Optimization of a Solar-hybrid System

for the Village of El Rescate, El Salvador

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***Abstract*—While access to electricity in El Salvador is high, about 93% according to the World Bank, there are still many communities without access to power. Typically, these communities are made up of poor, small villages in remote areas. Because they're difficult to access and because the populations are not sizeable, power providers and the government are slow or unwilling to bring power to them.**

This paper explores the design process for a hybrid solar-diesel central power system for a remote village in El Salvador. El Rescate is a small village in Usulután, El Salvador with a population of 56 people living in 17 homes. It's located approximately at 13.5 degrees north and 88.5 degrees west. The design aims to meet the daily load with a central solar power plant most of the time with a battery bank to get through the nighttime hours as well as rainy and cloudy days. A generator will be considered for providing backup power during extended periods of low sun. The amount of time the generator is run will be minimized to reduce fuel costs and pollution. Three different distribution system configurations will be examined to find the most economical option.

The lowest cost design was composed of a central solar plant with no generator and one islanded home with all DC appliances. This design yielded a cost of $0.86/kWh over the 20-year life span of the system. Compare this with the cost of using a generator alone at $2.44/kWh for the same system setup. As solar panel technology advances and becomes more affordable, and as fossil fuels become more scarce and expensive, the best solutions for powering remote locations will include solar power and only solar power.

Keywords—off-grid; hybrid; solar; photovoltaic; energy; microgrid; El Salvador

I. INTRODUCTION

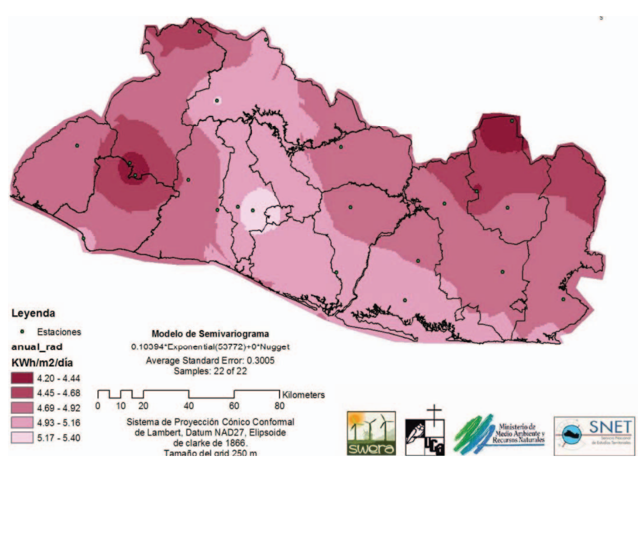
El Salvador is a small country in Central America located at approximately 13° 50’ N latitude, 88° 55’ W longitude. It's densely populated with an area slightly smaller than the state of Massachusetts and a population of about 6 million people. Overall, 93.7% of the population has access to electricity [1], with access at 98% for urban dwellers [2], and 85.7% for rural areas [3].

The Solar Wind Energy Resource Assessment (SWERA) initiative in collaboration with the Ministry of the Environment and Natural Resources (MARN by its initials in Spanish) and the Universidad Centroamericana “José Simeón Cañas” (UCA) published a report detailing wind and solar potential in El Salvador in 2005 [4]. The report includes a solar irradiation map of El Salvador that can be seen in Fig. 1. It shows that solar irradiation is high in the majority of the country. Most regions have irradiation levels near or above 5 kWh/m2/day [4]. This makes El Salvador an excellent candidate for solar power. In fact, there are several solar installations currently operating. This includes a 90kW installation for the Legislative Assembly building that produces 6% of the building's energy and saves approximately $2000 per month on the electric bill [5].

Despite the fact that El Salvador has a high electrification rate, there are many underserved rural areas which are impoverished and in hard to reach locations. Often the customer base and their income level is too low for power companies to invest in expensive infrastructure projects for these communities. Terrain that is difficult to traverse also adds to the cost of such projects and creates technical challenges. Some of these areas are not accessible by vehicle during the rainy season further complicating things for transportation.

Photovoltaic, or PV, systems provide a feasible alternative for powering underserved, remote communities. With the ever decreasing cost of solar panels and more efficient solar cells, the ability to light up small villages is becoming more viable through solar energy compared to running utility lines. Solar panels have a distinct advantage in that they're relatively light

Fig. 1. Solar irradiation map of El Salvador



and easy to transport when compared to the heavy machinery and equipment needed for grid power.

II. El Rescate Community Background

El Rescate is a small village located in the municipality of Berlin in the department of Usulután in El Salvador. It neighbors the bigger village of San Lorenzo of which it is considered a part. This causes El Rescate to be overlooked by the local government. Help from outside organizations is important to address the village faces.

A. Village Geography

El Rescate is located at approximately 13°27'35"N latitude, 88°32'00"W longitude. It is composed of 17 houses distributed along a main road with a couple of isolated homes located further away from the main village area. The village exists on land that used to be a plantation. Trucks used to regularly travel back and forth between El Rescate and the main town of San Lorenzo to bring down product and bring back supplies. Since the plantation has ceased to operate, the roads are no longer cared for. However, a pick-up truck can still easily access the village during the dry season. The isolated homes are only accessible by foot. The distance from these homes to the center of the village varies between a tenth of a mile and a quarter mile, but the furthest one is ¾ of a mile away through dense vegetation. The entire village spans about a mile.

B. Community Overview

El Rescate's population is 56 as of the last census taken in November 2014. There are 35 adults and 21 children. The majority of the population is literate with the exception of young children and some seniors. There is at least one literate adult in each home with few exceptions. High school is the highest level of education attained in the village.

The community has organized a *directiva*, a small council with an elected president, treasurer, secretary, security chair, and environmental protection chair. There are various spoke persons that speak for the rest of the community when the entire village isn't able to attend meetings. The *directiva* has approached a local charity, *Casa Pastoral*, for help with various issues in the village such as lack of latrines and potable water.

There is no potable water or electricity in the village. There are large tanks made of concrete and metal that were used to store water in the past but they were damaged in a big earthquake in 2001. Most families have a household makeshift water tank, usually a barrel, to collect rainwater for daily use. Many communities in Berlin use water collection tanks with filtration systems. *Casa Pastoral* can help the community acquire water tanks but they lack the ability to provide or advocate for electricity in the village.

C. Village Economy

Understanding the village economy is a critical factor in determining the possible energy consumption levels and in designing an affordable power system.

Paid jobs with regular wages are scarce around El Rescate. Most jobs are seasonal plantation work that pay $48 every 2 weeks. These are only available a couple of months out of the year. There are also "administrator" jobs available but these are even scarcer. Administrators take care of day to day tasks on plantations. They are employed year round and are paid the same $48 every 2 weeks.

All of the inhabitants of El Rescate are subsistence farmers with the exception of one who has a plantation administrator job. Land is measured in *manzanas* in El Salvador. One *manzana* is equivalent to about 0.7 hectares (1.73 acres). The amount of land each family has available to farm on varies from as little as a quarter *manzana* to 1.5 *manzanas*. The crops they grow are mainly maize and beans. The majority of what they grow is used for food the rest is sold to obtain staples like sugar, salt, cooking oil, batteries, candles, etc. Some families own livestock like chickens and ducks. The poultry is used for food sometimes but can also be sold when extra money is needed.

D. Community Interest

In November 2014, a meeting was held with El Rescate's *directiva*. The village's economic conditions and access to water and electricity were discussed. A survey and census of the entire community was also conducted. Interest in electrification was high. There was consensus among the community members that electrification would improve their economic status and their quality of life by allowing adults to continue work and children to study after sunset hours. It would also eliminate the constant need to travel 2 hours by foot to the nearest town to purchase candles. They all felt that having power would allow small businesses to open in the village further improving their economic situation. The community expressed great interest in learning how to service and maintain and build a solar power system. This would be beneficial for an isolated, off-grid PV system that is not easy to access for engineers and technicians.

E. Current Energy Costs

The people of El Rescate use various methods to light their homes at night. Kerosene lamps are very common, but candles and different types of battery-powered lamps are also used. Battery powered lamps can be as rudimentary as a single LED light wired to a scavenged battery pack from another device to commercially sold lamps resembling a lightbulb.

The batteries, candles, and kerosene gas must all be obtained from Berlin, which is two hours away by foot. The price of these commodities is reasonably stable. On average, the people of El Rescate use about 2.7 hours of lighting per day. This comes to an average of $5.30 per month but can range from as little as $1 to as high as $11 per month depending on the home and family size. They are willing to incur $3 to $5 per month for the cost of electric power.

F. Berlin Grid Expansion Plans

The local government is responsible for providing power for all the communities in the town. The power grid has slowly been expanding and power has been brought to a couple more communities over the past years. In November 2014, a meeting was held with the mayor's office. The mayor himself was not present but his council attended. They disclosed that it is one of their goals to expand the reach of the power grid but not to El Rescate.

G. *Existing Solar Power Projects in Berlin*

El Corozal, another small village in the municipality of Berlin, has electricity available through solar panels. These power systems were installed by Intervida, an NGO based out of Barcelona, Spain. The PV systems have been in operation since 2008. Rather than a centralized system with distribution lines, each home gets its own solar panel, battery, and in some cases an inverter. The system consists of a 75 W solar panel from Isofoton, a 120 Ah battery, support structures, wiring, and light bulbs. 400 W inverters were also available but they were not distributed to every family. Each installation costs around $1,000.

A total of 39 systems were installed in El Corozal. After 7 years, a third of the 20-year lifespan, several of the systems were no longer functioning, some of them had a life span of only two years. The most common point of failure is the battery. Batteries fail because of the high temperatures, lack of proper ventilation, placement next to hot stoves, and water damage. In one case, the battery failed after two years because it was placed along the southern wall of a corrugated metal home and next to the home's wood burning stove. The sun heats the metal wall of the home throughout the day creating an oven-like environment where ambient temperatures within the home and next to the southern wall are much higher than the ambient temperature outside the home. While many of El Corozal's villagers received training for maintaining the PV system and for wiring their homes, none of them were instructed to keep the batteries cool and well ventilated or that high temperatures would shorten the lifespan of their batteries.

The initial $1,000 cost of the system is low but it does not include replacement costs for batteries or other components. Replacement batteries cost hundreds of dollars and require a 6-hour round trip to the capital. The cost is out of reach for most villagers and thus PV systems sit wasted once the battery fails.

III. Solar Power System Design

Providing power to El Rescate can be accomplished with a centralized power system comprised of solar panels, batteries, and distribution system. The National Renewable Energy Laboratory (NREL) estimates El Salvador's solar potential to be 65,682,559 MWh/year [6]. This high solar energy potential makes El Rescate an excellent candidate for photovoltaic energy systems.

The objective of the effort presented in this paper is to design a centralized solar power system and provide an economic analysis for it. The aim is to power the village with an array solar panels and a battery bank for storage. Additionally, a backup generator option will be considered to compare solar to diesel costs. The transmission system will encompass the 16 most centralized homes, while the last and most removed home will be powered by a standalone system.

A. *Sun Angle and Insolation Levels*

Solar insolation data is readily available on the internet from various sources including NASA and NREL [7]. The level of insolation a panel may receive depends heavily on the angle at which it's tilted. To determine this angle, we need to look at the sun's path at the desired location on Earth and the insolation data for the various angles being considered.

Gilbert Masters, in Renewable and Efficient Electric Power Systems [8], suggests that the rule of thumb for good year-round performance is to angle the solar panels at the same angle as the latitude where the panels are located. For El Rescate this angle will be 13 degrees. The monthly average insolation levels at this tilt in El Rescate are shown in Table I [7].

B. *Load Analysis*

One of the first steps in any PV system design is analyzing the loads. El Rescate has no power and hence no loads to itemize. However, we can compare it to other villages of similar size and economic status to estimate what the loads in El Rescate will be. We can also look at the size of the homes in El Rescate to estimate the amount of light bulbs that will be needed to illuminate them.

Many people living in and around Berlin live in one room or two room houses made from corrugated metal or bamboo and adobe. Some houses are made of bricks and mortar but they are few and far between. Most houses only have lightbulbs and an outlet to charge a cell phone, which are inexpensive and widely available. Few people have televisions or radios but there are always a couple of families in a typical community that have them. In communities like El Rescate, people typically own 13" black and white televisions because they consume less energy and because they're affordable. Families with more resources often opt for small 20" LCD TVs. The radios that people in Rescate currently own are small hand-radios with 1 W or less output power. Appliances like TVs and slightly higher powered radios will be included in the load analysis to account for the maximum possible peak load and to account for load growth. It is unrealistic to assume that the community will not want to acquire entertainment loads soon after receiving power [9].

Table II shows the total amount of loads in El Rescate for 16 homes in the village. It lists the name of the appliance, the amount of power a single unit of that appliance consumes, the total amount of power all units will consume, the amount of hours per day (h/d) the appliance will be used, and total of

Table I - Avereage Montly Insolation Levels for El Rescate at 13 degree tilt

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Avg.**
Insolation(h/d)	6.34	6.61	6.61	6.19	5.7	5.72	6.22	5.88	5.25	5.57	6.04	6.13	6.02

watt-hour per day the appliance will consume for the 16 homes. The loads for a single home can be seen in Table III.

C. Battery Bank Size

El Rescate has an average annual of peak sun hours of 6 h/d [7]. The Stand-Alone Photovoltaic Systems Handbook of Recommended Design Practices by Sandia National Laboratories suggests a two-day storage battery bank to provide 95% availability for this level of insolation [10]. However, because batteries are very expensive the battery bank will be reduced to 1.5 days of storage. The number of ampere-hours per day the battery needs to deliver is found by dividing the total daily load by the system voltage.

$$\text{Battery Delivery}\left(\text{Ah / d}\right)=\frac{\text{Total kWh / d}}{\text{System Voltage}} \qquad (1)$$

A 48 V system is chosen for the 16 home load to limit current. 48 V will allow DC only appliances to be used, but also limits how far power can be distributed and the sizes of the loads that can be run. The final size of the battery bank depends on the size of the central system as well as the type of battery technology used due to the different depths of discharge (DoD) for different battery technologies. Lead-acid batteries have a DoD of 80%, while lithium-ion and zinc flow batteries can be discharged completely (100%).

Lithium ion batteries are much more expensive than lead-acid and they are not readily available in El Salvador. The bigger depth of discharge does not make up for the difference in price. The same thing can be said of zinc flow batteries. Zinc flow batteries are not available in many markets. Redflow, an Australian company, recently launched battery storage product for households called ZCell [11]. It's a zinc bromine flow battery with 10kWh of storage capacity and a 10 year life. The price point for these batteries is between $17,500 and $19,500. According to Redflow, the 100% discharge rate, the long life, and the greater capacity make their product economically competitive with what's on the market now Redflow indicates solar energy storage as a main use for their battery. However, the cost makes it better for bigger installations. It's not an ideal battery for El Rescate due to the small size of the load. Lead-acid and lithium-ion are a fraction of the cost and that makes lead-acid the best choice for this PV system.

TABLE II – LOADS FOR 16 HOMES

Appliance	Power (W)	Qty	Total W	h/d	Total Wh/d
Lights	10	55	550	4	2200
Cell Phone	5	23	115	3	345
15.6" LED DC TV (Active)	24	16	384	4	1536
15.6" LED DC TV (Standby)	1	16	16	20	320
Radio/Stereo (Active)	10	16	160	3	480
Radio/Stereo (Standby)	1	16	16	21	336
Total	49		1209		5217

TABLE III – LOADS FOR A SINGLE HOME

Appliance	Power (W)	Qty	Total W	h/d	Total Wh/d
Lights	10	3	30	4	120
Cell Phone	5	2	10	3	30
15.6" LED DC TV (Active)	24	1	24	4	96
15.6" LED DC TV (Standby)	1	1	1	20	20
Radio/Stereo (Active)	10	1	10	3	30
Radio/Stereo (Standby)	1	1	1	21	21
Total	49		74		317

The size of the required storage can be calculated with equation (1) and equation (2), shown below.

$$\text{Min Storage}\left(\text{Ah}\right)=\frac{\text{B.D.}\left(\text{Ah / d}\right)\text{ x Days Storage}}{\text{MDOD x Charge Ctrl Efficiency}} \qquad (2)$$

In (2), B.D. is the battery current delivery calculated with (1), MDOD stands for the maximum depth of discharge for the battery being considered. Using 97% for the charge controller efficiency, 48 V for the system voltage an 80% for the depth of discharge, the results are summarized in Table IV below.

Even though the battery banks for each case are different sizes, the most economical choice for a battery is the Koyama NPG-150 lead-acid battery. This battery is readily available from Tecnosol, a PV system supplier in El Salvador, for $129. It has a 150 Ah capacity and a rated lifetime of 10 years, which will be estimated at 5 years for this application due to the hot climate. Two parallel strings of four batteries in series will achieve a capacity of 300 Ah at 48 V, which more than meets the minimum storage found in Table IV.

D. Solar Array Design

The base size of the solar array is determined by the size of the battery bank and the levels of insolation. Also taken into account are typical derating factors that lower the amount of energy produced. Temperature has a big effect on the losses of the system and will be examined separately from other common derating factors because temperature varies by location.

$$Base\,Size\left(W\right)=\frac{B.D.\,\left(Ah/d\right)\times Voltage}{Insolation\left(h/d\right)\times Derate\left(\%\right)} \qquad (3)$$

The base array size can be calculated with (3). We will use the lowest insolation month, September with 5.25 h/d, to design the array. The system voltage is 48 V and the battery current delivery will vary by load size. Calculations will account for a general panel derate factor of 88%, which does not include temperature losses, 97% efficiency for the charge controller, and 80% for the battery round trip. Plugging in the current delivery for each scenario yields a base size of 1455 W for the 16 home load and 88.4 W for the single home load.

TABLE IV – BATTERY CURRENT DELIVERY AND STORAGE

Load Size (homes)	System Voltage	Max Current (A)	Battery delivery (Ah/d)	Minimum Storage (Ah)
16	48	25.19	108.69	210.09
1	12	6.17	26.42	51.06

Before temperature losses can be calculated, a panel needs to be chosen because the effects of high temperatures vary by panel and panel technology. The bigger the temperature loss, the more panels will be required to make up for the loss. Just like lead-acid batteries, silicon solar panels are widely used in solar installations due to their lower prices and wide availability. Thin film technologies are not as pervasive but are better for higher temperatures because the material properties lead to a lower temperature coefficient. Cadmium telluride (CdTe) panels are increasing in popularity and efficiency, and they're decreasing in cost. However, CdTe panels are only available for utility-scale applications. First Solar, a major manufacturer of CdTe panels, tightly controls their distribution due to the high toxicity levels of Cadmium. CdTe panels cannot be considered for this project because they are not available for residential applications. CIGS panels are another type of thin film technology. These panels are available from Stion, a company based out of San Jose, California. Stion produces CIGS panels of several different capacities. Their efficiency isn't very high but they perform well under high temperatures. Taking all this into consideration, a 150 W CIGS panel from Stion give us the best combination of cost and high temperature efficiency for this application.

$$Tcell = Tamb + \left(NOCT - 20°C/0.8\right)S \tag{4}$$

$$P_{max}' = P_{max} \times \left[1 - \left(T.Coeff\,\% \times \left(Tcell - 25°C\right)\right)\right] \tag{5}$$

Use (4) and (5) above to calculate the temperature losses where NOCT stands for nominal operating cell temperature. It is listed in the panel specifications. Tamb is the ambient temperature and S stands for 1 Sun, the nominal sunlight intensity on a clear day. T.Coeff is the temperature coefficient for Pmax. The loss can be calculated by dividing the adjusted Pmax' by the original Pmax. The results from the temperature loss calculations for the Stion 150 W panel yield 13% average monthly loss. The resulting compensatory increase in solar capacity will be 13% to make up for the loss. The number of panels the system will need is simply the array size divided by the panel capacity. It can be multiplied by the cost of the panel to get an overall cost for the entire array.

We can start building the panel strings with the final size of the array. We can use the capacity of the chosen panel to calculate the number of panels we will need to produce the required amount of energy. At 150 W per panel, eleven are enough to meet 1644 W for the 16 homes and just one for 99 W for the single home.

Finally, the layout and structure of the array can be determined. It is desirable to combine as many panels in series as possible while staying below 600 V to minimize the current flow. This will help reduce cost by minimizing wire gauge sizes and will improve system safety. The specifications for the charge controller need to be taken into account too. There are several ways each number of panels can be arranged in a solar array. Too many panels in series will yield too high a voltage capability while too many panels in parallel will yield too high a current capability.

The Midnite Solar Classic 250 charge controller can handle input voltages of up to 250 V. The Stion 150 is rated at 80.8 V for open circuit voltage and 2.72 amps for short circuit current. Three of these panels in series yields an open circuit voltage of 242.4 V, which is marginal. Two panels in series adds up to 161.6 V which is comfortably within spec. Five strings with this panel will output a maximum short circuit current of 13.6 A which is reasonable. We cannot add more than 2 series panels because the output voltage would get too big. A lower current is preferred to save on wiring costs and to facilitate safety as well. Based on these considerations, five strings with the panels distributed evenly among them is the best configuration

IV. Distribution System

A distribution system is required to distribute power throughout the community. The entire length of El Rescate is about a mile but most of the houses are clustered about a quarter mile from what can be said to be the village center. The village center is where the concrete water collection tank is located. There are also some homes and some unused structures. These structures used to be the plantation offices and store room when the plantation still existed. Now one of the rooms is used as a community meeting area, but the rest of it is unused.

Berlin's City Hall and the local power plant, La Geo, recently put together a budget proposal for electrifying El Banquito, another small community in Berlin. It contains an itemized list of all the materials, labor, and associated costs required to install distribution lines for a span of 2300 meters [12]. El Rescate will require 2112 meters of distribution line if all the houses are included in the distribution system. If some of the further away houses are excluded from the distributions system and powered by islanded PV systems then the amount of distribution line required drops dramatically. Excluding house number 17 (upper-right corner in the map below) reduces the distance to 1365 meters. The distribution system plan for El Banquito can be scaled down to meet El Rescate's needs depending on the number of homes we include on the central PV system. Fig. 2 shows the distribution lines and levels represented on a map of the village. Including all the homes, the blue, yellow and red lines, results in a distribution length of 2112 meters. For 16 homes, blue and yellow lines, only 1365 meters of transmission like is required. To connect the 11 closest homes, blue line, approximately 646 meters are needed. The islanded, single home system has a transmission length of 0, of course. The cost of the islanded systems must be weighed against the cost of the transmission system to determine the most economically efficient option.

V. Economic Analysis

The total cost for the PV, battery storage, and distribution system will be outlined in this section. Cost analysis for including a backup generator will also be included. To estimate the cost we will assume that the system will be financed with a 4%, 20-year loan. The expected lifetime of the system is 20 years although PV systems can last longer. Several of the system's components have a shorter life span and will need to be replaced in the life of the system. The inverter life cycle is 10 years. The battery life cycle is rated at 10 years but we will use 5 because of the high ambient temperatures in El Salvador and the short lives of lead-acid batteries.

TABLE V - PV COSTS FOR 16 HOME SYSTEM

Components	Qty	Cost	Total	Product Names
Panels	11	$180.00	$1,980.00	Sto-150
Charge Controller	1	$750.75	$750.75	Midnite Solar Classic 250
Batteries	8	$129.00	$1,032.00	NPG-150
BOS Hardware ($1/w)			$1,644.36	
Conductors		$1,720.00	$1,720.00	
Hardware Total			$7,127.11	
BOS non-hardware (15%)			$1,069.07	
Initial Wholesale			**$8,196.17**	
Battery Replacement cost	3	$1,032.00	$3,096.00	
Lifetime Solar System Cost			**$11,292.17**	
Distribution System Cost			$9,872.43	
Island Systems Cost	1	$1,021.13	$1,021.13	
Solar System Total			**$22,185.73**	

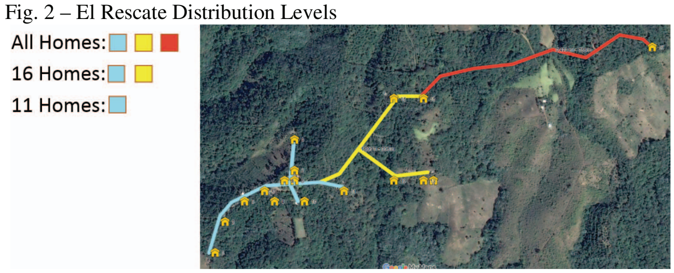
TABLE VI - PV COSTS FOR SINGLE HOME

Components	Qty	Cost	Total	Product Names
Panels	1	$180.00	$180.00	Sto-150
Charge Controller	1	$35.00	$35.00	MorningStar
Batteries	1	$129.00	$129.00	NPG-150
Inverter Charger	0	$749.00	$0.00	AIMS 2kW
BOS Hardware ($1/w)			$99.92	
Conductors		$107.50	$107.50	
Hardware Total			$551.42	
BOS non-hardware (15%)			$82.71	
Initial Wholesale			**$634.13**	
Battery Replacement cost	3	$129.00	$387.00	
Solar System Total			**$1,021.13**	

A. *PV System*

The costs of the various components for the PV system for the 16 home village load are shown in Table V. The costs include the panels, the Midnite Solar charge controller, and the batteries. Balance of system costs are estimated at $1 per watt. This is a rather conservative estimate as a quote for an 825 W PV system from Tecnosol had support structures priced at $52, just $0.06/W [13]. Another quote for a 75 W system combined the cost for the support structure and the cost for installing the entire system at $107.50 or $1.43/W [14]. The price of the conductors is also included in the system cost. Conductor pricing for cabling in each home is taken from [14]. Balance of system non-hardware costs include the labor costs associated with mounting and installing the systems. They are estimated at 15% of the total hardware costs for this system. Again, this might be an over-estimation because of the low cost of labor in El Salvador compared to the United States. Replacement costs for the batteries are included to account for their short lifespans. The total lifetime cost of the PV system on its own comes out to $22,185.73.

Fig. 2 – El Rescate Distribution Levels



The island system cost refers to the cost of a stand-alone system for a single home. Island systems are DC only, use a smaller charge controller, and just one battery and panel. A single NPG-150 battery can supply near three times the amount of minimum storage for a single home. The costs for the PV system for a single home are shown in Table VI.

B. *Distribution System*

El Banquito required a distribution system to cover 2300 meters. El Rescate doesn't require as much. Berlin's city hall and La Geo calculated the budget for El Banquito's project at $17,306.85. The budget takes into account material costs which include posts, cables, transformers, mounting equipment, etc. It also takes into account labor, design costs, and licensing costs. A simple way to estimate the cost of the distribution system for El Rescate is to use the proportion of the two village's lengths to find a scale down factor. In this case the scale factor will depend on the number of houses on the distribution line. The design size is 16 homes so the cost will be $9,872.43. It will cost $15,892.20 to have all 17 homes on the distribution network and it will cost $4,863.98 to only have 11. However, the cost of the islanded systems gets too high if the distribution lines are kept short.

C. *Operation and Maintenance*

Solar power systems can be generally maintenance free with the occasional short lifespan equipment replacement. Occasional inspection of the system is still required to assess the health of the components and fix any malfunctions. Tecnosol offers maintenance service for a cost of $500 per year [15]. The following is included: an inspection visit every 6 months, a status report of the system, simple repairs, training for users, budget estimates for replacements or repairs.

Initially Tecnosol engineers will be required to carry out maintenance, but over time the people of El Rescate can be trained and take over inspections. Engineers will only need to be called in case something needs to be ordered for replacement or if there's an issue that requires more expertise. Intervida carried out a similar strategy in the village or Corazal when its solar power system was installed.

For El Rescate, in the first three years of the system's life, Tecnosol engineers can visit twice a year to conduct maintenance and inspections. A group of people from El Rescate can receive training and training refreshers with each visit. The objective will be to familiarize the trainees with all the different components of the system, basic science and functionality behind them, how to inspect their health, how to conduct simple repairs, and best practices for system maintenance and longevity. After the first three years, engineers can visit once a year for the next two years carrying out the same procedures and training. After the first five years of the system, the village trainees should be able to maintain the system themselves and visits from engineers will be requested on a case by case basis. The cost for the first three years of maintenance services adds up to $1,500 and for years four and five it will be $500. In total, services will cost $2,000.

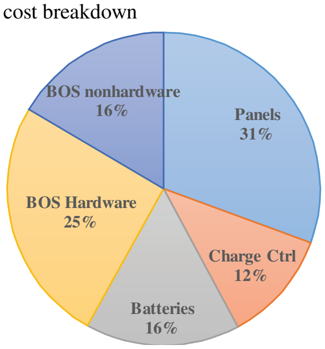
The community can form an energy council with a president/manager, treasurer, secretary, and head technician. The president/manager will ensure the system is running smoothly and can address any questions and concerns from the community. The treasurer will manage a communal fund for system repairs and can collect payments for the community's energy usage. The secretary will assist the other members of the council in preparing reports that assess the health and status of the overall system. The head technician will be the person responsible for carrying minor repairs and assessing the condition of the various system components. Several other technicians can work under the head technician to facilitate and expedite reviewing the entire system. The entire council will be required to attend training when engineers from Tecnosol visit the village. Besides maintaining the system, the energy council will also be responsible for educating the rest of the community members and ensuring that the system is not being abused.

D. *Cost Breakdown*

Fig. 3 shows a cost breakdown pie chart for the cost of the various components that make up the PV system for the 16 home load. The panels make up 31% of the cost of the PV system. Balance of system makes up about 40% of the cost when hardware and non-hardware costs are combined. The distribution lines add considerable cost to the whole project. They account for 44% of the total cost while the PV system accounts for 56%.

A simple way to estimate the cost per kilowatt hour generated by the system is to take the entire cost of the system and imagine taking out a loan on it. This is the same method used by Masters [8]. The annual payments required on this "loan" can be divided by the energy generated in a year to determine the $/kWh value. The annual payments can be calculated with the following equation:

Fig. 3 – Component cost breakdown



$$A = P \times CRF\left(i,n\right) \quad (6)$$

P is the principal which is the amount borrowed. In our case that's the total cost of the system. The CRF, capital recovery factor, is a function of the interest rate, i, and the period, n, measured in years, over which the loan will be paid back. The CRF values for various periods and rates can be found in a table in [8]. This system has lifetime of 20 years. This is the period that will be used in the CRF along 4% as an interest rate to help calculate the system cost.

$$\$/kWh = \frac{P \times CRF\left(i,n\right)}{Energy\,Generated\left(kWh/d\right) \times 365\,d/y} \quad (7)$$

We can use the equation above to calculate the cost of the energy produced by the PV system. Each of the $/kWh rates will be calculated using the respective system costs as the principal, P, in the equation. The results is $0.86/kWh for the 16 home system and $0.65/kWh for the single home system.

Including a generator in the design will dramatically increase costs. In addition to the cost of the generator, the fuel, and other components like a charger/inverter, the costs of maintenance like tune ups and overhauls have to be taken into account. The longer a generator runs, the more maintenance and fuel it will require. Even when the use of the generator is limited to providing only 10% of the yearly load, the price of energy increases to $1.10/kWh. It is much more economical to omit the generator and rely solely on solar power and battery storage.

E. *Business Plan Possibilities*

The people of El Rescate are subsistence farmers, whatever crops they can spare are sold in Berlin. The price of grains fluctuates throughout the year and from year to year. Their sale value is not very high when the effort to grow them is taken into account. There is also risk due to unpredictable weather. If a more profitable and stable product can be used in place of grains then the village economy can have a chance to grow.

Many people in the village already keep chickens to eat or to sell in a pinch. The amount of chickens that can be raised is limited without an artificial incubation method. With power, artificial incubation can be achieved with just a couple of light bulbs. This can facilitate the mass production of chickens. Chickens can be used to lay eggs and/or sold. The money saved from not having to buy kerosene gas, candles, and batteries can be fed into a chicken growing business. The grains that were being sold to buy these things can be used as feed. Eventually, with enough chickens, the village will be able to reliably sell two products: chickens and eggs. Profits can be used to invest in other ventures.

Chickens sell on average for about $5 and can be sold for $3 more during Christmas. Depending on the chicken breed and method used to raise them, it can take anywhere from as little as 2 months to as much as 6 months for chickens to be ready to be used for meat. A single 60 W incandescent light bulb can provide enough heat to raise about 25 chicks [16]. In cooler climates, it's necessary to keep the heating bulb on all day. In El Salvador, temperatures can get very high during the day so a heating element may not be required to be on 24/7

[17]. If it is, it will require 1440 Wh/d. That's 26% of the maximum load for the village. A better solution to keeping chicks warm is a radiant heater like the EcoGlow 20 Chick Brooder that consumes up to 18 W. Having it on all the time requires only 432 Wh/d. Brooding, the act of keeping chicks warm, is only required when chicks are young and lack real feathers. Chickens usually have all their feathers in by the time they're five weeks old [17]. Adding a single EcoGlow to the loads increases the cost of the PV system by about $364 over its lifetime. However, more energy is produced and the cost per kilowatt-hour for the full DC system drops from $0.86/kWh to $0.80/kWh. The total spent on energy per chicken in a group of 20 comes out to about $0.61. Assuming that 20 chickens are raised every 6 months, the first group of chickens can sell for $5 in the summer and the second group can sell around the holidays for $8. This will amount to $247.90 in profit in a year. It will take 1.5 years to cover the additional cost the EcoGlow adds to the system.

VI. Conclusion

The least expensive design will yield a cost of $0.86/kWh over the 20-year life span of the system. If the system is well maintained, it may last even longer. The cost is high compared to grid power but there are other factors to consider. The difficulty in bringing grid power to El Rescate is great and this will contribute to the cost of installing power lines. These costs may be passed on to the consumers. Power companies normally charge customers for utility pole installations outside their homes and for the right to run cables from the pole to the house. Grid power can also be unstable. It is not unusual for power to go out during strong storms even in the bigger cities. Some villagers in Berlin with grid power report that it may go out for days during a storm. It is difficult for the power company to get engineers and equipment to remote areas to fix issues.

A centralized solar energy generation system requires a distribution system. In this case, the cost for the distribution lines was 44% of the total. Eliminating the need for distribution can significantly lower the overall cost, however, certain advantages will also be lost. Centralized systems are easier to regulate and maintain, and harder to abuse. With standalone systems, people can caused overloads with power hungry appliances. In El Corozal, DC to AC inverters were not included in their setups for this reason. Also, the batteries can be removed from the system and used in ways they were not designed for shortening the lifespan. Improper use and maintenance can increase the cost of a standalone system in unexpected ways. A bad battery renders a PV system useless and irreparable for families with limited means. Communities can come together to fund repairs but with standalone systems, a couple of bad apples can cripple the communal maintenance funds. Centralized systems, however, can still fall victims to the same problems. A strict supervisory structure has to be created and adhered to for the system to have a long, useful life.

A deep understanding of El Rescate's population, economy, and interest is key to a successful project of any kind [18]. Direct involvement by the community in planning, installing, and maintaining the PV system will maximize the possibility of long-term success. Without this, efforts like these become charity cases that assume that communities cannot help themselves and projects are likely to fail quickly, living out only a small fraction of their intended lifecycle [19]. El Rescate understands this and is willing to learn, cooperate, and invest. PV systems can provide more than just lighting for motivated communities, they also have the potential to illuminate a path out of poverty.

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