

Solar Water Pumping in the Ewavio Village, Uganda

Nadya Alexander
Nick Depsky
Jessica Schweiger

TTP 289 Winter 2013
UC Davis D-Lab

Table of Contents

Table of Contents	ii
List of Figures	iii
List of Tables	iv
Executive Summary	1
Introduction	2
Problem Statement	2
Background of Ewavio	3
Methodology and Results	6
Scenario 1: Pump Sizing	7
Scenario 2: Maximum Potential Crop Water Use (ETc)	11
Step 1: ETo	12
Step 2: Local Crop Parameters.....	12
Discussion of Results	14
Economic Feasibility	15
Methodology	15
Cost to the Community	15
Per Household Payment.....	18
Results	18
Cost to the Community	18
Per Household Payment.....	19
Social Sustainability and Community Feasibility Analysis	20
Methodology	20
Social Benefit.....	21
Results	21
Stakeholders.....	21
Community Management Options	22
Training	22
Social Benefits	22
Discussion	23
Conclusion and Next Steps	24
Appendix A: Citations	26
Appendix B: Arua MFIs	28
Appendix C: Water Management	29

List of Figures

Figure 1. Approximate location of Ewavio (Google Maps).	4
Figure 2. 100W ShurFlo Pump System.	8
Figure 3. Pump test results.	8
Figure 4. Pumping efficiencies increase with higher TDH.	9

List of Tables

Table 1. Ewavio Cropping Patterns.....	12
Table 2. Crop Multipliers (Kc).....	13
Table 3. Household Water Needs for Full Agricultural Activity.....	14
Table 4. PV Pumping System Costs.....	19
Table 5. Pumping System Costs per Household.....	20
Table 6. Value of Women's Time and Labor Saved.....	23

Executive Summary

The project outlined in this paper is to provide a pumping solution for the village of Ewavio, Uganda (pop. 200). Ewavio has a need to develop technologies that will increase the amount of water available to villagers (for farming and household use) and decrease the amount of time spent pumping the water during the dry season. Currently the only source of water available year-round is a 14-meter deep borehole with a manual pump. This project designed a solar pump to replace the current manual pump and analyzed the economic and social feasibility of such an installation. The design was limited by the current flow rate out of the borehole: during the dry season, the borehole runs dry every day and must be locked in the middle of the day for three hours to recharge. Therefore, without identifying another source for water, it was not possible to increase the amount of water available to the village. Within the constraint, a labor-saving pumping option was designed. The specified pump has a flow rate of 20 litres per minute (lpm) and requires a 300W solar array. Due to the high capital and installation costs, this pumping system has a significantly negative Net Present Value (NPV = -\$2,900 US over a 15-year lifespan). However, there are many potential social benefits such as decreasing child labor (perhaps increasing time available for school or other activities), decreasing the amount of time fetching water from other sources and potential dangers associated with doing so, and other hard-to-quantify positive social externalities that may offset the economic cost of the project. It is therefore recommended that further research be done to identify these social benefits, as well as assess the feasibility of other alternatives for water resource development. This paper provides one tool for such research – an estimate of the potential crop water needs for the desired agricultural activities. If agricultural activities were maximized, without the current borehole flow rate constraints, a pump of up to 300 lpm could be utilized by the village. It is recommended that before further design work is done on this project, a comprehensive water, village, market, and cropping survey be performed to identify and map the community needs and assets.

Introduction

This project examines the feasibility of a solar pump installation in the village of Ewavio, Uganda. Ewavio is a small rural village with a population of approximately 200 people, or 25 families. The families current gather water from a variety of sources, including shallow- and deep-wells that are manually pumped, surface rivers and springs, and a few houses have rain water catchment and storage tanks. The proposal submitted to D-Lab at UC Davis was for a solar pumping system that would help the village address their water needs. The villagers would like to increase the volume of water available to them during the dry season, so that they may expand their agricultural activities. Dry season farming of leafy green vegetables would provide nutrition to agricultural households and income through the local market. The market is well-established and accessible, but the water scarcity makes dry season agricultural activities difficult. In addition, the current year-round water supply, the deep-well, is manually pumped from a depth of 14 meters, and the villagers would like an automated pumping option to save hours of labor. The village has a small, portable solar pump brought by Gloria Androa from UC Davis and they would like to expand the local use of that technology.

Problem Statement

Is it possible to use solar pumping technology in order to decrease the amount of time women and children in the Ewavio village spend manually pumping water?

Both the lack of perennially reliable water sources, as well as the high amount of labor currently required to retrieve water for daily household domestic and agricultural use within Ewavio are the two main water-related issues in the community. As it stands, only one borehole (14m) in the community and one distant spring (~3 km) yield water all year long, and even the borehole runs dry in the dry season, requiring some few hours of non-pumping to recharge. However, with increasing climate variability and longer droughts, these supply problems will likely only become more exacerbated, as rains will become irregular and extreme in nature, making these sources highly susceptible to running dry for extended periods of time.

A solar pumping option, however, will likely not solve this issue of supply scarcity and unreliability. Unless the existing hand-pumps do not pump from the full depth of the aquifer and therefore do not exploit the full potential of the well (something which a solar pumping system would be capable of), there is no scenario in which installing a solar pump will increase the amount of water available to the village. It may even worsen the problem if it is over-used, and hastens over-draft of the aquifers from which it pumps. The only way to obtain more water would be to drill another deeper borehole, which is prohibitively costly, to implement large-scale rainwater harvesting, or to enact conservation and water-use efficiency practices.

The problem that a solar pump would most definitely address is the large amount of labor spent hand-pumping water for domestic and agricultural use every day village-wide. Our local partner estimated that it takes roughly 3 minutes for an individual to pump enough water from the borehole to fill a 20L jerrycan, and that each person requires roughly 30 L /day for domestic use only. This equates to roughly 15 man-hours exerted every day by the village just to pump enough water for baseline domestic water use, which is still below the WHO guidelines of 40-50L / person /day. This doesn't account for additional pumping labor required for livestock or agricultural water uses. A solar pump would offset a large majority of this labor, if properly installed on the main borehole. The community also lacks proper storage tanks, with only a few installed to collect rainwater from the metal roofs of a handful of houses belonging to the richest members. Therefore, community members must transport water in small 5 – 20L jerrycans and various containers to their homes and agricultural plots. However, a household-scale solar pumping system is not feasible for every household in the community, and distribution is thought to be too costly as well. Therefore, a central solar pumping system with a storage tank (the tank would provide a few day supply to allow flexibility during droughts), which offsets the amount of labor required for manual pumping, is the only possibly feasible option, and is what we consider in this paper.

Background of Ewavio

Ewavio is a small rural village outside the large Arua municipality in northwest Uganda (**Error! Reference source not found.**), and is home to roughly 200 people, or approximately 25-30 families (local partner: Gloria Androa). It receives 1200-1400mm rainfall each year, with a lengthy dry season from November – March, and a rainy season from April – October, making it a *Tropical Savannah Climate* (BakamaNume 2011). Average temperatures range from 70 – 76 F, although a 2-4 F increase in mean annual temperature is projected by 2100 (NAPA 2007). Like the majority of the country's population (~67%), Ewavio's residents practice subsistence agricultural in order to make a living (NEMA 2010). Uganda is home to some of the region's most fertile soils, and it has been estimated that ~75% of its land surface is arable land, and that if sustainable agricultural practices were to be implemented and adopted, the nation could become a major regional exporter of agricultural products to surrounding nations. However, poor farming practices and severe land and soil degradation is compromising the vitality of the farming sector (Olsen and Berry 2003).



Figure 1. Approximate location of Ewavio (Google Maps).

Currently, only about 5% of the Ugandan population has access to electricity, with those that do subject to erratic load shedding and blackouts, making off-grid solutions an appealing option (Osende, Abraham, & Mowry 2011). Solar technology is undergoing very quick development, narrowing the gap of accessibility for low-income consumers (Hankins 2000).

Given that most of the population relies upon subsistence rain-fed agriculture, increasingly unreliable and variable climate patterns due to shifting global climate change makes Uganda extremely vulnerable. As rains may increase overall in the coming years (est. 7-15mm annually), this will be in fewer, but much larger storm events separated by extended periods of drought, as has been the case in the last decade (NEMA 2010). The unreliability of rain, and its ferocity when it does arrive, will wreak havoc on the small-scale farming population, as crop yields will die due to drought, or be washed away along with fertile topsoil in extreme flooding during storms. This unreliability warrants various adaptive solutions in order to mitigate the effects of the inevitably shifting climate. Some of these include diversifying crops to include drought-tolerant varieties, expansion of non-farm sector production of goods/services, or increasing pastoralism, which is more resilient to local variability in climate than sedentary agriculture (NEMA 2010). However, reliable water sources able to provide flexibility during the dry season is crucial to any of these activities.

Our local partner is hoping to implement solar-powered water pumps in order to bolster the reliability of local water sources, as well as to decrease the amount of time and labor required to manually pump water from the multiple existing wells (~7-10m depth) and one deeper borehole (14m depth). However, only the deep borehole is able to provide water throughout the dry season, and even that is prone to running dry, requiring 4-6 hours to recharge. Pumping of this borehole is managed by the community water user committee (5 members), which allows for pumping from 7am – 1pm, and then again from 4pm – 7pm. There is a creek nearby, which is also subject to seasonal variability, and is also prone to harmful pollution from surface runoff from nearby communities lacking proper sewage and sanitation facilities. There exists one spring, which also yields water all year-round, but is roughly a two-mile walk from Ewavio.

The average household in Ewavio has a roughly ¼ acre plot for small-scale agriculture, none of which are irrigated. The main crops in the dry season are maize, beans, and ground-nuts (peanuts), and in the rainy season are lettuce, carrots, and cabbage. However, the largest growth in the agricultural sector is in the production of export/cash-crops, which have been receiving a majority of government subsidies, and also happen to be more resilient to climate variability compared to staple crops (NEMA 2010). These plots are sustained by rainfall and hand watering from small containers with water pumped from wells. Water storage tanks and roof-top rainwater harvest systems exist only at a few of the richer households in the village, meaning that the rest of the village must practice daily retrieval of water from the town's various sources for domestic, livestock, and agricultural uses. This requires much labor, due to fact that most families only have a few small (5 - 20L) jerrycans for transporting water.

It is estimated that the village uses roughly 30L water / person / day for solely domestic use. Additional daily demand for livestock was thought to be somewhere around 10L / household / day, and agricultural demands remain largely un-quantified. Women and children bear the brunt of this labor demand, doing a vast majority of pumping and transportation of water. One household spends between 30 – 45 minutes pumping water each day from one of the wells, entailing roughly 15 man-hours of pumping each day village-wide, which would be largely reduced were a solar pump to be installed on the principal pumping well.

Given the high seasonal vulnerability of the existing water sources in the village, it is questionable whether or not installing a solar pump would improve the quantity or reliability of water supply. If installed, it would likely pump from the deep borehole, but if not managed well, it may end up over-drafting the well, and decrease the rate of recharge from the surrounding aquifer. Drilling another deep borehole is not being considered due to its high cost (~\$5000 USD). If the pump were able to guarantee a higher volume of deliverable water, it would vastly improve the livelihood of the village, as well as allow them to extend their growing seasons for valuable market crops, such as leafy greens normally limited to rainy season growth. However, given the susceptibility of current sources to going dry, it is doubtful that a solar pumping option would provide additional water year-round, but merely reduce the amount of labor required to pump existing sources. However, given the lack of hydrologic data regarding the groundwater conditions in the existing boreholes, as well as the depth of pumping with current hand pumps, it is possible that a solar pump may be able to pump at a deeper level, and potentially access more water volume. Although if existing pumps already extend to the bottom of the boreholes for pumping, and the sources run dry during the dry season, a solar pump would not solve the issue of supply. A large central storage scheme, with tank(s) to store solar-pumped water may be a viable option in order to provide some resilience during dry conditions, although piping / distribution from such a tank to individual households is thought to be to expensive. Pumping into a central storage tank may be one major benefit of having a solar pump, which could pump to higher elevations that hand pump, were the tank to be elevated.

Maintenance and safety of a solar pumping system is also a major issue, with a high concern for vandalism or theft of the valuable solar panels and components. Therefore, a system would have to be installed in a protected manner, likely on an elevated platform. Local pump mechanics are available to conduct repairs on the non-solar technology portions of the system, but expertise

required to fix any solar panel-related problems is not local available. This lack of local human resources has already derailed one local project in the village, in which a solar cooling room for agricultural goods was designed and built, but when the inverter malfunctioned, not available repairmen or replacement parts were available, and the solar panels are now used for various unrelated energy needs (phone charging, household lighting etc.). However, given the simplicity of our ideal solar pumping system (no charge controller or inverter needed, the pump can run dry, no moving parts etc.), we expect maintenance and repairs to be minimal, if the system were to be installed. Training of local community members how to deal with any such maintenance issues would be a crucial process to enable system longevity and would have to be thoroughly planned and implemented. Decentralizing the base of knowledge and expertise regarding solar technology is vital to enabling the dissemination of such technology to the rural and remote sectors of developing countries (Murphy 2001).

Methodology and Results

There are two central needs addressed by this project: one is the implementation of technology to save labor currently used for pumping, and the other is to increase the amount of water available to the village of Ewavio. The specific dimensions of these problems are outlined below:

- Collection of water requires too much labor
 - The water must be pumped manually using a hand pump or treadle pump
 - There is a large distance from the village to some of the utilized water sources
 - The water collection cans are too small, requiring multiple trips to carry the water home
 - There is no piping; all water must be carried by hand
- There is not enough water to grow desired greens during the dry season
 - During the dry season all the wells and surface water sources run dry with the exception of the single deep 14-m borehole.
 - The deep borehole pumps approximately 2 lpm and, in the dry season, runs dry after approximately 6 hours of pumping. The borehole is then recharged for 3 hours.

There are a multitude of solutions that could be examined to address these two problems.

Potential avenues include:

- Purchasing larger water collection cans to minimize trips to the well
- Installing a pipeline system to transport the water from a well or surface source to a central location
- Building water storage tanks that utilize rainwater catchment
- Improving composting and soil water storage to allow for more planting during the dry season
- Installing an electric or diesel pump to replace the manual pump

At the request of the client, this study focused on evaluating the costs and benefits of installing a solar powered well pump on the existing 14-m deep year-round borehole. The justification for this focus was:

- Electric power is available via power lines in the village, but the electricity is unreliable (approximately 4 days / week of power, frequent blackouts) (Androa, February 28 2013).
- Only a few houses in the village have metal roofs and water tanks
- The primary goal of our project partner was to reduce the labor currently used for pumping by installing a solar pump

Such an installation would benefit the village by reducing the amount of labor currently used to manually pump the water by hand. However, this project would not address the issue of water scarcity. Although there is a desire in the village to have more water available for agriculture during the dry season, with the current pumping rates and volumes, the borehole runs dry and must be recharged on a daily basis. Therefore, even though a larger pump would have the capacity to pump water at a higher rate, the water supply is limited by the capacity of the existing well. It is therefore not possible to increase the amount of water available during the dry season without digging a new deep well. The cost of a new well is approximately US\$5,000, and this is not considered economically feasible for the village at this time (Androa, January 27 2013). Therefore, the scenario evaluated for this study limited the flow rate from the new pump to the 2 lpm currently pumped from the well (Scenario 1: Pump Sizing).

Although a second well is considered cost-prohibitive at this stage, the potential water use for such a system was also roughly estimated. The purpose of this exercise was to give a rough estimate of the size of an optimal pumping system that would provide the village with sufficient water for all households to engage in dry-season agriculture. This scenario is discussed below in Scenario 2: Maximum Potential Crop Water Use.

Scenario 1: Pump Sizing

Due to the generosity of our local Davis partner Michael Reid, we were able to conduct a pumping test with a small solar pump system he had built and been using in his backyard garden. The small pump was a ShurFlo Aqua-King Model 4008, which is a small 12V DC marine pump, rated at a flow rate of 11.4 L / min , which costs ~100 USD, and is very small and portable (Figure 2). The pump is able to run dry, and does not require a charge controller, reducing the complexity and vulnerability to failure of the system. The set-up had a small intake filter, which would be essential in removing sand / grit from the water source in order to prevent cavitation and destruction of the plastic pump components (M. Reid). Mounted on a simple wooden frame, the pump and filter attached to a 100W solar panel laid across the frame at a 20-30 degree angle towards the sun (Figure 2).

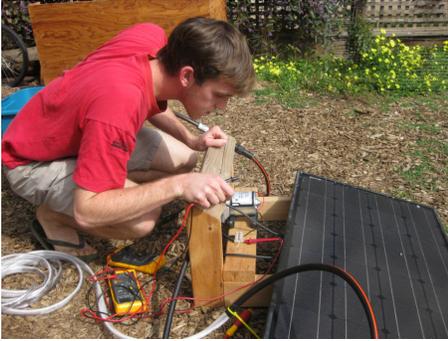


Figure 2. 100W ShurFlo Pump System.

Using this system, we conducted a simple pumping testing around 3pm in the afternoon, increasing the total vertical lift of the system at 5 foot (~1.5m) intervals, and measuring the flow rate (gal / min) at each height. This was to study the changing performance of the pump (flow rate, efficiency, power requirement etc.) with increasing pumping height. Our experiment produced the following results:

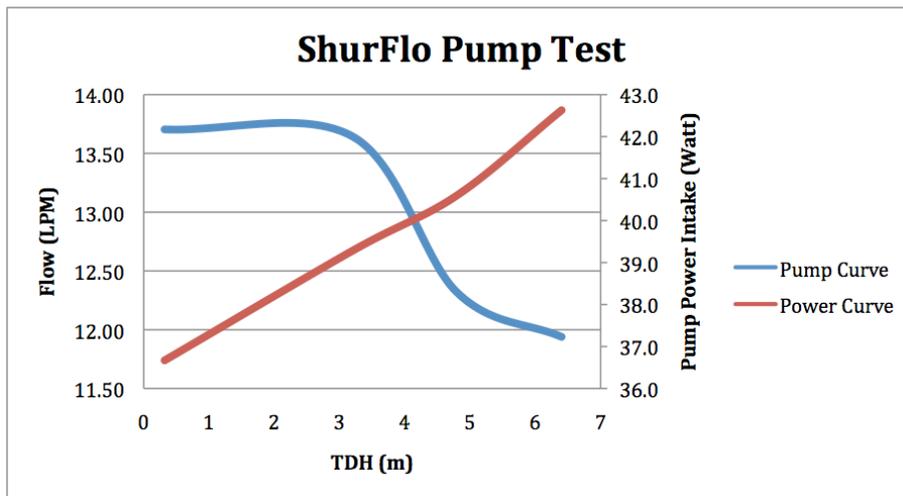


Figure 3. Pump test results.

TDH represents the total dynamic head in meters, which is equal to the height of pumping in meters (total vertical lift) multiplied by a factor of 1.05, which approximately accounts for frictional losses of energy throughout the system.

The “Power Curve” represents the power being drawn from the solar panel by the pump as monitored with volt and current meters:

$$\text{Power (Watts)} = \text{Current (Amps)} * \text{Voltage (Volts)}$$

As we can see from Figure 1, there is an inverse relationship between the power requirement of the pump (red), and the flow rate of the pump (blue). As the height of pumping increases, the flow-rate both decreases, and the power intake increases. This implies that as the TDH goes up, more power is required by the pump to sustain a constant flow rate, and given that the panel (100W) is oversized for the pump’s power requirements, the excess power is available, and the pump draws additional power. However, even while drawing more power as TDH increases, it is not enough to prevent the decline in flow rate as seen with the blue pumping rate curve.

Despite not being able to sustain a perfectly stable flow rate even with available excess power, the pump performed better than expected, exhibiting flow rates above the rated 11.4 L /min specification for all heights we tested (flow rate ranged from 11.94 – 13.7 L / min), making it a good candidate for possible use in an installed solar pumping system.

Another observed characteristic of the pump was the fact that its pumping efficiency (efficiency in converting the electrical power produced by the solar panel into hydraulic lifting power) increased as the TDH increased as seen below in Figure 4:

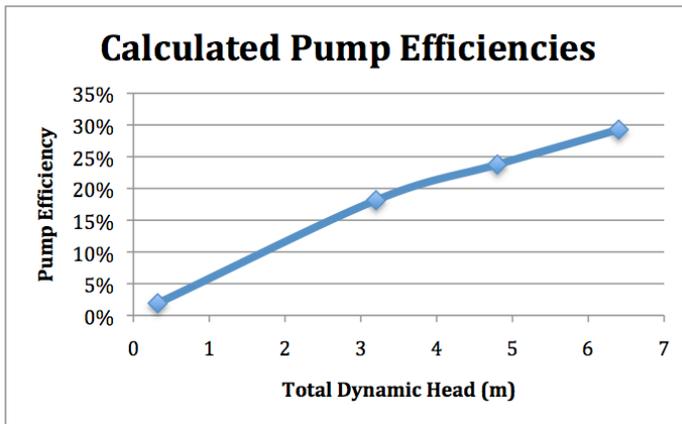


Figure 4. Pumping efficiencies increase with higher TDH.

Normally, the efficiency would be expected to level off at some value (many pumps operate at peak efficiencies of around 30%), and we can see the slope beginning to decrease at our highest TDH values, indicating that it is approaching such a value. However, given the limitations of our experimental design, we were unable to increase the TDH high enough to observe a leveling-off of efficiency. The highest observed efficiency was ~29%, which occurred at a TDH = 6.4 LPM. These efficiencies were calculated as follows:

Pump Efficiency = Horse-Power In / Horse - Power Out

Horse - Power In = (Voltage * Current) / 746
produced from panel (as monitored with multi - meters)

Horse - Power Out (Hydraulic Lifting Power) =
TDH * Flow Rate (in GALLONS / min) / 3960

The durability, simplicity, and ability to maintain higher-than-rated flows rates of this pump and overall solar pumping system make it a very good candidate for potentially being used in a system in Ewavio. However, the scale of the system must be determined first, as it is likely that a small 11.4 L / min pump and 100W array size may not suffice for Ewavio's needs. Therefore, calculations of the estimated flow rate required of the pump based on village water use, as well as the array size calculations based on these flow rates and expected TDH of the Ewavio system were carried out to size the potential system.

However, before carrying out our calculations, we had to make a number of assumptions regarding water use, the system design, pump specifications, expected solar insolation, expected solar panel and pump efficiencies as follows:

Assumptions

1. Daily Household Demand ~250 L / day (1 household = 8 people * (30 L / person / day) + 10L / day for livestock)
2. Ewavio consists of 25 households = 6250 L / day total demand
3. Ewavio receives ~5 Perfect Sun Hours (PSH – defined as 5 hours during which the solar irradiance is 1000 W/m² (corroborated by literature regarding solar irradiance in Uganda (Saundry 2009)), in other words it represents the integrated total amount of solar irradiance throughout the day as 5 PSH, which can be interpreted as the amount of time that the pump will be operating (@ peak power). (Green Empowerment)
4. The pump will be installed at the deep (14m) borehole, and must be sized to satisfy all of the village's daily water demands during the dry season
5. Total Vertical Lift (TVL) ~17m (14m borehole depth + 3m storage tank height). (Green Empowerment)
6. 5% Friction Losses Factor: Total Dynamic Head (TDH) = 1.05*TVL (Green Empowerment)
7. 20% loss in system efficiency due to dirtiness of panel, temperature fluctuations (higher temp. = lower panel eff.), panel performance degradation over time, losses in wiring , so that overall power requirement of the system should be scaled by $1 / 0.8 = 1.25$ to account for these losses (Green Empowerment).
8. Pump Efficiency = 29% (a conservative estimate , the highest efficiency we observed during our pumping test)
9. Slightly larger pumps of the same manufacturer have similar traits to the model we tested (can run dry, similar efficiencies, no charge controller needed etc.)

Results are as follows:

$$\begin{aligned}\text{Required Flow Rate (L / min)} &= \text{Daily Water Demand} / \text{minutes of pumping} \\ &= 6250 \text{ L} / 5 * 60 \text{ (5 pumping hours * 60 minutes)} \\ &= \underline{20.83 \text{ L / min}}\end{aligned}$$

This flow rate is higher than the pump we tested, and therefore we can expect our required solar array size to be larger than the 100W system tested as well. Calculating appropriate panel size can be done with the following equation:

$$\begin{aligned}\text{Panel Size (Watts)} &= \text{System Losses Factor} * [(\text{Required Flow (L / min)}) * (\text{TDH (m)}) * 0.163] \\ &\quad / (\text{Pump Efficiency}) \\ &= 1.25 * (20.83 * 17 * 0.163 / 0.29) = 261.3 \text{ Watts}\end{aligned}$$

which should be rounded up to a required panel size of :
300 Watts (Green Empowerment)

This solar panel array would be roughly three times the size of the one we tested, or three-100W panels. The surface area of the panels themselves depends upon the manufacturer and the efficiency of the photovoltaic cells in converting solar radiation into electrical output (ranges from 9-15%), with a 10% efficient 100W panel being 1.5 times the area of a 15% efficient panel array.

This sizing calculation procedure may be carried out for numerous scenarios of various water demands. The World Health Organization recommends that the daily mean water demand for *domestic-use only* is 40-50 L / person / day (Practical Action, 2012a). Using an average of 45L / person / day, these calculations yield a village-wide water demand of 9000 L / day, a required pumping rate of ~30 L / min, and a solar array required of 389.7 Watts, or ~400 Watts.

Scenario 2: Maximum Potential Crop Water Use (ETc)

This scenario was evaluated to give a general sense of the amount of water that would be needed by the village if all households were to grow crops throughout the dry season. Since there is no available data on local water use for each of these crops, the crop water use was estimated using the FAO Penman-Monteith (FAO-PM) equation for crop evapotranspiration (ETc). The FAO-PM method is a widely accepted tool used to estimate the rate of ETc relative to cropping patterns and local climate and weather conditions. There are two steps in the evapotranspiration model: first, the reference evapotranspiration (ETo) must be calculated using local weather data, and then the crop multipliers must be developed (Kc), along with crop patterns, in order to calculate ETc. The model for this project was built in Microsoft Excel using the parameters and equations published in FAO 56: Crop Evapotranspiration.

Step 1: ETo

1. Inputs to the FAO-PM Model for ETo (FAO 1998)
 - a. Local weather data from the FAO
 - i. Minimum, maximum, and mean daily temperatures
 - ii. Precipitation
 - iii. Wind speed
 - iv. Vapor pressure
 - b. Ewavio elevation above sea level
 - c. Ewavio latitude and longitude
2. Outputs from the FAO-PM Model for ETo
 - a. Daily reference ETo in mm/day

Step 2: Local Crop Parameters

The local crop plantings were determined through conversations with our in-country partner. Dry season and wet season cropping patterns are detailed below in Table 1.

Table 1. Ewavio Cropping Patterns.

Crop	Season	Plant Date	Final Harvest Date
Beans	wet	March	May
		Aug	Nov
Peanut	wet	March	May
		Aug	Nov
Maize - grain	wet	March	May
		Aug	Nov
Lettuce	dry	June	July
		Dec	Feb
Carrots	dry	June	July
		Dec	Feb
Cabbage	dry	June	July
		Dec	Feb

The general crop multipliers for each crop were obtained from FAO56, as detailed in Table 2 below. The mid-season and end-of-season Kc values are from the text, the adjusted Kc value, which was used in the model calculations, was estimated by reducing the peak Kc by 2/3, in keeping with the changes in Kc over the course of the season and the changes in crop canopy during the different growing seasons.

Table 2. Crop Multipliers (Kc).

Crop	Kc mid	Kc adj	Kc end
Lettuce	1	1.00	0.95
Beans	1.15	0.76	0.35
Peanut	1.15	0.76	0.6
Maize - grain	1.2	0.79	0.475
Carrots	1.05	1.05	0.95
Cabbage	1.05	1.05	0.95

In order to calculate the daily volume of water required for agricultural activities, the following assumptions were included in the model:

1. Each household plants their entire ¼-hectare plot
2. During the wet season the ¼-hectare is divided into thirds of beans, peanuts, and maize
3. During the dry season the ¼-hectare is divided into thirds of carrots, cabbage, and amaranth (lettuce was substituted as having comparable water use)
4. The crop canopy cover density is 50% of the numbers published for commercial agriculture
5. Crops are grown for the entire wet and dry seasons
6. Crops are under-irrigated 72.5%
 - a. This is a rough estimate that was calculated by comparing the average monthly precipitation to the average monthly crop water needs. For the wet season, when all crops are rainfed, the monthly deficits were averaged (excluding months where rainfall exceed crop water needs). The average deficit was 72.5% (applied rainfall / estimated crop water needs).
 - b. The 72.5% multiplier was applied to the monthly volume to adjust for the fact that crops will most likely be deficit irrigated due to water scarcity

The estimated crop water needs, in volume of water per household per month, is estimated in Table 3 below.

Table 3. Household Water Needs for Full Agricultural Activity.

Month	Monthly Volume (litre)	Adjusted Monthly Volume (litre)	Rainfall (mm)	Volume of Rain (litre)	Volume less Rain (litre)	Daily Volume less Rain (litre/day)
1	257,000	186,325	56	69,722	116,600	3,761
2	232,000	168,200	63	78,757	89,400	3,193
3	191,000	138,475	133	166,195	(27,700)	(894)
4	185,000	134,125	167	209,262	(75,100)	(2,503)
5	191,000	138,475	147	183,378	(44,900)	(1,448)
6	249,000	180,525	79	98,970	81,600	2,720
7	257,000	186,325	68	84,700	101,600	3,277
8	191,000	138,475	109	135,858	2,600	84
9	185,000	134,125	111	138,148	(4,000)	(133)
10	257,000	186,325	150	187,247	(900)	(29)
11	249,000	180,525	111	139,043	41,500	1,383
12	257,000	186,325	74	92,495	93,800	3,026

The numbers presented in Table 3 are rough estimates – weather data into the FAO-PM model and monthly volume of rain are country-wide averages for Uganda from 1990-2006.

Discussion of Results

Based on the assumptions and estimates in this model, the maximum agricultural water need for a household is 3,650 litres per day during the month of January. Assuming 40 households engaged in agricultural activity and 10 hours of pumping per day, this equates to a 500 lpm pump, approximately 25 times larger than the pump sized for this project. While this flow rate is not possible given the current well installation, it gives a sense of the volume and flow that would be required under optimal agricultural conditions. This estimate could be further refined by a more detailed survey of land use and crop scheduling, weather data that is more local or on a finer timestep (daily rather than monthly), and a survey of irrigation methods and deficit irrigation estimates.

Economic Feasibility

Methodology

According to our local technical partner, the decreasing cost of PV panels and the availability of off-the-shelf pumps designed for boats or RVs would allow the construction of a cost effective solar pumping system (M. Reid, personal communication, February 14, 2013). To test this theory, we assessed the feasibility of the solar pumping system by attempting to answer the following key questions:

- What is the **cost** to the community of a solar pump system that meets current domestic household water demand from a single borehole source?
- What are the **payment** or financing options available?

Cost to the Community

Assumptions

1. **Lifespan of PV system and pump = 15 years.** Most reference materials cite the durability of PV systems as a major advantage; fifteen years is within the widely-cited range of the lifespan (Mapoux, 2012; Doig, 2012).
2. **Lifespan of the pump = 8 years.** Information on the lifespan of RV and boat pumps was difficult to find. Our technical partner, Michael Reid, believed that such pumps were designed to endure the heat and vibration of boat and RV use, and thus would prove long-lived in harsh village conditions. Based on this assessment, we assume that the pump will not need to be replaced during the lifespan of this project—even though the manufacturer warranty for the Aqua-King pump model we selected for this study is only 3 years (“Warranty Information”).
3. **No maintenance will be required for PV panels; 2 technician visits will be required for the pump.** If properly installed, PV panels require minimal service and maintenance over their lifespan (Mapoux, 2012; Doig, 2012). We therefore assume that the solar array, properly secured and periodically cleaned, will not require technical repairs that must be sourced outside the village. In contrast, we expect the pump will require repairs approximately every four years due to intensity of daily use, water quality, and potential wear and tear should the pump (which is not fixed) be moved by villagers to use with other water sources.
4. **Exchange rate (UGX:1 USD) = 2493.4 Ugandan shillings (CIA World Factbook)**
5. **Discount rate = 12% (Uganda Central Bank)**

Method

Installed Costs

Total installed costs for the system consist of capital costs for equipment purchase of initial system components and costs of installation. We calculated total installed cost using the basic equation:

Installed Costs (USD) = Capital Costs (USD) + Installation Costs (USD)

Capital Costs

Capital costs were calculated by itemizing system components followed by pricing using online sources, a local informant (fellow IAD student and Ugandan national Moses Timbiti), and the recommendations of our technical partner, Michael Reid.

- *Pump and panel sourcing and shipping.* Our local technical partner, Michael Reid, advised us not to procure system components such as the pump and panel in Uganda (personal communication, February 28, 2013). He suggested we would greatly increase the quality and longevity of system components by sourcing from outside Uganda, where equipment is of highly variable quality. Given that other solar panel projects in Arua district have failed due to the difficulty of repairing and replacing failed equipment (i.e., the CoolBot inverter, (Androa, January 31, 2013) , we agreed that equipment quality and reliability was a key concern and resolved to source the major system components (pump and panels) from vendors outside Uganda. As expected, this decision increased the purchase price and transportation costs (shipping) considerably. Should this pumping configuration be pursued, the expense of shipping system components could be reduced by hand carrying them into the country.
- *Water storage.* The system includes water storage capacity of 10,000 L, over a 1.5-day supply of water at the current domestic household demand (30 L/ person/ day * 200 people = 6,000 L/ day). A 3-5 day supply is recommended for drier areas of Africa such as the Sahel (Doig, 2012); given the tropical climate and existence of other water sources, we reasoned we could safely downsize the storage capacity. Corrugated iron was selected for the tank as the cheapest of the large manufactured tank options we could find in the literature; there may be built-in-place local options such as tarpaulin or ferrocement tanks that could offer costs-saving potential (Blanchard, 2012).
- *System components and design elements.* Our system configuration assumes that certain key system components are not necessary due to the type of pump being used. A pump controller typically is connected between the panels and pump and adjusts electrical flow from the solar array for optimal efficient operation of the pump, as well switches the pump on and off. It is a key factor in efficient and safe pump operation, however it is frequently left out of system design in village contexts to cut costs, leading to system failure and shorter equipment lifespans (Ratterman et al, 2012). The pump originally recommended to our team was ideal in that it did not require a controller, unfortunately the flow rate of the original pump was not sufficient to meet Ewavio's daily water requirement. We assume that the larger pump selected for this analysis does not require a controller, although should this assumption be false, we must add this expense to our capital costs.

System components that we deemed unnecessary due to equipment specifications or the specific system design were zeroed-out in the cost analysis, but left in the itemized list to indicate that these components may impact variable costs if system design changes.

Installation Costs

Installation costs were estimated for transport of system components from Kampala to Arua, labor for installation, and metal pole and mounting structure for the panel array. Installation on one 55W solar panel including mounting hardware costs 1,900,000 Ugandan shillings (USD \$762). However, this figure could vary considerably, up to USD \$1,000 (M. Timbiti, personal communication, March 12, 2013). We estimated the costs of installation for this project would be at the high end of the estimate, due to the distance the solar technician must travel, the 300W size of the array, and the necessity of a robust, reinforced mounting structure to prevent theft.

Operation & Maintenance (O&M) Costs

To calculate the operation and maintenance costs of the PV pump system over the lifespan of the system, we tabulated approximate local costs for pump and solar array repair and maintenance visits from a technician based in Kampala, and for spare parts. In actuality, pump technicians may be based much closer to Ewavio, but without complete knowledge of local pump technical resources, we budgeted for travel to and from the capital (where there will certainly be pump technicians located). As mentioned above (Section I, Assumptions), our cost analysis assumes a high degree of reliability and longevity for the solar PV system, therefore no costs have been assigned to PV repair, maintenance or parts. The analysis includes two visits from a pump technician for maintenance and repair.

Net Present Value/ Cost Calculation & Annualized Cost

Net Present Value was then calculated using the following formula:

$$NPV(i, N) = \sum_{t=0}^N \frac{R_t}{(1+i)^t}$$

Where:

t = the year in the lifespan of the project

i = the discount rate. A discount rate of 12% was set according to the Bank of Uganda central bank rate for February 2013

R_t = the net cash flow i.e. cash inflow – cash outflow, at time t

N = the lifespan of the project, 15 years

In this first analysis there is no cash flow/ revenue into the system (no income or fee collection), therefore the result represents net present cost of the system.

Annualized Cost was calculated using the following formula:

$$\text{Annualized Cost (USD)} = (\text{Total Installed Costs (USD)} + \text{Total O\&M Costs (USD)}) / \text{Life of the system}$$

Per Household Payment

Assumptions

1. All assumptions made in the cost analysis hold true here.
2. Households in Ewavio = 25 (200 people total, 8 people/ household) (Androa, January 27, 2013)

Method

To calculate an approximate per household payment, we used the Solver add-in in Excel to set NPV equal to zero and calculate the total annual benefits (revenue) needed for each year of the project lifespan in order result in an NPV of zero. This amount (in USD) is the amount of cash inflow yearly into the system in order for the project to break even. We then divided the yearly total revenue by the number of households in the village (25) to arrive at a per household sum that would need to be collected to cover the project costs over the lifespan of the project.

$$\text{Per household payment per year}_t (\text{USD}) = \text{Annual revenue}_t (\text{USD}) / 25$$

Results

Cost to the Community

As would be expected, a solar PV pumping system capable of handling the current supply from the 14-m borehole would incur some significant upfront expenses. Most of the expense results from the high costs of the pump and panels themselves, and shipping into Uganda. It is possible that system components could be sourced closer to Uganda (for example, Kenya has a reputable supplier of solar pumping equipment, Davis & Shirtliff, <http://www.dayliff.com/>), without sacrificing quality or reliability. In any case, it is clear from Table 4 that the high upfront costs of the solar PV system would be prohibitive for the community. Outside financing such as a microloan would be one option; see Appendix B: Arua MFIs for a list of microfinance providers operating in Arua district.

Table 4. PV Pumping System Costs.

Costs		
Installed Costs	Equipment	Cost (USD)
	PV panels (300W, 12 V)	750
	Rack for solar array	50
	Pump (20 LPM, 12 V)	250
	Controller	0
	Irrigation filter	15
	Water Piping – Well to Tank (1.5"x17 m, 16,000 UGX/20 ft)	17
	Piping – Tank to Water Points (1.5", 16,000 UGX/20 ft)	0
	Foundations for Solar Array (included in Installation)	0
	Electrical Wiring (40 m)	50
	Electrical Disconnect Switch	35
	Shipping & customs	422
	Storage tank corrugated iron, 10000 L capacity)	381
	Storage tank tower	0
	Installation (incl. foundations & panel mounting)	1000
	Labor	0
	Truck transport	0
	TOTAL Installed Cost	2970
O&M	Maintenance & Repair	
	RT travel from Kampala solar panel technician	0
	Panel technician fee	0
	Spare parts, solar panel	0
	Pump technician fee + travel (USD 140 * 2 visits)	280
	Spare parts pump (2x)	200
	Total O&M Cost	480
	TOTAL Annualized Cost	230
	Net Present Value/ Cost	(2865.24)

Per Household Payment

In order for a solar pumping system to “break even” (NPV = 0) over the life of the system, it must recoup nearly \$5,600 in revenue. “Revenue” in this situation could be the amount private entrepreneur would need to charge to balance out his/ her investments, or it could be a water use fee collected of all villagers who use the borehole. If we adopt the latter scenario, and equal division of the yearly required revenue across 25 families in the village would result in a n annual per household payment ranging from \$23 to \$12, with the annual payment decreasing towards the end of the project. If we assume that GDP per capita (2009) is \$523 (World Statistics Pocketbook) and that there is one full time earner per household, then this annual amount could prove a significant drain on a family’s finances. More research needs to be done on the willingness to pay of Ewavio residents for this previously free and unlimited resource.

Table 5. Pumping System Costs per Household.

Project Year	Required Annual Revenue	Per household payment per year	Payment % of GDP
1	575.12	23.00	4%
2	531.02	21.24	4%
3	491.64	19.67	4%
4	456.48	18.26	3%
5	425.09	17.00	3%
6	397.06	15.88	3%
7	372.04	14.88	3%
8	349.69	13.99	3%
9	329.75	13.19	3%
10	311.93	12.48	2%
11	296.03	11.84	2%
12	281.83	11.27	2%
13	269.15	10.77	2%
14	257.83	10.31	2%
15	247.73	9.91	2%
TOTAL	5592.39		

Social Sustainability and Community Feasibility Analysis

Methodology

In addition to economic and technical suitability, the ability of the solar pumping system to address social issues in the community, meet social acceptability standards, and be supported by existing community management structures would determine its success. The example of the solar powered CoolBot storage room in a town near Ewavio illustrates this last point: PV panels installed to power a cool storage unit for many families were instead being used to charge cell phones, after the inverter failed and the expense to bring a technician from Kampala was too great for the community to bear (Androa, February 28 2013). Thus, the diffusion of new technology depends not as much on the innovation of the technology itself as the capacity of people to adapt to the new technology and to manage it as a communal resource. Neither of these factors can be well understood without consulting and engaging local people to understand the context that will shape their adoption patterns. Murphy (2001) criticizes early PV dissemination attempts as “leading with technology, not people”-- being overly focused on the technological solution, rather than participation, with the result that community needs and technical capacity are misunderstood or ignored. Green Empowerment, a solar energy NGO, advocates an endogenous, bottom-up approach to energy project design (Ratterman et al, 2012). In assessing social sustainability, we adopted their process of focusing on community needs assessment and local capacity before technical needs assessment. We developed key questions

for our client to ascertain whether Ewavio would be organizationally ready for the technology, their willingness to pay, roles and responsibilities, expectations, and training needed (Appendix C: Water Management).

Social Benefit

Since women and children are responsible for gathering water in Ewavio, it was clear that this project had the potential to save both groups time and labor. For women, this time saved could be put to other productive use engaging in income generating activities-- that is, the opportunity cost of using a treadle pump can be quantified and assigned a monetary value. Assuming:

- Women do all of the pumping at the deep borehole
- The daily domestic water requirement in Ewavio = 30 liters/ person/ day (Androa, January 27, 2013)
- Using a treadle pump, women are able to pump 30 liters in 4.5 minutes (Androa, January 31, 2013)
- There are income-generating activities and opportunities for women to earn money
- Women possess 50% of the earning power of men
- The earning power of a local villager in Ewavio is equivalent to GDP per capita (2009) or USD \$523 (World Statistics Pocketbook)
- The borehole is very centrally located to women's houses, such that travel to the water source is not a factor

We were then able to estimate the value of women's time saved by a solar pumping system that requires no manual labor:

Hours spent treadle pumping/ day/ household (4.5 min/30L * 8 people/ household) = 0.6 hours

Hours spent pumping/ year/ woman = hrs spent pumping/day/household * 365 = 0.6 hrs * 365

Days spent pumping/ year/ household = Hours spent pumping year⁻¹ woman⁻¹/ 24

Value of Days saved per household was calculated by expressing the Days spent pumping/ year/ household as a fraction of a year and multiplying by GDP * 50% (female earning power).

Results

Stakeholders

The sustainability of a solar pumping system in Ewavio will depend on whether it addresses a problem that the residents of Ewavio have identified as a priority. In addition to outperforming other solutions, it must meet or exceed community expectations for a pumping solution, and be culturally acceptable. Before moving ahead, we must have a clear idea of who will benefit from the pump, and whether benefit is spread equally over all those who must bear the cost and burden of management for the pump. However, our understanding from our client is that a complete stakeholder analysis has not been done in Ewavio for a solar pump solution in particular or to

examine the larger issue of water supply in general. Identification and involvement of village stakeholders is needed to clarify the demand in Ewavio for a solar pump, the capacity and assets available to support the projects, and community needs and expectations for a new pump.

Community Management Options

Ewavio has a preexisting Water User Committee that currently administers and manages use of the treadle pump and boreholes (Androa, February 28, 2013). The deep borehole has operating hours that are enforced by a well manager of sorts who lock and unlock the pump daily, including a midday rest period of three hours to allow the well to recharge. This administrative structure could be readily to monitor pump operation and maintenance and collect user fees for repair. The Water User Committee may also be able to take a microloan on behalf of the village to finance up front installation and capital costs.

Another option for management of a solar pumping system is to involve a private investor/local entrepreneur or businessman who could assume the risk and burden of funding and operating the system. Since the community does not currently pay for water or water lifting services, it is unlikely they will be willing to pay for water under this scenario unless the new cost of water from the PV-pumped well results in great increases in agricultural production or other financial benefit. Nonetheless, the local capacity and model for social entrepreneurship to take over this project exists in that Ewavio has a privately-run grain mill (Androa, February 28, 2013). A better understanding of the willingness to pay for water could be used to engage this local businessman in a pump enterprise.

Training

It is not clear whether anyone in the community is trained in electrical pump or PV panel maintenance, however given that a malfunctioning inverter (Cool Bot project) in a neighboring community required a technician from Kampala to fix, it is probably safe to assume that Ewavio and the local communities do not have the skill base to repair or maintain a solar PV pumping system. We recommend investigating NGOs that install solar home systems or pumps, as they may be able to provide training in solar system and pump installation and maintenance to some villagers, that would enable Ewavio to better manage maintenance and minor repairs and increase self-sufficiency.

Social Benefits

On average, a woman pumping 30L/ person/ day for an average household size of 8 people would save about 9 days per year, or USD \$6.54/ year. Across the entire village (25 “pumping” women, one per household), this amounts to 225 days per year. Although the monetary value is small, it is hard not to imagine the impact the combined productive use of this time might have on the village. However, before getting carried away with imagined impact, it is essential to return to the need for a stakeholder analysis to confirm with women in Ewavio—primary stakeholders—whether the time spent pumping is a problem at all, or whether it has important social value as a time when women can interact with each other.

Table 6. Value of Women's Time and Labor Saved.

Uganda GDP per capita (2009 USD)	523.1
Female earning power - 50% (USD)	261.55
Hours spent pumping/ year (treadle)/ woman (0.6h * 365)	219
Days spent pumping/ year/ household	9.125
Value of Days saved per household - USD (9.125/365*261.55)	6.54
Days spent pumping/ year/ whole village (9.125*25)	225

Nadya English 3/20/13 3:33 PM
Formatted: Centered, Widow/Orphan control

For children, the benefit of a solar pump is clear—though treadle pumps have enjoyed popularity in Ewavio in part because children enjoy using them (Androa, January 27, 2013), pumping may interfere with school attendance. The extent of the interference must be evaluated further, as depending on children's involvement in pumping, there could be great social benefit to local children's education by introducing an automatic solar pump.

The promising social benefits for a solar pumping system in Ewavio and potential local capacity to support such a system may offset the significant financial and technical challenges involved in this project. Stakeholders should be involved more deeply to establish needs, expectations, and potential unintended impacts, and a broader needs assessment conducted to establish how a solar pump fits into village priorities. This project has the potential to build local capacity via training in maintenance of solar pumping systems, if an appropriate training partner can be found.

Discussion

This report analyzed several dimensions of this problem. Shifting rainy season patterns due to climate change have increased water insecurity in Ewavio, further exacerbating the water limitations faced during the dry season. Most of the sources of water available to the village run dry, and the only reliable source of water is pumped manually in the morning and afternoon, with a mid-day 3-hour pump lockout for aquifer recharge. This water must be carried to each household in small jerrycans, which adds to the labor spent fetching water. Aside from the time devoted to pumping, there is also a minimal amount of water available in the dry season. The estimated per-person use of 30 L/day (Androa, January 27, 2013) is the absolute minimum of the WHO recommended levels (30-50 L / person / day, Water and Engineering Development Center). If additional water was available it could be used for drinking, livestock, and for growing leafy greens that would supplement household diets and income from the market. There was not sufficient information available during the design stage of this project to offer a comprehensive assessment of all the dimensions of this problem. Therefore, the research focused on four key areas:

1. The technical considerations and feasibility of a solar pump installation
2. The potential crop water use for an optimal year-round agricultural scenario
3. The economic feasibility of option 1
4. The social feasibility of implementing such a project

The pump test discussed in Scenario 1: Pump Sizing above demonstrated that a compact, inexpensive pump could easily meet the needs of the Ewavio village. The pump system designed was optimized to minimize the number of components (and potential system failure points). Per discussions with the in-country partner, the village has access to both local pump mechanics and electricians who are familiar with solar panels. By designing a system that does not include additional components, such as charge inverters, the risk of project failure due to breakage and lack of access to repair is minimized. The 300 W panel and 20 lpm pump specified in this scenario would supply the village with same volume of water that is currently pumped from the deep well during the dry season.

The crop water needs discussed in Scenario 2: Maximum Potential Crop Water Use (ETc) above estimates the additional daily volume of water that would be required by each household if they were maximizing their agricultural activity within the local farming parameters (Androa, January 27, 2013). If all households engaged in this agricultural activity, the village would require a pump with a flow rate of approximately 500 lpm, or 25 times the flow rate of the current deep well. Further exploration of this option would require a hydrogeologic survey of the area and the drilling of a second well, if it was determined that the water table or aquifer could support it.

The economic dimension discussed in Economic Feasibility above outlines the costs and benefits associated with the 300 W, 20 lpm pump sized in Scenario 1: Pump Sizing. Given the assumed 15-year lifespan, which is not a conservative estimate, the NPV of the system is still -\$2,900US. This means that the labor saved by the pump does not begin to offset the capital and installation costs of the project. In order for the project to be economically feasible, another source of funding would have to be identified, either through a fee-for-service, private-sector social entrepreneurship, or through grant organizations. However, it should be acknowledged that social benefits of a labor-saving solar pump (often woman and child labor), such as additional time for children to attend school, additional safety for those who may otherwise have to travel long distances to find water (most often women and children), are not easily quantified and not represented in our economic analysis, but are real benefits nonetheless.

Conclusion and Next Steps

The village of Ewavio has implemented solar and pumping projects in the past. The village acquired a treadle pump in 2010 and also built a solar-powered cool room in 2010. The treadle pump project was successful and the pump is still used today. The solar-powered cool room project failed, because the inverter for the solar panel was broken and there was not enough capital to have it repaired. The solar panel from this project is still used informally as a source of power. The design tested in this project seeks to minimize the risk of failure by specifying a robust system with minimal components. However, the solution put forward only answers one of the many design questions that surround the problem statement. In order to assess the best use of capital within the village, it is recommended that further information be obtained before the project moves forward. Specifically, the following parameters and constraints should be defined:

- The total sources of water available to village, along with the daily volumes they provide and when they run dry
- The average distance from each source to the households it serves
- The breakdown of water use by household into drinking, washing, livestock, and agricultural uses
- The number of days when irrigation would be required to grow crops
- A more precise estimate of the amount of water that would be required to grow crops during the dry season, both optimally and minimally (per households and by number of households that would participate)
- The number of houses that currently have metal roofs, catchment systems, and / or water storage tanks
- Spaces where additional catchment systems or tanks could be constructed
- The feasibility of constructing water storage tanks vs. the possibility of having a second deep-well drilled
- An assessment of water-conveyance methods, particularly regarding the possibility of piping or larger water carrying containers
- The amount of income that could be generated by expanded agricultural activities, including access to markets and seasonal market prices
- The specific stakeholders to this project and their willingness to invest in these services
- Identification of partnering institutions to provide training in system maintenance and repair and capital financing options

Final considerations should also examine the value of the pump to the village. As detailed in the Economic Feasibility section, the estimated NPV does not justify the investment in the pump. Although a labor-saving device is beneficial, with the current value of time the labor saved does not offset the cost of the pump. A stronger proposal would use a pump investment to generate revenue through agriculture; however, for this type of project to move forward, a different source of water would need to be identified.

Appendix A: Citations

Androa, Gloria. Personal Communication (emails and Skype calls). January 27, 2013 – February 28, 2013.

AMFIU. (2011/2012). The Uganda Microfinance Directory. 5th ed. Association of Microfinance Institutions in Uganda: Kampala, Uganda.

BakamaNume, B. B. (2011). A Contemporary Geography of Uganda. Dar es Salaam, Mkuki Na Nyota.

Blanchard, Jonathan Peter. (2012). Rainwater Harvesting Storage Methods and Self Supply in Uganda.

Central Intelligence Agency. (n.d.) World Factbook: *Uganda*. www.cia.gov/library/publications/. Retrieved March 8, 2013 from <https://www.cia.gov/library/publications/the-world-factbook/geos/ug.html>.

Doig, Alison. (2012, April). Solar photovoltaic energy. *Practicalaction.org*. Retrieved February 3, 2013 from <http://practicalaction.org/solar-photovoltaic-energy>.

FAO (1998). Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. Rome, Italy.

Freightcalculator.com. Retrieved March 13, 2013, from http://www.freight-calculator.com/wholeier_cal.asp.

Fresh Water Pumps. (n.d). *Bias Boat Warehouse*. Retrieved March 8, 2013 from http://www.biasboating.com.au/Fresh_Water_Pumps_s/114.htm.

Mapoux, Michel. (2012, May) Solar (Photovoltaic) Water Pumping. *Practicalaction.org*. Retrieved February 1, 2103, from <http://practicalaction.org/solar-photovoltaic-waterpumping-1>.

Murphy, James T. (2001). Making the energy transition in rural East Africa: Is leapfrogging an alternative? *Technological Forecasting and Social Change*, 68(2), 173-193.

NAPA (2007). Climate Change. U. N. A. P. o. Action, NAPA: 92.

NEMA (2010). State of the Environment Report for Uganda 2010. State of the Environment Report. N. E. M. Agency. Kampala, Uganda, NEMA. 2010: 205.

Olson, J. and L. Berry (2003). "Land degradation in Uganda: its extent and impact." available at lada.virtualcentre.org/eims/download.asp.

Osende, Brian, Abraham, John Patrick, & Mowry, Greg. (2011). Small-Scale Use of Solar Power in Remote, Developing Regions: A Case Study. *Journal of Sustainable Development*, 4(3). doi: 10.5539/jsd.v4n3p3

Ratterman, Walt, Cohen, Jonathan, and Garwood, Anna. (2007). *Solar Pumping Systems (SPS): Introductory and Feasibility Guide*. Retrieved from http://www.greenempowerment.org/attachments/SolarWaterPumpingManual_jan2007.pdf

Reid, Michael. Personal Communication (emails and Skype call). February 10, 2013 – March 15, 2013.

Saundry, P. (2009). "Energy Profile of Uganda." *Encyclopedia of Earth*: 6.

Uganda Central Bank. Central Bank Rate. <http://www.bou.or.ug/>. Retrieved March 12, 2013 from <http://www.bou.or.ug/bou/home.html>.

Warranty Information. (2012, July 3). Warranty Information 2013. Defender.com Retrieved on March 16, 2013 from <http://www.defender.com/pdf/WarrantyInformation2013.pdf>.

Water, Engineering, and Development Centre. (n.d.). *Minimum water quantity needed for domestic uses* (WHO/SEARO Technical Notes for Emergencies, Technical Note No. 9). Leicestershire, UK: B.J. Reed.

World Statistics Pocketbook United Nations Statistics Division. (n.d.) *Uganda country profile*. <http://data.un.org/>. Retrieved March 8, 2013, from <http://data.un.org/CountryProfile.aspx?crName=Uganda>.

Appendix B: Arua MFIs

MFIs and their Branches, Arua District.

ARUA	
	Blue Employee Benefits
	BRAC-Uganda
	Centenary Rural Development Bank
	PostBank (U) LTD
	PRIDE Microfinance Limited (MDI)
	Wazalendo SACCO
	FINCA- Uganda

Appendix C: Water Management

Questions for Client: **Water Management/ Governance/ Sustainability**

1. How did the idea for this project come about/ who in the village requested it? Can she talk more about the project/ project goals?
2. Is the intention that one pump would be supplied per farmer? (please clarify) What would be the best scenario for the village?
3. Would the pumps be the property of the individual farmer who received it? If so, how are these farmers chosen? Is their any contribution on his/ her part (money or in kind)?
4. If the property of a group of farmers, how would they coordinate/manage use/ water allocation/ repair of the pump, i.e. whose responsibility would it be? Are there any existing management bodies or local governance structures (water and sanitation committees, grain banks, or farmer cooperatives or groups) among the farmers that could be used to manage pump-related issues
5. How is water allocation currently done (centrally managed or everyone takes as needed)?
6. How accessible would solar panel repair, supply of parts be? (location to larger towns/ cities)
7. Is there a plan for the repair and maintenance?
8. Any concerns about vandalism and theft?