Providing Sustainable Power through Renewable Energy for Developing Communities in Central America

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Citation

Providing Sustainable Power through Renewable Energy for Developing Communities in Central America

A thesis submitted in partial requirements for the honors program in Biological Engineering.

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Abstract

Rural electrification through an expansion of the power grid into remote villages in Central America is a development that is still years away. Using renewable energy technology, access to electricity is available even in the most remote areas of the world. These individual power grids are also called “microgrids.” Creating microgrids in rural areas provides the people living there with access to power they did not have before. With this newfound access to power, these communities can expand their access to education, using computers or mobile devices. They can power lights, refrigerators, and other devices to continue development.

The design for a community center that can meet the needs of a developing community was based on a village called Los Chilitos, outside of Cuilapa, Guatemala. These clients wanted to provide power for an internet café (study area) for the students to work on homework, adults have access to the internet, and to have a location close to their homes to charge their cell phones. They wanted a clinic area that can provide first-aid and basic triage care. The clients also wanted a kitchen with multiple work stations to cook food for the children attending school. The clients wanted a place for community members to gather together and socialize, as well as play soccer on a field with lights. Additionally, the community members need more access to water, since their current water well does not provide them with as much as they need.

In the area of study, the most viable source of energy is solar energy. Wind energy in the area would require site-specific wind studies. Hydroelectric power would only be viable if there was a moving water source, which there is not in the area. Using solar energy, a community center with all of the clients' wishes, except the water well, can be run on nine solar panels and 10 batteries. The electrical loads and basic solar supplies would also cost under $15,000, so it could be reasonably fundraised.

This report, my honors thesis in Biological Engineering at the University of Arkansas, was intended to provide a preliminary design to facilitate fund-raising efforts that will lead to implementation.
Acknowledgements

I would like to thank Dr. Thomas Costello, P.E. for his guidance and mentorship throughout the duration of the project, and for encouraging me to find creative solutions to difficult problems.
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I. Background

In order for developing countries to improve the quality of life for their people (at least from a Western point of view), people need to have access to clean water, safe and nutritious food, sanitation, education, health care, and technology. In order for people to escape poverty, they need to have access to education. In most developing countries, education is not available for free, so citizens experiencing poverty have a small chance of being able to access education and escape a life of poverty. Access to education and technology is significantly easier with access to electricity and cell phones. But projects to extend electric services to remote areas could be decades away. By harnessing solar power and PV arrays, an upfront capital cost provides access to electric power for a whole village. Providing power that is accessible to an entire community also improves communal relations and can provide jobs and opportunities for anyone with access. Providing power for a computer to run on can allow multiple people to have access to course work to learn a new language, computer programming, or take an online class. Having power and access to basic health care and knowledge of new medical developments can also greatly improve communities.

A design for a community center that has access to computers, a health center, and open classrooms could greatly improve an entire community’s way of life. The focus of this study will be on a small village outside of Cuilapa, Guatemala (Figure 1, 2). Los Chilitos sits on a mountainside, located about two hours south of the capital city. I visited the community in 2015 and 2016 as a part of a mission trip and work project. I was able to see the areas for potential development, visit the school, and meet some of the members of the community and learn about their day-to-day lives. This community already has a building for children to attend school, so there isn’t a need for a standard classroom. This community’s most pressing needs are common
spaces with electricity, a health center, some computers with access to the internet and basic software, and easier access to clean water.

Figure 1. Map of Central America (Google Maps).

Figure 2. Map of Guatemala (with Cuilapa shown in red, Google Maps).
Currently, in Los Chilitos, there is a school for the younger children to attend. The school is a cinder-block building with 3 classrooms, a covered patio, and a small kitchen. There is currently no access to electricity. There are about 60 children that regularly attend this school. Many of the older children, who must commute to get to their school, have assignments and work that must be done on a computer. Currently, they have to travel to the nearest city’s internet cafe to complete these assignments.

There is also a covered area for the community to meet for church or other gatherings. The village shares a water well with other surrounding communities. Most of the families in the village live in houses constructed with metal siding or wood. Currently, the well is not meeting the water demand. There are no public water or sewer lines servicing the area, but sanitation is managed well in Los Chilitos through outhouses.

II. Problem Statement

The community of Los Chilitos would greatly benefit from the construction of a community center; however, they currently lack the resources to build it on their own. There are many fundraising groups in the United States that would be willing to work on such a project. In order to keep the project within a reasonable amount to be fundraised, in consultation with a local missionary, the preliminary budget was arbitrarily set at $15,000. This would include estimated costs for a new micro-grid (local power system) installation, and the basic electrical appliances.

The design of this community center will include a common space with areas to sit or work and areas for children to play, a health clinic for basic care, a computer lab with printers and outlets for charging cell phones, a library, a kitchen, a bathroom, and a soccer field with lights. The design will also include plans for a second phase, which would power a pump for a
well that could meet the water demands of the communities. This micro-grid will be completely independent of the wider utility grid and will require several batteries for energy storage. This energy system should meet the current needs of the community and also have room for expansion in the case of further development.

III. Design Goals

The goal of this project is to provide a central gathering place with access to electricity and the internet to a rural village in Guatemala. This design will use renewable energy, in the form of solar energy, to provide power to the building. Using renewable resources also provides an example of sustainable development in areas that have not been exposed to any kind of development. The ultimate goal of the project is to improve accessibility to sustainable development in rural areas in Central and South America. This project could serve as an example of sustainable development.

The system design has been developed with the intent to meet the specific needs of Los Chilitos, with the following design objectives, with the hope of improving the quality of life for the residents of the community. Understanding people’s needs and wants is a very important part of the design. The student-engineer has spent two weeks at the village and is in contact with Mitch and Amanda Munoz who are currently living and working in the community. They have shared their insight into the needs and dreams of the client community.

IV. Design Objectives

The project’s design objectives describe the clients’ ideas for improvement for their community. The people of Los Chilitos are interested in improving the overall quality of life for themselves and the surrounding area. They want to improve access to education for the
community. Internet access (through computers or mobile devices) would open up a wealth of educational opportunities, access to news and literature, music, and other information sources. The clients also want to be able to charge their cell phones, as they would in an internet café.

The client wants to improve access to basic health care and medicine in the area. The client has requested a walk-in clinic with first-aid and basic triage supplies. The client also wants to be able to provide food for the younger children who attend school in the village. There are several people available to cook, so they would like for a kitchen to have enough space for at least 5 people to be cooking at one time.

Finally, the client wants to provide a space where the community can gather together, for meetings or social gatherings. Many of the people in Los Chilitos play soccer in a league against other teams in the area. Currently, the players have to travel into the city to play any of their games that aren’t during the day time, because their field does not have lights. They play on a standard 6 v. 6 size (150 ft x 100 ft) field and would want enough lighting to play a night game.

The client would also like for the design to account for space to expand. The most pressing expansion would be adding more panels to power a pump for a new water well.

In all these components of the desired community center, the people would hope for infrastructure having these attributes:

- fairly simple and easy to operate by local staff,
- low operating costs,
- reasonable capital costs so that fund-raising can be successful,
- everyone should have access to the computers, internet, and cell phone charging,
• reliable service and no blackouts,
• increased community interactions.

V. Design Constraints

The design constraints represent a listing of the required characteristics of any proposed solution. These are conditions that are absolutely required or conditions that cannot be tolerated. Based upon discussion with Mitch and Amanda Munoz, the constraints that the people would demand are:

• Total capital cost should not exceed 15,000.00 USD – budget was chosen based on the reasonable cost for renewable energy equipment, batteries, devices consuming electricity, and accessories needed for the function of renewable energy devices,
• PV array will comply with necessary electric safety codes and will be safe for operators to maintain,
• PV array will meet essential power needs of the building and have the ability to operate continuously (unless an unusual period of cloudy weather occurs),
• Installation and maintenance of the array will be relatively simple, so the community members can manage it themselves with help from international volunteers,
• Any construction needs to be built with locally available resources and workers, so the local economy can benefit (this does not include the major electrical system components which will probably be imported).
VI. Literature Review

In the 1960s and 1970s there was a push from the United Nations to increase access to electricity in developing countries through the extension of the power grid. Many utility companies extended power lines to rural areas but did not get a large return on their investment, as most of the users could not afford to use the power. Thus, a policy debate over rural electrification has persisted (Barnes, 2014). Most people would agree that electricity is a significant part of modern society but getting access to electricity in isolated rural areas can be incredibly expensive. Public or private subsidies could be necessary in order to make these projects financially sustainable (Barnes, 2014). These services can have significant socioeconomic impacts. These off-grid systems can also be called “micro-grids” that can provide power to rural areas that need to charge cell phones or other small devices, and they have been successful in expanding access to electricity in rural areas (Barry, 2016).

The increase in cell phone use since the 1990s has provided opportunities for development worldwide. As of 2016, more people in the world have access to mobile phones than have access to clean water (Pramanik, 2017). This increase in access to information and technology, increases access to education. With an increase in access to education and increased quality of education, more opportunities are created for socioeconomic advancement. Many of these opportunities come from access to mobile internet. This access to mobile internet is important for education in developing countries as well. Due to the increase in cell phone access, mobile internet is fairly widespread and user friendly. Studies focused on Asian distance education have shown that mobile internet can provide more opportunities for advancements in education than traditional distance education (Motlik, 2008). Increasing the quality of education in rural areas in developing countries will greatly increase their chances or improving their socioeconomic status.
The Institute of Electrical and Electronics Engineers (IEEE) has set standards for stand-alone photovoltaic systems (IEEE, 2008). These standards were developed to aid PV system designers in sizing photovoltaic arrays using the “peak sun hour” method, which is based on the worst-case data for monthly irradiance and load demand. These standards are only applicable for off-grid systems. Systems that are tied to the power grid are generally sized based on an average annual load.

VII. Evaluation of Alternatives

When considering alternatives for renewable energy, the most important factors are that there will be consistent and strong availability of the resource. When considering the village of Los Chilitos, Guatemala, solar energy is a very viable option. Even in September, the area still gets 5.25 kWh/m² per day of solar radiation. (U.S. Department of Energy, 2019). Hydroelectric power was also considered for the project but was eliminated because there is not a river close to the village of Los Chilitos. Hydroelectric power could be available in other areas of Guatemala or even another location in Cuilapa, but it would not be accessible to a local micro-grid in Los Chilitos. Wind energy is uncertain because of the position of the village on a hillside in a mountainous region.

There are multiple options within photovoltaic arrays for alternatives. The most common options are using a fixed array or single-axis tracking array. The fixed array is stationary, and the tilt angle is selected based on the latitude. The single-axis tracking array still has an azimuth of due south but moves the tilt angle to track the location of the sun at all times of the day. This can maximize the amount of solar radiation a panel can take in but is a more complex design and includes more parts and moving parts that may later need repair. Typically, tracking systems aren’t installed in residential solar projects due to the need for maintenance and higher
installation costs and are more likely to be used in larger industrial projects because of the increase in energy capture (EnergySage, 2019). At the site, solar energy capture would only increase by 19%, calculated on PVWatts (U.S. Department of Energy, 2019), where in other projects, tracking can increase energy capture by 25-35% (EnergySage, 2019). Since there is less access to this technology in rural Guatemala, and one of the design constraints is that the system needs to be relatively simple to maintain; hence, the fixed array would be the best option.

When considering the viability of wind energy, wind speeds need to be at least 4 m/s for small turbines (Culture Change, 2004). At a 50 m hub height, the area surrounding Los Chilitos could be classified as moderate wind potential (6.4 to 7.0 m/s, Figure 3, U.S. Department of Energy, 2005). Since the terrain around Los Chilitos is mountainous, the wind profiles are very location-specific. A wind study at the proposed site is needed before the feasibility of wind power can be adequately assessed. While wind energy can’t be ruled out as a viable option, due to the lack of wind study results at present, we have decided that wind is not a good option at this time. When considering the design objectives and constraints, the fixed photovoltaic array emerges as the best alternative to move forward with.
Figure 3. Wind Map of Guatemala (U.S. Department of Energy, 2005)

VIII. Engineering Design Process

This section describes the process of applying the clients’ needs and design constraints to the development of possible solutions. The initial design is outlined below.

Building Configuration and General Layout

Although the scope of this project does not include the design of the structures that will make up the community center, it would be helpful in the power system design to at least have an idea of a potential layout.

In recent years, there has been an increasing trend in the United States in a small home, or “tiny house” living. Small homes are more environmentally friendly than larger houses, because these homes require less energy to power, and they are significantly cheaper. Many types of tiny houses exist, but one specific type has advantages for rural areas: shipping container homes. Shipping containers, used for importing and exporting goods, are very inexpensive, and
for many companies, it is cheaper to make new containers rather than shipping used containers back. This creates a huge excess in used containers. “A good use for these old shipping containers is to incorporate them into building construction. Containers offer several advantages. They are designed to carry heavy loads in harsh environments, are stackable, can be interlocked, and are made in several standard sizes. Properly secured, a container is capable of withstanding Category 5 hurricanes, which makes them stronger than many other structures. They can be easily transported by sea, truck, or rail and are relatively inexpensive” (Koones, 2019).

Using shipping containers for the structure of the community center is certainly a viable option, but the structural components of the building are beyond the scope of this project. The general dimensions of the rooms in this preliminary plan for the community center will be based on standard sizes of shipping containers. Even if shipping containers aren’t used during construction, keeping the room sizes small will use less energy. General room layouts have been produced to verify the chosen size of the room, using an online room designer (Living Spaces, 2019). The overall layout of the community center could be configured in several ways. Figure 4 shows one potential layout.
Photovoltaic Array Overview

In order for the client to accurately choose which of the potential devices or electric loads to install, the options will be analyzed independently based on the amount of energy needed to run each device. The tilt angle chosen for the array is 14.48°, as that is the latitude of the location. This is a general recommendation for stationary PV arrays, but adjustments of 10°-15° are often used in the summer and winter to optimize energy collected (Allen, 2018). Using a fixed open rack array type with the azimuth = 180° (due south), the PV Watts calculator from NREL provided monthly data for solar radiation (Figure 5). I chose the worst-case scenario value
to size the panels; in this case, September is the worst-case value (5.25 kWh / m² per day) (USDOE, 2019).

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar Radiation (kWh / m² / day)</th>
<th>AC Energy (kWh)</th>
<th>Value ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>6.46</td>
<td>1,487</td>
<td>N/A</td>
</tr>
<tr>
<td>February</td>
<td>6.84</td>
<td>1,421</td>
<td>N/A</td>
</tr>
<tr>
<td>March</td>
<td>6.66</td>
<td>1,497</td>
<td>N/A</td>
</tr>
<tr>
<td>April</td>
<td>6.19</td>
<td>1,358</td>
<td>N/A</td>
</tr>
<tr>
<td>May</td>
<td>5.40</td>
<td>1,232</td>
<td>N/A</td>
</tr>
<tr>
<td>June</td>
<td>5.28</td>
<td>1,181</td>
<td>N/A</td>
</tr>
<tr>
<td>July</td>
<td>5.82</td>
<td>1,338</td>
<td>N/A</td>
</tr>
<tr>
<td>August</td>
<td>5.67</td>
<td>1,300</td>
<td>N/A</td>
</tr>
<tr>
<td>September</td>
<td>5.25</td>
<td>1,172</td>
<td>N/A</td>
</tr>
<tr>
<td>October</td>
<td>5.44</td>
<td>1,247</td>
<td>N/A</td>
</tr>
<tr>
<td>November</td>
<td>6.15</td>
<td>1,397</td>
<td>N/A</td>
</tr>
<tr>
<td>December</td>
<td>6.49</td>
<td>1,507</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Annual</strong></td>
<td><strong>5.97</strong></td>
<td><strong>16,137</strong></td>
<td><strong>0</strong></td>
</tr>
</tbody>
</table>

Figure 5. Results from NREL's PVWatts Calculator, with inputs of location, tilt angle, and Direct Current (DC) Load (approx. 10 kW). We are interested in the solar radiation data provided for the site.

Specific panels, batteries, and inverters can’t necessarily be specified for the project, because of the currently unknown availability and cost in Guatemala. Many stores don’t have online catalogs of their inventory, and American stores that have online options do not ship their products worldwide. Due to the proximity of Guatemala to Mexico and the United States, I will assume that the discussed technology will be available in some form. Example panels, batteries, and inverter were chosen for the purpose of calculations and can be adjusted within reason. The
chosen panels and batteries, in conjunction with the chosen inverter efficiency, give a ratio of
0.0012 panels per Wh per day (of alternating current (AC) load required) and 0.0023 batteries
per Wh (of AC storage required). These ratios are based on solar energy received at the site-
location each day, the efficiency of the panels, batteries, and inverter, losses inefficiency of the
panels and batteries due to site conditions, and compatibility of the panels and batteries. These
calculations can be found in Appendix A.

The chosen panels need to be evaluated in conjunction with the chosen batteries, so that a
common system voltage can be chosen, compatible with the chosen inverter, so there is minimal
wasted energy. The example panels (MC4 CS3K-315MS, Canadian Solar, Canada) were chosen
because of their high-power output and the fact that they work well with the chosen batteries and
a system voltage of 30 VDC. The sample batteries (CR-305, Crown, United States) were selected
because of the low-cost and readily-available technology. Flooded lead-acid batteries require
some regular maintenance, but maintenance instructions are readily available (Evirs, 2018).
Several flooded lead-acid batteries were researched, and the example battery was chosen because
of its high energy storage and relatively low cost.

Load Determination. The preliminary power system design depends upon the
determination of the electrical loads (energy use per day, in kWh/d). Quite often, engineers will
be generous in estimating loads, but in this application, excessive load estimation can easily
double the final cost. So, I had to consider carefully, the types and number of electrical devices
that would really be needed for the client, in each space within the center.

Library and Internet Café. The client is interested in improving access to education for
the community. Therefore, the design will include a room with access to computers and printers,
for the older children to work on their homework and study. The client has suggested 5 computers with a printer will greatly improve these students’ ability to complete their work and study. Additionally, adding a library with books with a variety of reading levels for the entire community to have access to, could improve the access to education. This library area would also be well lit, so users would have access after the sun has set (and during daylight hours depending upon windows and natural light availability).

The first load to consider is the lighting of the room. LED bulbs should be chosen due to their increased life, efficiency, and brightness when compared to competitors. These bulbs need to be able to provide adequate lighting to the entire library area. Assume this area is approximately 200 ft², based on the standard size of a shipping container (Figure 6).

Using a light calculator, with an area of 18.6 m² and choosing a light requirement of 300 Lux (or Lumens/m²), recommended for classrooms (Charleston Lights, 2019a).

\[
\text{Lumens required} = 300 \text{ (Lux)} \times 18.6 \text{ m}^2 = 5,580 \text{ Lumens}
\]

Each LED bulb can provide approximately 800 lumens (Philips, 2019).

\[
\text{Bulbs required} = \frac{5,580 \text{ Lumens}}{1350 \text{ Lumens per bulb}} = 4.13 \text{ bulbs}
\]

I rounded 4.13 bulbs up to 5 bulbs distributed evenly across the ceiling. I chose a standard bulb for ease of purchase and installation. I assume the lights will only be on when it is dark outside, a maximum of 5 hours each day, 7 days per week.
A laptop uses approximately 60 Watts when it is in operating mode (U.S. Department of Energy, 2017). I assume the computers will be used periodically throughout the day, and when they are not being used, they will be completely powered off. I assumed daily use of computers would be about 5 hours each day, 7 days each week. The printer connected will use 30-50 Watts when printing and 3-5 Watts when on stand-by. I assumed stand-by time will be minimized by users powering down printer each night. I assume the printer will consume 50 Wh per day, 7 days a week (Energy Use Calculator, 2019).

The system should also account for individuals needing to charge cell phones. Based on a report by the Consumer Technology Association, a mobile smartphone uses 4.5 kWh/year. This is 12.3 Wh/day (Singh et al., 2017). I assumed there will be 50 mobile smartphones in the village, the phones would take approximately an hour to charge, and they would need to be charged 7 days a week.
The system design should also be able to support a ceiling fan running for the hottest part of the day; assume it runs for 6 hours each day, 7 days a week. The average ceiling fan was found to be about 35 Watts (U.S. Department of Energy, 2017).

In total, the library section uses 1,660 Wh per day (AC). This area can be run on 2.0 panels and 2.3 batteries (Appendix B).

**Medical Clinic.** For the clinic, assume any first aid or triage care supplies do not require electricity. If the clinic were to include an automatic external defibrillator or other emergency devices, they would be run on separate batteries. In this case, the only electric demands are lights and airflow. Assume the clinic would only need to have 4 people in the room at a time, so the area would only need to be about 100 ft² (Figure 7).  

![Figure 7. Medical clinic area (Living Spaces, 2019).](image)

A hospital (or medical facility) of this size would require 4460 Lumens; assuming the lights are placed evenly at a distance from the corners of the room (Charleston Lights, n.d.-b). This room would require 4 bulbs to light the room. I assumed the lights would only be on when
the clinic is in use, worst-case would be about 4 hours each day. The fan will also be on whenever the lights are on. The medical clinic will consume 348 Wh per day (AC). The clinic could be run on 0.42 solar panels and 0.49 batteries (Appendix B).

**Kitchen.** The kitchen area needs to have enough space for about 5 people to cook in at the same time. In order to properly ventilate the room, there will need to be windows that can be opened. This will allow the sun to warm the room even more, so trees or some sort of shade will be needed to mitigate the heat in this area. The client also wants to have access to a refrigerator for perishable goods to be stored. Unlike the library and clinic areas, the most important load in the kitchen is a refrigerator. The refrigerator would operate 24 hours a day, 7 days a week, and consumes a significant amount of electricity, especially when the compressor is actuated. The Whirlpool Bottom-Freezer Refrigerator uses approximately 570 kWh per year, for high usage (Whirlpool, 2019). In order for the system to minimize needed panels and batteries, I chose a period of autonomy of 1 day. Hence, the system can only run without sunlight for 1 day. I would recommend using a small generator as backup power for the refrigerator, in case of an unusual period of cloudiness. For an elementary school of approximately 60 students, assume the kitchen would need to be about 300 ft² (Figure 8).
The light requirement for the kitchen area would be 5 bulbs, distributed evenly across the ceiling. Calculations can be found in Appendix C. The kitchen would also benefit from a fan, which would be on whenever the lights are on. The kitchen will also include a wood-burning stove to reduce the number of solar panels needed, and because the community members have easy access to firewood.

The kitchen area would use 2,189 Wh per day (AC). The kitchen could be run on 2.6 panels and 3.1 batteries (Appendix B).

**Outdoor Courtyard.** The outdoor courtyard (Figure 9) can be used as a social gathering place, so the lights don’t need to be sized for a specific brightness. For ease of installation, outdoor lights can be strung and plugged in. The lights would only be needed in the evenings, after the sun has set, for a maximum amount of 5 hours a day, 7 days a week.
The client requested lighting for a 6v6 full-size men’s soccer field, 45.7 meters x 30.5 meters. Figure 10 shows general size comparison. Currently, the players have to travel into town to play their games. Adding stadium lights to their field in the village would increase the needed number of solar panels and batteries; standard stadium lights would require 70,000 Watts to light the area (GT Grandstands, 2019). Normally, a stadium would have a light requirement of 750 Lux (Charleston Lights, 2019a). In order to economize the light requirement was reduced to 300 Lux, for minimal lighting for practice or recreational games. The field can be lit with 16 mounted lights (Appendix C).
Adding the soccer field lights would increase the total number of panels needed by 2 (Table 2). Since these lights aren’t a necessity for the community center to run, they don’t need to be purchased right away. The outdoor courtyard could be run on 1.9 panels and 2.2 batteries (Appendix B).

**Addition of a Water Well.** The clients have expressed a need for a water well that can supply their needs. Currently, members of the community can only use their current well every 15 days. Providing a design for adding a new well goes beyond the scope of the project. However, since this is an important addition to the community, the project will include a plan to provide power for the expansion. I assumed the current problems with access to the water in the well are mostly related to the depth to the water table and perhaps the existing pump is inadequate.

The Office of the United Nations High Commissioner for Human Rights states, “the water supply for each person must be sufficient and continuous for personal and domestic uses.
These uses ordinarily include drinking, personal sanitation, washing of clothes, food preparation, personal and household hygiene” (OHCHR, 2003). The World Health Organization has determined the sufficient water intake for adults in high average temperatures (above 32 °C) to be 3.4 liters per capita per day. They determined the consumption of water for hygiene and cooking purposes to be about 15.8 liters per capita per day, when the water source is within a 30-minute travel time to the users. WHO determined the amount of water needed for laundry and other hygiene needs to be about 20 liters per capita per day for basic access to water (5-30 minute walk) (Bartram and Howard, 2003).

At these given consumptions, the average person would use about 39.2 liters per day. Assuming there will be other uses of water, the World Health Organization recommends a water use of 50 liters per capita per day (Davis, 2014). The clients suggested there are about 2,500 people that use the well. The pump needs to have a flow rate of 0.00661 m³/s (104.7 gpm) when it is running in order to supply the necessary water for the people in the village, assuming the pump runs 5.25 hours each day (worst-case value for solar hours, when the pump could run directly from the PV array).

\[
2,500 \text{ people} \times 50 \frac{\text{Liters}}{\text{person} \times \text{day}} = 125,000 \text{ L/day}
\]

\[
125,000 \frac{\text{Liters}}{\text{day}} \times \frac{1 \text{ day}}{5.25 \text{ hours}} \times \frac{1 \text{ hour}}{3,600 \text{ s}} \times \frac{1 \text{ m}^3}{1000 \text{ L}} = 0.00661 \text{ m}^3/\text{s}
\]

Groundwater depth can be estimated to be 40-80 meters below the land surface for the area of Guatemala (Figure 11, Fan et al., 2013).
The chosen (example) pump (1.5 HP) is rated to operate at 22 gallons per minute (Water Pumps Direct, 2019). Obviously, this isn’t a high enough flow rate, but working with pumps any larger than 1.5-2 HP generally requires more specific expertise. A hydraulic analysis using the pump’s pump curve was performed (see Appendix D). From that analysis, I confirmed my initial assumption that the pump would not provide the necessary flow, because the performance curves do not intersect (Figure 13, Appendix D).

\[
Power = W \times Q \times \rho \times g = 86.3 \text{ m} \times 0.00621 \frac{\text{m}^3}{\text{s}} \times 999.9 \frac{kg}{\text{m}^3} \times 9.8 \frac{m}{s^2} = 5,592 \text{ W}
\]

For the given conditions, power consumed can be estimated to be 5,592 W (7.5 HP) (Henderson et al., 1997). A specific pump selection analysis would be needed and performed by a qualified engineer after visiting the site and acquiring other specific details. The electric load from the pump can be initially estimated using the above calculations.

Adding the well would increase the needed solar panels by 35.2 (Appendix B). Batteries are not necessary for this specific load, because autonomy can be provided by a sufficient water storage tank. The pump will run and pump water into a tank. If there is a rainy day and the pump does not run, the tank could capture the stormwater instead of pumping groundwater. The tank
should have a large enough storage capacity to meet minimal water demands if there are multiple cloudy days in a row (when the pump does not run).

Since this addition is more expensive and will take more specific designs to implement, the villagers could start by adding some devices to capture stormwater. Rain barrels and gutters are effective ways to capture relatively clean stormwater. If the first phase of the proposed micro-grid is implemented, the design should provide for the future expansion for the water system pump.

**Summary of Loads.** The total electric load for the community center was estimated to be 5,800 Wh per day (Table 1, Figure 12). The breakdown of panels and batteries required for specific electrical loads can be found in the following sections. By listing these separately, the community and fund-raising can have flexibility in choosing to implement a partial or full system.

**Table 1. Total Electric Loads for System**

<table>
<thead>
<tr>
<th>Type</th>
<th>W</th>
<th>No.</th>
<th>Use (h/d)</th>
<th>Use (d/wk)</th>
<th>Wh/week</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Library Lights</td>
<td>13</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>2275</td>
<td>LED bulbs</td>
</tr>
<tr>
<td>Computer</td>
<td>19</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>3325</td>
<td>Laptop</td>
</tr>
<tr>
<td>Printer</td>
<td>50</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>Cell phone</td>
<td>12</td>
<td>50</td>
<td>1</td>
<td>7</td>
<td>4200</td>
<td></td>
</tr>
<tr>
<td>Library fan</td>
<td>35</td>
<td>1</td>
<td>6</td>
<td>7</td>
<td>1470</td>
<td></td>
</tr>
<tr>
<td>Kitchen Lights</td>
<td>13</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>2730</td>
<td>LED bulbs</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>66.2</td>
<td>1</td>
<td>24</td>
<td>7</td>
<td>11122</td>
<td></td>
</tr>
<tr>
<td>Kitchen Fan</td>
<td>35</td>
<td>1</td>
<td>6</td>
<td>7</td>
<td>1470</td>
<td></td>
</tr>
<tr>
<td>Lights</td>
<td>13</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>1456</td>
<td>LED bulbs</td>
</tr>
<tr>
<td>Clinic Fan</td>
<td>35</td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>980</td>
<td></td>
</tr>
<tr>
<td>Outdoor Lights</td>
<td>11</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>1456</td>
<td>String Lights</td>
</tr>
<tr>
<td>Stadium Lights</td>
<td>200</td>
<td>16</td>
<td>3</td>
<td>1</td>
<td>9600</td>
<td>Mounted LED lights</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>40434</th>
<th>Total, Wh/week</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5776</td>
<td>Wh/day (AC)</td>
</tr>
</tbody>
</table>
Array and Battery Sizing

Based upon the load calculations and the performance of the chosen PV panels and batteries, the entire photovoltaic system can be operated on 7 panels and 8 batteries (Table 2).
Table 2. Number of PV panels and batteries needed for each component of the system.

<table>
<thead>
<tr>
<th>Type</th>
<th># Panels Needed</th>
<th># Batteries needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Library Lights</td>
<td>0.39</td>
<td>0.46</td>
</tr>
<tr>
<td>Computer</td>
<td>0.57</td>
<td>0.67</td>
</tr>
<tr>
<td>Printer</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>Cell phone</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td>Library fan</td>
<td>0.25</td>
<td>0.29</td>
</tr>
<tr>
<td>Kitchen Lights</td>
<td>0.47</td>
<td>0.55</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>1.91</td>
<td>2.22</td>
</tr>
<tr>
<td>Kitchen fan</td>
<td>0.25</td>
<td>0.29</td>
</tr>
<tr>
<td>Lights</td>
<td>0.25</td>
<td>0.29</td>
</tr>
<tr>
<td>Clinic fan</td>
<td>0.17</td>
<td>0.20</td>
</tr>
<tr>
<td>Outdoor Lights</td>
<td>0.25</td>
<td>0.29</td>
</tr>
<tr>
<td>Stadium Lights</td>
<td>1.65</td>
<td>1.92</td>
</tr>
<tr>
<td>Total:</td>
<td>6.36</td>
<td>7.41</td>
</tr>
</tbody>
</table>

(7) (8)

Economic Analysis

The economic analysis of this project will focus on estimating capital costs for the main components of the system. Since the projects would be funded through donations, fundraising, and grants it is important that the initial capital costs be estimated accurately. The solar panels chosen were estimated at $227 per panel. Other panels this size can range from $300-$400. Other solar components include a pre-wired power center, mounts for the panels, and cables and wiring necessary for operation. These components can be estimated to be around $6,000 (Wholesale Solar, 2019). The initial capital cost for power supplies and devices consuming electricity is estimated to be $27,300 (Table 3). This is significantly over the initial budget, but it includes supplies for powering the water well, which was already designated as a second phase of the project.
### Table 3. Breakdown of Costs for the System Components.

<table>
<thead>
<tr>
<th>Item</th>
<th>Model #</th>
<th>Qty.</th>
<th>Cost Ea. ($)</th>
<th>Sub-Total Cost ($)</th>
<th>Retailer</th>
<th>Website</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter</td>
<td>Proline 10,000 W Inverter</td>
<td>1</td>
<td>$1,015</td>
<td>$1,015</td>
<td>Camping World</td>
<td><a href="http://www.campingworld.com">www.campingworld.com</a></td>
</tr>
<tr>
<td>Panels</td>
<td>MC4 CS3K-315MS</td>
<td>9</td>
<td>$227</td>
<td>$2,043</td>
<td>Wholesale Solar</td>
<td><a href="http://www.wholesalesolar.com">www.wholesalesolar.com</a></td>
</tr>
<tr>
<td>Misc. Panel Components</td>
<td>(cables, circuit breaker box, disconnect, etc.)</td>
<td>1</td>
<td>$6,000</td>
<td>$6,000</td>
<td>Wholesale Solar</td>
<td><a href="http://www.wholesalesolar.com">www.wholesalesolar.com</a></td>
</tr>
<tr>
<td>Batteries</td>
<td>CR-350</td>
<td>10</td>
<td>$249</td>
<td>$2,490</td>
<td>Battery Guys</td>
<td><a href="http://www.batteryguys.com">www.batteryguys.com</a></td>
</tr>
<tr>
<td>Laptops</td>
<td>Intel Celeron N4000</td>
<td>5</td>
<td>$150</td>
<td>$750</td>
<td>Walmart</td>
<td><a href="http://www.walmart.com">www.walmart.com</a></td>
</tr>
<tr>
<td>Printer</td>
<td>HP - DeskJet 2680</td>
<td>1</td>
<td>$20</td>
<td>$20</td>
<td>Best Buy</td>
<td><a href="http://www.bestbuy.com">www.bestbuy.com</a></td>
</tr>
<tr>
<td>Ceiling Fan</td>
<td>Hampton Bay Malone 54 in</td>
<td>3</td>
<td>$70</td>
<td>$210</td>
<td>Home Depot</td>
<td><a href="http://www.homedepot.com">www.homedepot.com</a></td>
</tr>
<tr>
<td>Refrigerator</td>
<td>WRB322DMBM</td>
<td>1</td>
<td>$1,600</td>
<td>$1,600</td>
<td>Whirlpool</td>
<td><a href="http://www.whirlpool.com">www.whirlpool.com</a></td>
</tr>
<tr>
<td>Overhead Lights</td>
<td>Philips LED 545921</td>
<td>14</td>
<td>$30</td>
<td>$420</td>
<td>Amazon</td>
<td><a href="http://www.amazon.com">www.amazon.com</a></td>
</tr>
<tr>
<td>Field Lights</td>
<td>AntLux FT-SBS200W57K</td>
<td>16</td>
<td>$159</td>
<td>$2,544</td>
<td>Amazon</td>
<td><a href="http://www.amazon.com">www.amazon.com</a></td>
</tr>
<tr>
<td>Well Pump</td>
<td>AMT Heavy Duty Straight Centrifugal Pump</td>
<td>1</td>
<td>$1,119</td>
<td>$1,119.00</td>
<td>Absolute Water Pumps</td>
<td><a href="http://www.absolutewaterpumps.com">www.absolutewaterpumps.com</a></td>
</tr>
<tr>
<td>Panels for Well</td>
<td>MC4 CS3K-315MS</td>
<td>35</td>
<td>$227</td>
<td>$7,945.00</td>
<td>Wholesale Solar</td>
<td><a href="http://www.wholesalesolar.com">www.wholesalesolar.com</a></td>
</tr>
<tr>
<td>Mounts for Panels</td>
<td>Renogy Adjustable Solar Panel Tilt Mount Brackets</td>
<td>35</td>
<td>$30</td>
<td>$1,050.00</td>
<td>Amazon</td>
<td><a href="http://www.amazon.com">www.amazon.com</a></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>$27,300</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Analysis of Environmental Impacts

The addition of a solar PV micro-grid will provide power for the community using renewable energy with no direct emissions of global warming potential (GWP) gases. There are imbedded emissions associated with the manufacture and transport or PV arrays that should not be ignored. Producing a 1 kW photovoltaic system, consumes 3,700 kWh of energy (Reddaway, 2016). The direct avoided consumption of fossil fuels to provide electric power (2,100 kWh per year) was estimated to be 1.6 tons CO₂ equivalent per year (found by inputting 2,100 kWh into EPA’s Greenhouse Gas Equivalency Calculator) (U.S. EPA, 2019). The embedded energy invested in the system (a one-time consumption) will be overtaken in the second year that the system produces power. It is desirable to provide a growing demand for power in the developing world using renewable energy sources.

The increase in the use of solar energy is still relatively new, and there is still much research being done about the impacts of large photovoltaic arrays. An initial concern could be the amount of shading the panels will provide to the ground below them. This can cause changes to the soil and wind patterns, which could cause micro-climate changes. There is also an idea that solar panels could help the growth process by shading certain crops, which would improve their growth (Armstrong, 2014). Having any crops or plants below the panels has several benefits. This symbiotic relationship between panels and crops is sometimes referred to as “agrivoltaics.” The plants and panels share the land. Plants grow under the shade of the panels and cool the panels, and these shaded plants also require less water. The cooled solar panels can capture more energy from the sun (Research Communications, 2018). The system implementation should consider specifying the planting of native plants below the array.
Social Impacts

The project will have tremendous positive social impacts. It can increase the potential for education in rural areas, increase the health of the population through a clinic, and provide a greater strength of community through having a central place to gather. There are some negative social impacts that should be considered in the design of the community center. Since there won’t be any air conditioning, the buildings will get hot. One way to mitigate the heat-island effect, is through a green-roof. If shipping containers are incorporated into the system, the design should call for ample windows for natural ventilation and natural day-lighting. The addition of overhangs, especially on the south side of structures would help to shade the walls and any window from direct solar heating.

IX. System Overview

Considering the economic, environmental and social impacts, and based on cost and availability of resources, there are a few choices for systems to implement, possibly in phases over some development time period.

- The clients could choose to the only size for basic electrical needs at first. These would include lighting, fans to provide air movement for comfort, a refrigerator, and a cell phone charging station. For the community center to be effective, it needs to provide power for at least these electric loads. The total capital cost for this basic system would be $13,900. This does not include electrical boxes for connections, shutoff, circuit breakers, or the electric cabling and supplies needed to connect the micro-grid. It does not include mounting structures or the cost of the buildings.
If the clients are interested in a little bit larger initial investment, they could go ahead and add the computers and printers. This moderate system would cost $14,700.

- If the clients choose to purchase all necessary components upfront, the complete system would cost $27,300. This complete system would include the non-essential lighting for the soccer field, as well as the PV panels to power the pump for the water well. This cost does not include any construction related costs to the community center or the construction of the water well.

X. Conclusion

The recommendation to the client is to implement a stationary solar array to power the moderate system design. The laptops and printers don’t increase the cost significantly, and the total cost for the moderate system still falls under the budget of $15,000. This cost and design do not specify any specific electrical requirements. The clients should consult with a professional engineer and electrician before implementing any design. These designs don’t specify any structural elements, which would certainly need to be considered when planning for implementation. This initial design does not contain any specifications or design plans for the water well, as that would need to be further designed, seeking consultation from a professional engineer. The clients also need to consider the availability of internet in the area to maximize the usefulness of the computers.

Before implementation, the client should remember to double check all IEEE standards the design is based on, check the starting current of the system and confirm the inverter can handle the peak amount of power being drawn. The flooded lead-acid batteries should have a
vented box and be away from open flames. The devices selected should be energy efficient and should be turned off when they are not in use, so as to be good stewards of the resources. The system needs to be safe to maintain and operate. Most importantly, the clients need to ensure that the solar array (PV panels) have a clear view of the sun, by installing in a clear area or removing trees as necessary.

As an alternative to solar PV, wind energy could potentially be a viable option; however, a site-specific wind study would need to be commissioned.

The final system design should be approved by a professional engineer and installation should be supervised by a qualified electrician.
References


Camping World. (2019). Proline 10,000W Inverter + Remote. Retrieved November 17, 2019, from https://www.campingworld.com/proline-10000w-inverter-remote-110978.html?gclid=EAIaIQobChMI7f7f7F_PLy5QIVQP7jBx3pdAmNEAQYBCABEgIm-vD_BwE


Appendix A – Calculations for Watts to PV Panel Ratio

There are several variables to consider when sizing a photovoltaic array with batteries (Figure 13, 14).

---

**Figure 13 Flow chart for determining number of batteries needed.**
Most electric loads must be run on alternating current (AC) power sources, but PV panels output direct current. Therefore, the DC power needs to be converted to AC power using an inverter. Based on the AC load of about 10,000 Watts for the designed system, a 10,000-Watt inverter must be used. The peak power needs to double the wattage of the running load, 20,000 Watts in this case. An example inverter can be used to find efficiency. In this case, the maximum efficiency is 90% (Camping World, 2019). Rather than using the proposed total AC load for the calculations, we decided to compute the solar panel requirement for a unit load of 1 Wh/day. Knowing this, then for any component of AC load, we can find out how many panels and batteries are needed by multiplying the AC load by the number of panels and batteries per Wh/d.

\[
    DC \ Load = \frac{AC\ Load}{Efficiency} = \frac{1\ Wh/day}{0.90} = 1.11\ Wh\ per\ day
\]

The tilt angle was assumed to be 14.27° N based on the location of the system design. This location gets 5.25 kWh / m² / day of (worst-case) solar radiation. Using a solar constant of
1.0 kW/m², the area gets 5.25 hours of sun each day. De-rating factors are based on standards 1562-2007 from the Institute of Electrical and Electronics Engineers (Table 6). The A:L ratio can be determined based on the recharge period (RP, d) and period of autonomy (POA, d). These specifications were explored to see their impact on costs (Figure 15). I chose RP = 3 d and POA = 1 d to minimize the cost. I assumed the batteries do not need to be de-rated for cold temperatures because the temperatures in Central America are warm enough not to affect the batteries.

<table>
<thead>
<tr>
<th>Period of Autonomy (POA) (d)</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Panels and Batteries</td>
<td>$4,987</td>
<td>$8,612</td>
<td>$11,219</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recharge Period (d)</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Batteries</td>
<td>$4,987</td>
<td>$8,612</td>
<td>$11,219</td>
</tr>
</tbody>
</table>

Figure 15 Optimization of P.O.A. and recharge period to limit the capital cost.

\[
A:L \text{ Ratio} = \frac{POA}{Days \text{ to Recharge}} + 1 = \frac{1 \text{ day}}{3 \text{ days}} + 1 = 1.3
\]

Table 4. De-rating factors for PV array and batteries

<table>
<thead>
<tr>
<th>Battery</th>
<th>Maximum depth discharge</th>
<th>Design margin</th>
<th>Factor(mult)</th>
<th>System</th>
<th>Factor(sum)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50.0%</td>
<td>90.0%</td>
<td>45.0%</td>
<td>controller/diodes</td>
<td>2.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>coulomb</td>
<td>5.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>wirel loss</td>
<td>2.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mismatch</td>
<td>5.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>module aging</td>
<td>5.0%</td>
</tr>
</tbody>
</table>

Required energy storage in batteries = DC Load * POA = 1.11 \(\frac{Wh}{day}\) * 1 day = 1.11 Wh

PV array power requirement = \(\frac{DC \text{ Load} \times A:L \text{ Ratio}}{1 - \text{System Loss}}\) = \(\frac{1 \text{ Wh} \times 1.3}{1 - 19\%}\) = 1.83 Wh per day

In order to calculate the available energy storage in the batteries, I chose an example battery for the purpose of the calculations. The chosen battery should work well in conjunction with the chosen solar panels to minimize wasted energy.
Available storage in batteries = Capacity \times Nominal voltage \times Derating factor

Available storage in batteries = 305 \text{Ah} \times 6 \text{V} \times 45\% = 823.5 \text{Wh per battery}

In order to calculate the available power from the solar panels, choose an example panel. The chosen panel has a capacity of 9.52 A, a maximum voltage of 33.1 V, and a nominal voltage of 30 V based on the chosen batteries (Wholesale Solar, 2019).

Available power from panels = capacity \times voltage \times hours of sun

Available power from panels = 9.52 A \times 30 V \times 5.05 \frac{hours}{day} = 1,499.4 \frac{Wh}{day} per panel

Then, the ratio of AC power to batteries and panels can be determined.

Batteries needed = \frac{required energy storage}{available storage in batteries} \times P.O.A.

Batteries needed = \frac{1.11 \text{Wh/d}}{823.5 \text{Wh per battery}} \times 1 \text{ day} = \textbf{0.0014 batteries for 1 Wh (AC)}

Panels needed = \frac{PV array power requirement}{Available power from panels}

Panels needed = \frac{1.83 \text{Wh per day}}{1,499.4 \text{Wh per day per panel}} = \textbf{0.0012 panels for 1 Wh per day (AC)}
Appendix B – PV Panel and Battery Requirements for Each Area

A. Library Area

Table 5. Electric loads for library

<table>
<thead>
<tr>
<th>Type</th>
<th>W</th>
<th>No.</th>
<th>Use (h/d)</th>
<th>Use (d/wk)</th>
<th>Wh/week</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Library Lights</td>
<td>13</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>2275</td>
<td>LED bulbs</td>
</tr>
<tr>
<td>Computer</td>
<td>19</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>3325</td>
<td>Laptop</td>
</tr>
<tr>
<td>Printer</td>
<td>50</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>Cell phone</td>
<td>12</td>
<td>50</td>
<td>1</td>
<td>7</td>
<td>4200</td>
<td></td>
</tr>
<tr>
<td>Library fan</td>
<td>35</td>
<td>1</td>
<td>6</td>
<td>7</td>
<td>1470</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11620</td>
<td>Total, Wh/week</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1660</td>
<td>Wh/day (AC)</td>
</tr>
</tbody>
</table>

Load for library area = 1,660 Wh per day (AC)

\[
\text{Panels required} = \text{Load} \times 0.0012 \text{ panels per Wh per day (AC)} \quad \text{(Appendix A)}
\]

\[
\text{Panels required} = 1,660 \text{ Wh per day AC} \times 0.0012 \frac{\text{panels}}{\text{Wh per day (AC)}} = 2.0 \text{ panels}
\]

\[
\text{Batteries required} = \text{Load} \times 0.0023 \text{ batteries per Wh (AC)} \quad \text{(Appendix A)}
\]

\[
\text{Batteries required} = 1,660 \text{ Wh per day AC} \times 0.0014 \frac{\text{batteries}}{\text{Wh}} = 2.3 \text{ batteries}
\]

B. Clinic

Table 6. Electric Loads for Medical Clinic

<table>
<thead>
<tr>
<th>Type</th>
<th>W</th>
<th>No.</th>
<th>Use (h/d)</th>
<th>Use (d/wk)</th>
<th>Wh/week</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lights</td>
<td>13</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>1456</td>
<td>LED bulbs</td>
</tr>
<tr>
<td>Fan</td>
<td>35</td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>980</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2436</td>
<td>Total, Wh/week</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>348</td>
<td>Wh per day (AC)</td>
</tr>
</tbody>
</table>

Load for clinic = 488 Wh per day (AC)

\[
\text{Panels required} = 348 \text{ Wh per day AC} \times 0.0012 \frac{\text{panels}}{\text{Wh per day (AC)}} = 0.42 \text{ panels}
\]

\[
\text{Batteries required} = 348 \text{ Wh per day AC} \times 0.0014 \frac{\text{batteries}}{\text{Wh}} = 0.49 \text{ batteries}
\]
Kitchen

Table 7. Electric Loads for Kitchen

<table>
<thead>
<tr>
<th>Type</th>
<th>W</th>
<th>No.</th>
<th>Use (h/d)</th>
<th>Use (d/wk)</th>
<th>Wh/week</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lights</td>
<td>13</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>2730</td>
<td>LED bulbs</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>66.2</td>
<td>1</td>
<td>24</td>
<td>7</td>
<td>11122</td>
<td></td>
</tr>
<tr>
<td>Fan</td>
<td>35</td>
<td>1</td>
<td>6</td>
<td>7</td>
<td>1470</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15322</td>
<td>Total, Wh/week</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2189</td>
<td>Wh per day (AC)</td>
</tr>
</tbody>
</table>

Load for kitchen = 2,399 Wh per day (AC)

Panels required = 2,189 Wh per day AC * 0.0012 \( \frac{\text{panels}}{\text{Wh per day (AC)}} \) = 2.6 panels

Batteries required = 2,189 Wh per day AC * 0.0014 \( \frac{\text{batteries}}{\text{Wh}} \) = 3.1 batteries

C. Outdoor courtyard

Electric Loads for Outdoor Courtyard

<table>
<thead>
<tr>
<th>Type</th>
<th>W</th>
<th>No.</th>
<th>Use (h/d)</th>
<th>Use (d/wk)</th>
<th>Wh/week</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor Lights</td>
<td>11</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>1232</td>
<td>Mounted LED lights</td>
</tr>
<tr>
<td>Stadium Lights</td>
<td>200</td>
<td>16</td>
<td>3</td>
<td>1</td>
<td>9600</td>
<td>Total, Wh/week</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10832</td>
<td>Wh per day (AC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1547</td>
<td></td>
</tr>
</tbody>
</table>

Load for outdoor corridor = 1,547 Wh per day (AC)

Panels required = 1,547 Wh per day AC * 0.0012 \( \frac{\text{panels}}{\text{Wh per day (AC)}} \) = 1.9 panels

Batteries required = 1,547 Wh per day AC * 0.0014 \( \frac{\text{batteries}}{\text{Wh}} \) = 2.2 batteries

D. Addition of water well

Table 8. Electric Loads for Water Well Addition

<table>
<thead>
<tr>
<th>Type</th>
<th>W</th>
<th>No.</th>
<th>Use (h/d)</th>
<th>Use (d/wk)</th>
<th>Wh/week</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well</td>
<td>5,592</td>
<td>1</td>
<td>5.25</td>
<td>7</td>
<td>205,506</td>
<td>Little Giant Pump</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>205,506</td>
<td>Total, Wh/week</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>29,358</td>
<td>Wh per day (AC)</td>
</tr>
</tbody>
</table>

Load for water well = 29,358 Wh per day (AC)

Panels required = 26,846 Wh per day AC * 0.0012 \( \frac{\text{panels}}{\text{Wh per day (AC)}} \) = 35.2 panels
Appendix C – Lighting Requirements for Each Area

A. The 100 ft$^2$ clinic requires 4460 lumens to be well-lit. Each LED bulb can provide approximately 800 lumens (Amazon, 2019).

\[
Bulbs \ required = \frac{4,460 \ Lumens}{1350 \ Lumens \ per \ bulb} = 3.3 \ bulbs
\]

Round 3.3 bulbs up to 4 bulbs. Assume the lights will be on for a maximum time of 4 hours a day, 7 days a week.

B. The 300 ft$^2$ kitchen requires 6690 lumens to be well-lit (Charleston Lights, n.d.-b). Each LED bulb can provide approximately 800 lumens (Amazon, 2019).

\[
Bulbs \ required = \frac{6,690 \ Lumens}{1350 \ Lumens \ per \ bulb} = 4.96 \ bulbs
\]

Round 4.96 bulbs up to 5 bulbs. Assume the lights will be on for a maximum time of 6 hours a day, 7 days a week.

C. Reduce standard stadium lighting requirement form 750 Lux to 300 Lux, for practice or recreational use. A standard 6v6 men’s soccer field is 15,000 ft$^2$ (1394 m$^2$) (Small Goal Soccer, 2019).

\[
Lumens \ required = 300 \ (Lux) \times 1,394 \ m^2 = 418,200 \ Lumens
\]

A 200-Watt, mounted parking lot light can provide 26,000 Lumens per light (Amazon, n.d.).

\[
Lights \ required = \frac{418,200 \ Lumens}{26,000 \ Lumens \ per \ light} = 16.1 \ lights
\]

16.1 lights distributed evenly around the outer edge of the field and pointed toward the center should provide enough light for practice or recreational games.
Appendix D – System Performance Curve Calculations

Calculations performed using process from derived equations (Henderson et al., 1997). The required flow is 0.00661 m³/s (125 m³/day). Estimate velocity of 2 m/s for initial calculations.

\[
\text{Area} = \frac{Q}{V} = \frac{0.00661 \text{ m}^3/\text{s}}{2 \text{ m/s}} = 0.003 \text{ m}^2
\]

\[
\text{Area of circular pipe} = \frac{\pi D^2}{4}
\]

\[
D = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4 \times 0.003 \text{ m}^2}{\pi}} = 0.062 \text{ m} = 62 \text{ mm}
\]

Size up to the next standard pipe size, which is a 2.5-inch (62 mm) pipe. Assuming schedule 40 PVC pipe, the measured inside diameter of a pipe this size is 2.445 inches (0.0621 m). Calculate area based on standard pipe inside diameter.

\[
\text{Area of circular pipe} = \frac{\pi D^2}{4} = \frac{\pi \times (0.0621 \text{ m})^2}{4} = 0.00303 \text{ m}^2
\]

Calculate velocity based on area of pipe and required flow rate.

\[
\text{Velocity} = \frac{Q}{A} = \frac{0.00661 \text{ m}^3/\text{s}}{0.00303 \text{ m}^2} = 2.18 \frac{\text{m}}{\text{s}}
\]

Using Bernoulli’s equation in the form:

\[
\text{Work} = (z_2 - z_1) + \frac{(P_2 - P_1)}{\gamma} + \frac{(v_2^2 - v_1^2)}{2g} + F_{1-2}
\]

Ignore the pressure terms, because, for a worst-case scenario, there won’t be a pressure change that is unrelated to the change in elevation. Assume the change in elevation is 80 meters, as that is the worst-case value for depth to groundwater. Assume that the initial velocity will be 0 m/s, because the water will be still (Table 7). Calculate the friction losses/pressure drop.

| Table 6. Bernoulli’s Inputs for one point on system curve |
|-----------------|-----------------|-----------------|
| \( z_1 \) (m)  | 0               | \( z_2 \) (m)  | 80               |
| \( P_1 \) (kPa) | 0               | \( P_2 \) (kPa) | 0                |
| \( v_1 \) (m/s) | 0               | \( v_2 \) (m/s) | 2.18             |
Pressure drop is calculated using the equation:

\[ F_{1-2} = f * \frac{L}{D} * \frac{v^2}{2g} + k * \frac{v^2}{2g} \]

Friction factor can be calculated using the Colebrook equation:

\[ f = \left( \frac{1}{\log_{10} \left( \frac{\varepsilon}{3.7D_h} \right) + \left( \frac{2.51}{Re \cdot f^{0.5}} \right)^2} \right)^2 \]

Since it is an iterative equation, use the Altshul-Tsal equation to find an initial estimate:

\[ f' = 0.11 \left( \frac{\varepsilon}{D_h} + \left( \frac{68}{Re} \right) \right)^{0.25} \]

Surface roughness for schedule 40 PVC pipe is 0.0015 mm. Reynolds number is 18,331, calculated using the equation:

\[ Re = \frac{V * D}{u} = \frac{2.18 \frac{m}{s} * 0.0621 m}{0.00000152 \frac{m^2}{s}} = 89,164 \]

Assuming the pipe is full, for a circular pipe:

\[ D_h = \frac{D}{4} = \frac{0.0621}{4} = 0.0155 m \]

Then,

\[ f' = 0.11 \left( \frac{0.0000015 m}{0.0155m} \right) + \left( \frac{68}{22347} \right)^{0.25} = 0.0188 \]

Use this as an initial estimate of “f” in first iteration of the Colebrook equation:

\[ f = \left( \frac{1}{\log_{10} \left( \frac{0.0000015}{3.7 \times 0.0155m} \right) + \left( \frac{2.51}{22347 \times 0.0188^{0.5}} \right)^2} \right)^2 = 0.0189 \]
Use the value from the first iteration as the next estimate for “f” in the Colebrook equation, and if the values are similar, then no further iterations are required.

\[
f = \left( \frac{1}{4 \log_{10} \left( \frac{\frac{0.0000015}{3.7 \times 0.0155}}{\frac{2.51}{22347 \times 0.0189^{0.5}}} \right)^2 \right) = 0.0189
\]

Now, the pressure drop can be calculated using \( f = 0.0189 \), assume \( L = 80 \) m, use a k-value of 0.57 for a standard 90-degree elbow for a 2.5-inch pipe.

\[
F_{1-2} = f \frac{L}{D} \frac{v^2}{2g} + k \frac{v^2}{2g} = 0.0189 \times \frac{80 \text{ m}}{0.0525 \text{ m}} \times \frac{(2.18 \frac{\text{m}}{\text{s}})^2}{2 \times 9.8 \frac{\text{m}}{\text{s}^2}} + 0.57 \frac{(2.18 \frac{\text{m}}{\text{s}})^2}{2 \times 9.8 \frac{\text{m}}{\text{s}^2}} = 6.05 \text{ m}
\]

Total work for the system can be calculated using Bernoulli’s equation:

\[
Work = (80 \text{ m} - 0 \text{ m}) + \frac{(2.18 \frac{\text{m}}{\text{s}})^2 - (0 \frac{\text{m}}{\text{s}})^2}{2 \times 9.8 \frac{\text{m}}{\text{s}^2}} + 6.05 \text{ m} = 86.29 \text{ m}
\]

Repeat the process to determine two other points to create a system curve (Figure 13).

*Figure 16. System performance and pump performance*