be reused or new 1" plastic pipe (either PVC or polyethylene) could be purchased. The team therefore worked through the calculations for both scenarios to ensure that the pump was capable of delivering the necessary flow rate at both heads. Using the formulae given previously, the results given in Table 1 below were obtained.

Property	*Steel Pipe*	*PVC Pipe*
Diameter	0.0381 m	0.0254 m
Roughness Factor	0.00015 m	0.0000015 m
Relative Roughness	0.0039	0.000059
Average Velocity	0.19 m/s	0.42 m/s
Reynolds' Number	7225	10,647
Friction Factor	0.030	0.019
Head Loss	0.21 m	0.97 m
Total Head	79.21 m	79.97 m

Table 1. Properties of the flow in each type of pipe as calculated by the team.

From this the team concluded that friction was relatively insignificant with either pipe choice and the total head would be approximately 80 m in either case. Based on a conversation with Kevin Holme from RCC Solar, the team decided to purchase a pump capable of delivering a larger head than 80 m at a comparable flow rate. Mr. Holme warned the team that pumps often do not live up to their rated specifications and to ensure continuous successful operation in a remote area, including a factor of safety of about two would be appropriate. Mr. Holme's judgment is based on more than two decades of experience with solar pumps. With this knowledge, the team selected the Lorentz PS-1200 HR-04H pump and controller, which is capable of delivering 800 L/hour at 80 m of head and can handle up to 140 m of head with a decrease in output of 25%.

Appendix D: Solar Power System Design Alternatives

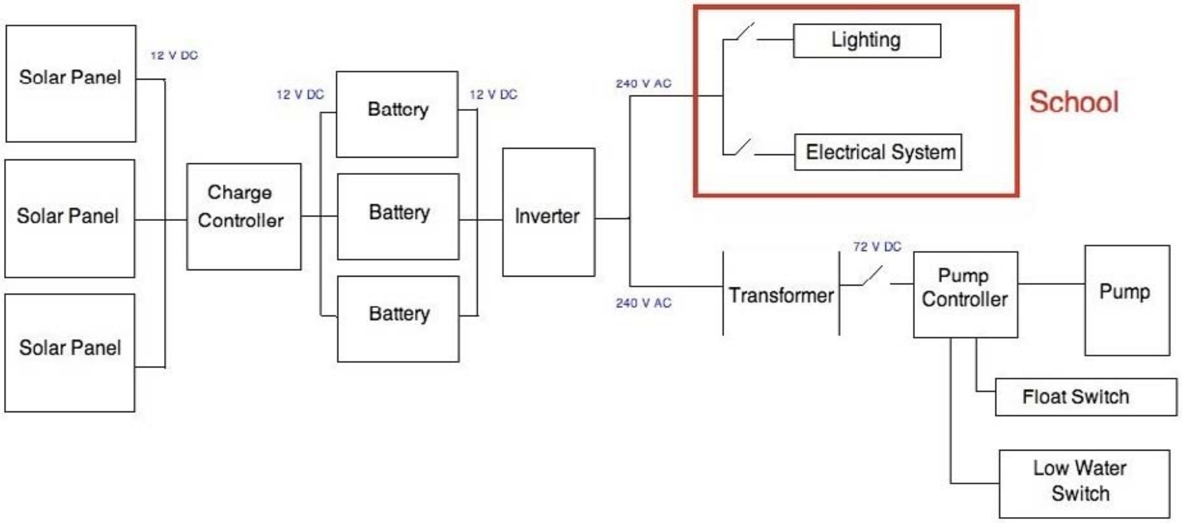

Fig. 14. In this alternative, the solar panels and batteries are wired in parallel at 12 V DC. Inverters and transformers convert this 12 V DC to the necessary voltages for the lighting and pump controller. In this design alternative, the pump runs off battery power.

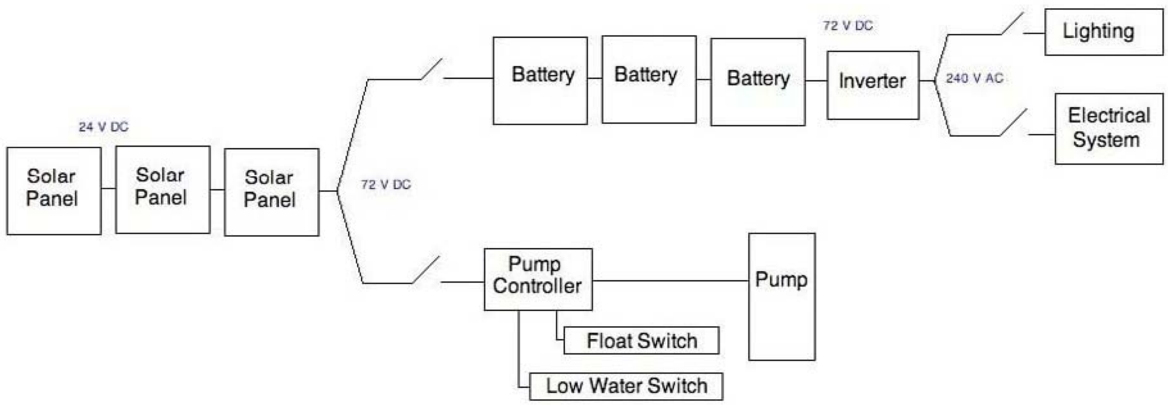

Fig. 15. In this alternative, solar panels and batteries are wired at 72 V DC for the pump controller. An inverter converts this to 240 V AC for the lighting system.

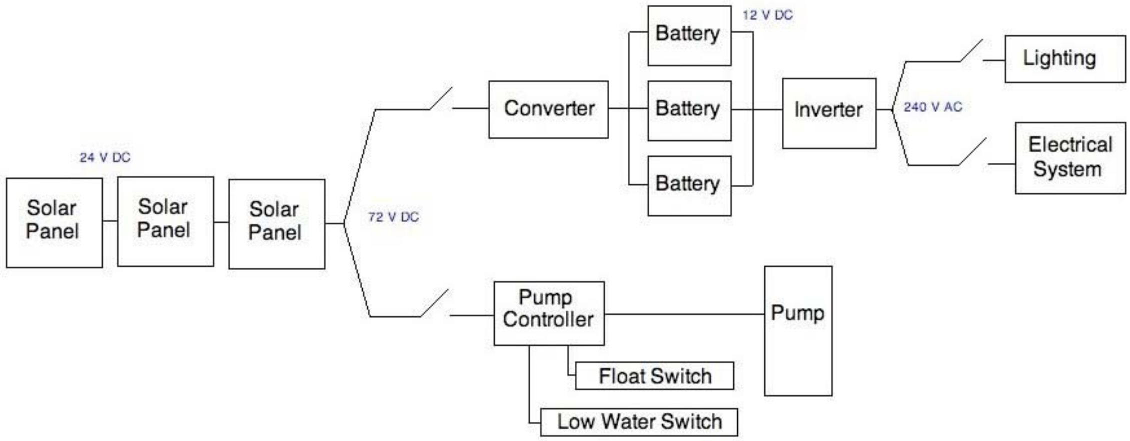

Fig. 16. In this alternative, solar panels are wired at 72 V DC for the pump controller, but this is converted to 12 V DC for storage in the batteries before the lighting system.

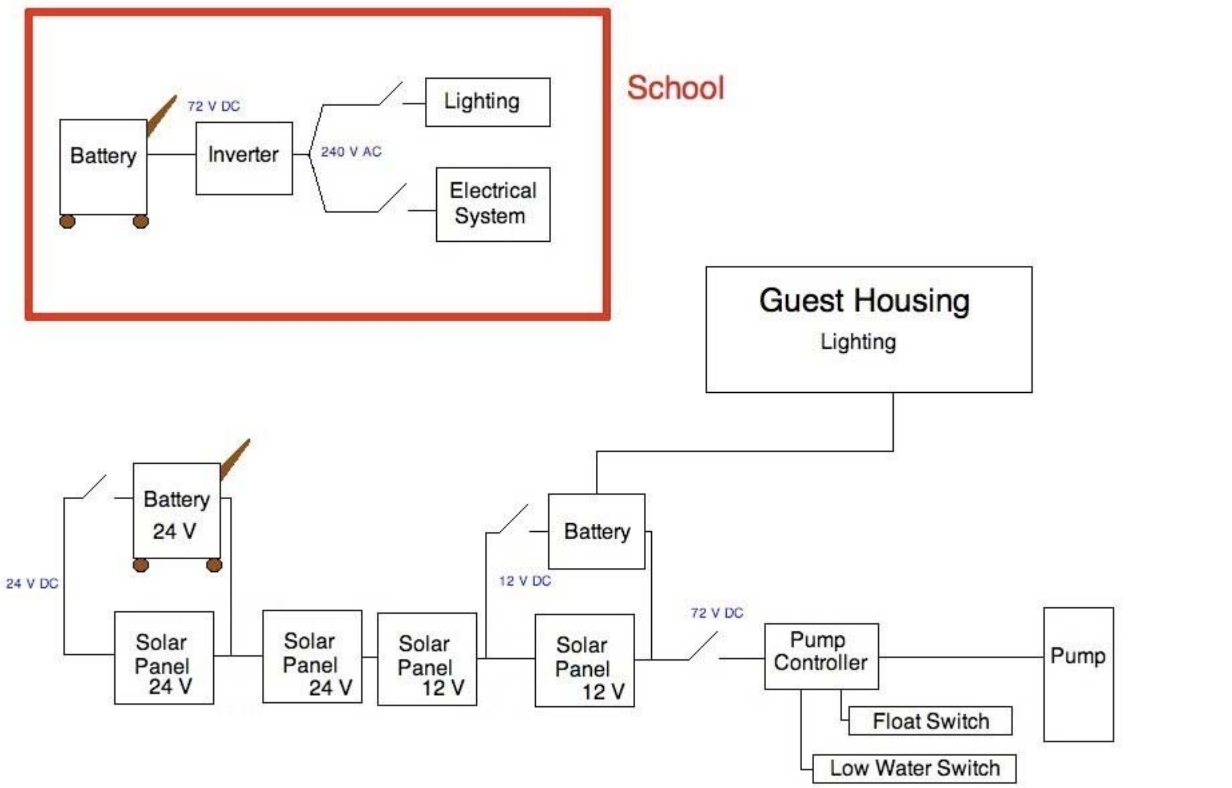

Fig. 17. In this design alternative, the solar panels are wired in series at 72 V DC for the pump controller, but individual solar panels are also connected to batteries to power the lighting system. Some of these batteries could be kept on wheeled carts to be carted up to the school buildings to power the lighting.

Appendix E - Preliminary "hook" designs to remove the pipe from the well

The first design that the team had fabricated by the blacksmiths in Wote was a harpoon-like hook, shown in Figure 18. It was constructed of two hinged metal arms that could easily slide down the pipe, but that would spread when pulled back up. The idea was that as the hinged arms opened on the ascent, the sharpened edges at the top would get caught in the gap between pipe segments on the inside of the coupling. The pipe could then be hauled up with the hook.

Fig. 18. Harpoon hook design

In order to insert this harpoon into the upper end of the pipe, which was resting against the side of the borehole 50 m below the earth's surface, the team designed a funnel-like structure to guide the harpoon. This funnel, shown in Figure 19, was constructed from a 20-liter water bottle, a plastic sheet, wire mesh, and plastic cable ties. The harpoon was designed to be lowered down the borehole inside the neck at the top of the funnel. The rest of the funnel would guide the neck to rest at the top of the pipe, allowing the harpoon to slip down inside.

Fig. 19. Funnel structure to guide the harpoon inside the pipe.

This design failed because it was not practically feasible to lower the funnel and harpoon at the same rate. The harpoon, attached to heavy chain, fell much more readily than the funnel, which was lowered by rope. As a result, it is unlikely the harpoon ever made it inside the pipe. More troubling, the material for the funnel proved not to be sturdy enough to handle the lowering process and broke apart within the borehole.