University
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Solar Energy System Design for the Electrification of the Former Bennett Freeze Area

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1. Executive Summary

The families that reside the Former Bennett Freeze Area have been living in substandard conditions for approximately four decades. In 1966 the Bureau of Indian Affairs Commissioner, Robert Bennett, put a ban on development until an agreement between the Hopi and Navajo tribes could be reached. The two tribes were involved in a land dispute, and the area in question became known as the Bennett Freeze Area. Due to ongoing legal battles the freeze was not officially lifted until 2009 (Donovan, 2009). During those 43 years tribal members could not build or repair roads, install electrical transmission lines, install piped water or open a business. This area encompasses approximately 1.5 million square acres of the Navajo Nation and is home to more than 20,000 people.

There are many impacts of the freeze, all of them detrimental to people living in the area. Poor resident health is of great concern, with many residents suffering from respiratory problems, cancer and other conditions. Another impact is the deterioration of homes, businesses and other structures. Without the ability to repair buildings for over four decades, many homes have been abandoned, or made uninhabitable from weather related events.

The worst impact of the freeze is the extreme poverty that has resulted. With no economic development allowed to take place, the area has become the poorest in the Navajo Nation by a large margin. The average monthly income per resident is $734.52, which is extremely low when compared to $2,296.00, the average monthly income of a U.S. citizen. The amount of money spent on energy services per household is high in comparison to other U.S. homes. Bennett Freeze area residents can spend up to $910.00 a month on fuel and batteries, while other U.S. residents pay a fraction of that for electricity and heat.

Despite the grim situation, there are some very practical solutions to these problems. Utilities cannot justify the cost of installing transmission lines through the area since the population is so diffuse and lacks the means to pay for electricity. Fortunately the area has an excellent solar resource; an average of 5.0-7.0 kWh/m^2 reaches the earth each day. Electricity generated from solar photovoltaic technology has the potential to greatly improve the lifestyle of those affected by the freeze. Relatively small solar PV systems could be installed on individual homes to run appliances such as refrigerators, radios, and stoves.

Residents could also use these technologies to pull themselves out of poverty and spur economic development in the area. Residents could open small businesses that install these systems, and the result would be higher incomes and an increase in education as community members developed specialized skills. This paper discusses the needs of the community based on survey data and provides policy and technical solutions to the problems caused by the Bennett Freeze.

2. Introduction

In 1966 Robert Bennett, former commissioner of the Bureau of Indian Affairs, enacted a ban on development that would destroy lives for decades to come. The ban was put in place until a land dispute between the Hopi and Navajo tribes could be settled. This ban outlawed any type of development including repairing roofs and installing electricity and running water. Over the last four decades the land has been dubbed "The Bennett Freeze Area", and encompasses 1.5 million acres of the Navajo Nation. It wasn't until 43 years after enactment that the ban was lifted by President Obama. On April 21, 2009, congress officially repealed the language that created the freeze (Anonymous, 2010). Joe Shirley, former president of the Navajo Nation, stated that the Navajo Nation immediately began to address the situation, but four years later living conditions are still substandard. The Former Bennett Freeze Area Task Force was established to develop a plan for the reconstruction and recovery of the region, yet reconstruction efforts are currently being led by non-governmental organizations (NGOs) who work in the area (Anonymous, 2010).

Close to 20,000 people currently live in the former Bennett Freeze area and the majority are without access to modern facilities. Only 3% of residents have access to electricity and 10% of residents have running water (US Congress, 2004). These living conditions resemble those seen in developing nations, with people suffering mentally and physically. Some are living out of their vehicles while others are living out of run down trailers or shelters deemed unfit for habitation (Minard, 2012). Currently individual families have yet to see any of the money set aside for reconstruction. Negotiations about how to divide and use the money are still ongoing as conditions for these people continue to deteriorate. A solution to this situation needs to be executed so that the quality of life in the area can improve. This study will attempt to facilitate discussion of the issues surrounding this community and hopefully generate interest in academia. A discussion of possible technical solutions will provide those involved with reconstruction efforts sufficient information to choose the best method of providing the electricity residents need and deserve.

3. Impacts of the Freeze

3.1 Poor Resident Health

The lack of electricity can be hazardous to individuals dependent on medicines that have to be kept cold. Without electricity, refrigeration is difficult and prescriptions are not kept at the correct temperature. This can cause the medicine to become ineffective. Another concern is the lack of refrigeration for baby milk. Breast milk can be kept at room temperature for up to 10 hours, and refrigerated for up to 24 hours (Flora, 2002). New mothers that reside in the Bennett Freeze Area can only keep their milk for 10 hours, making it difficult to have safe milk available for consumption. According to one new mother, she "tries to keep the baby's milk in the coldest corner of the room". While visiting this family, I saw a half filled gallon jug of breast milk; I have no idea how long it had been left at room temperature. This is one example where the lack of access to electricity and refrigeration caused residents to compromise their health and the health of their children.

Figure 1: Fern Benally Residence
Source: Doug Vilsack

Another concern is the indoor and outdoor air quality in the area. Outdoor air quality is very poor, especially for residents who live near the active Peabody Coal Mine. Multiple blasts from the open pit coal mine occur every day, sending clouds of coal dust into the air that residents breathe. Breathing particulate matter emitted from coal mines can cause heart and respiratory problems as well as cancer (Sapire, 2012).

3.2 Poverty

The worst effect of the Freeze was the devastating poverty it caused. The ban on development did not allow for infrastructure expansion and improvements or economic development (Linthicum, 2009). Many of the families that lived here were forced to relocate to find work or be thrown into a cycle of poverty.

Figure 2: Close up of mining blast dust near Begay residence
Source: Marsha Monestersky

The only realistic career options in the area are with coal mining companies. Employment opportunities in other economic sectors such as technology, business or education are scarce so many residents are forced into careers that can harm their health. According to surveys taken in the beginning of 2013, the average income of a household is $734.52 a month. It is important to note that this data is from a small survey sample of 48 households and average monthly income may be substantially lower. The average per capita annual income is approximately $27,554.00 (United States Census Department, 2011) which translates into $2,296.00 a month. Comparing this amount with the monthly income of those living in the Freeze area one can conclude that extreme poverty exists within the community.

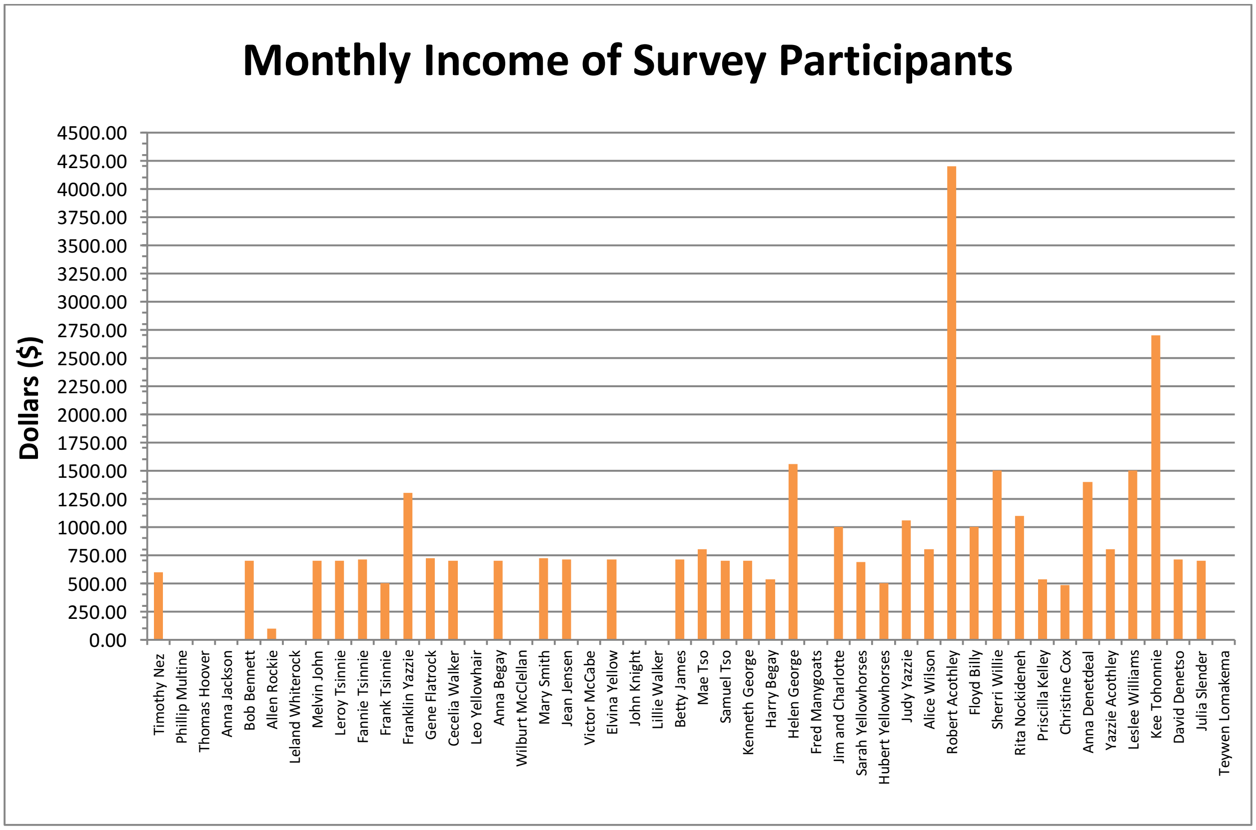

Figure 3: Monthly Income of Bennett Freeze Area Residents

3.3 Deterioration of Structures

Another devastating effect of the Freeze was deterioration of homes and buildings. For 43 years residents were unable to repair their homes in any way. This includes the repairing of roofs, walls, and windows, the installation of plumbing, and the installation electricity. After many years of extreme weather, including high winds and extreme UV exposure, many roofs are on the verge of collapse. While installing small solar systems for lighting, I came across many households that used tires to keep their roofs

Figure 5: Unhealthy home
Source: Project Pueblo

Figure 4: Bessie Wilson Residence
Source: Eagle Energy Trip, Meg McPherson

on their house. Above are some examples and their condition represents the majority of homes in the area. New roads and road repairs were not allowed, and the installation of electric transmission lines and municipal piped water was also not permitted. Due to the extreme poverty and rural nature of the area, the Navajo Tribal Utility Authority cannot afford to build new transmission lines that would only serve a few new customers (Vilsack et al. 2010).

4. Needs Assessment

The following needs assessment reflects data collected during the March 2013 Eagle Energy trip with local NGO, Elephant Energy/Eagle Energy. Surveys of 48 households were analyzed, yielding eye opening results. Working with translators, current energy expenditures for each household was collected, along with monthly income. Demographic information such as age, gender and number of household members was also collected. A summary of the data collected is presented along with a capacity and vulnerability analysis and a ranking of community issues.

4.1 Summary of Data Collection

4.1.1 Demographic Information

Percent Female Householders (%)	Percent Male Householders (%)	Average Age (Yrs.)	Average Household Size (Persons)
49	51	69.4	2.7

Table 1: Demographic Information of Survey Participants. See Appendix A for more details.

The average age of the survey participants is 69 years and the average household size is 2.7 persons. The older average age of the community is important to note because Navajo elders sometimes do not speak English and have lower education levels. Due to these unique demographic factors, the community suffers more health problems than a younger community would. The ability to work is also diminished due to mobility problems and the lack of skills desired in the workplace.

4.1.2 Average Monthly Income vs. Average Spent Monthly on Fuel Expenses

The figure and tables below show how much money residents spend on fuel per month. In some cases, the energy bill is higher than their monthly income. This leads to the borrowing of electricity among residents and reliance on outside help to continue their everyday lives. The need for outside aid can make residents feel helpless and can impact their mental health, leading to depression and other problems.

Average Monthly Amount Spent on Fuel ($)	Average Monthly Income ($)
260.29	734.52

Table 2: Average Income and Average Spent on Fuel of Survey Participants. See Appendix B for more details.

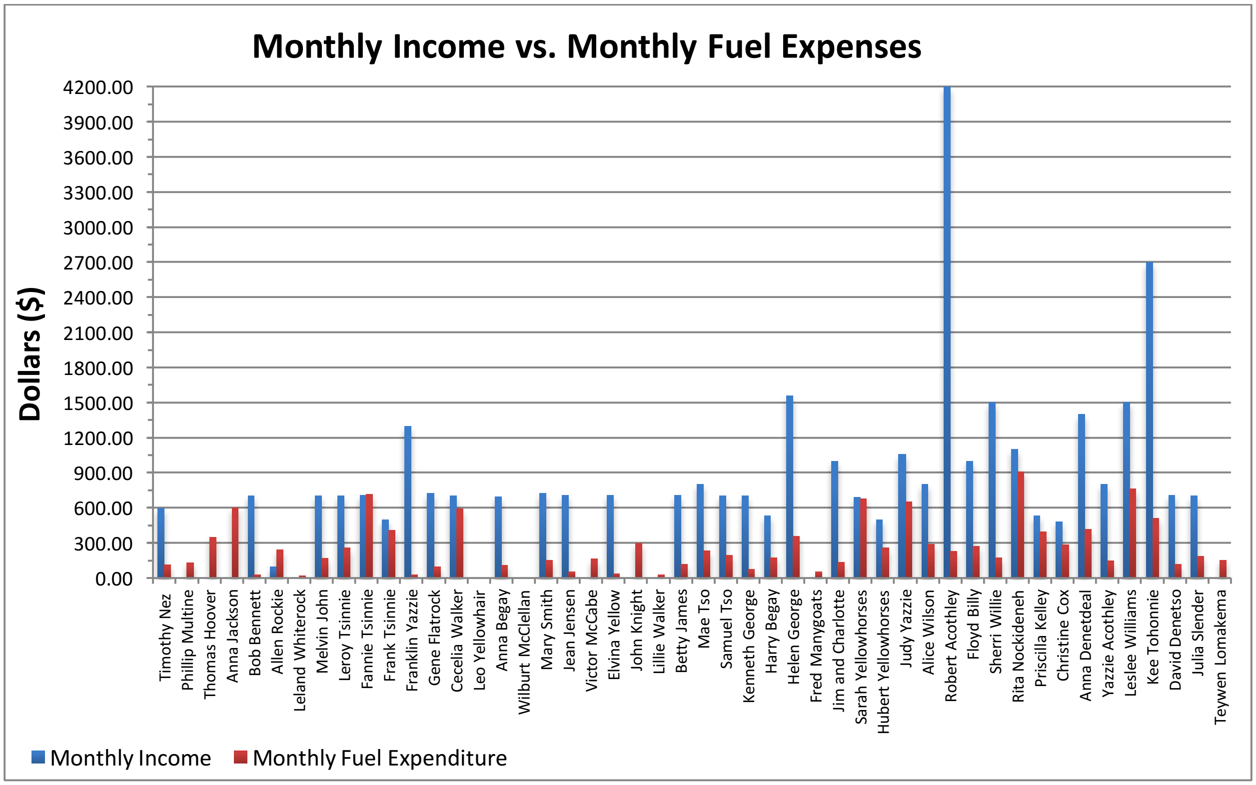

Figure 6: Monthly Income vs. Amount Spent on Fuel

4.1.3 Average Monthly Amount Spent by Fuel Type ($)

Electricity from Line	Generator Fuel	Batteries (Flashlight)	Batteries for Other	Car Battery	Cell Phone	Propane	Candles	Kerosene	Wood	Coal	Other
3.27	16.88	21.06	7.77	0.52	0.73	46.08	1.42	11.63	130.00	9.17	11.77

Table 3: Average Monthly Energy Expenditures by Fuel Type. See Appendix C for more details.

4.2 Capacity and Vulnerability Analysis (Amadei, 2012)

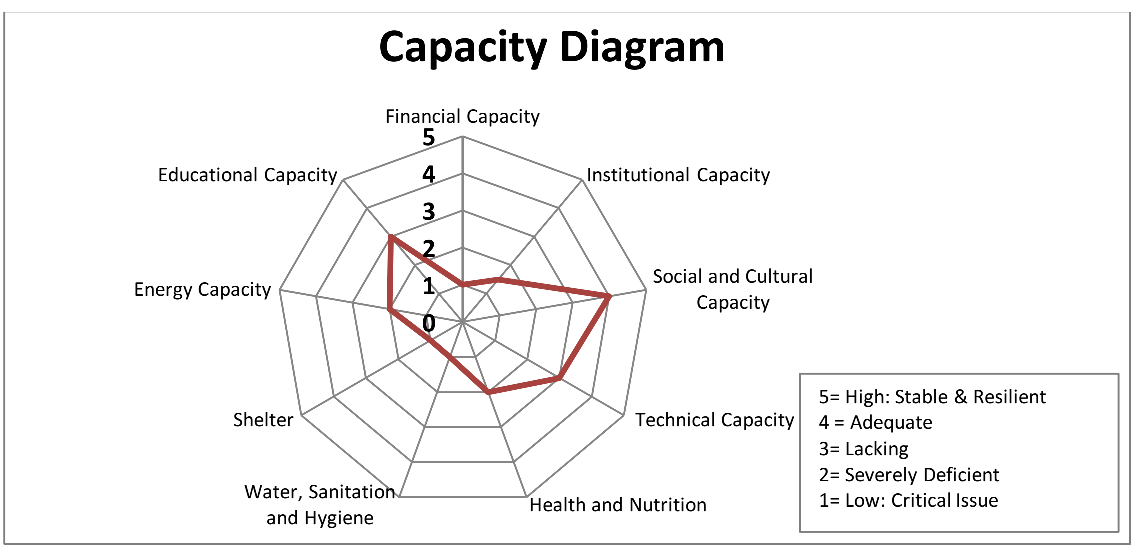

Figure 7: Capacity of Residents

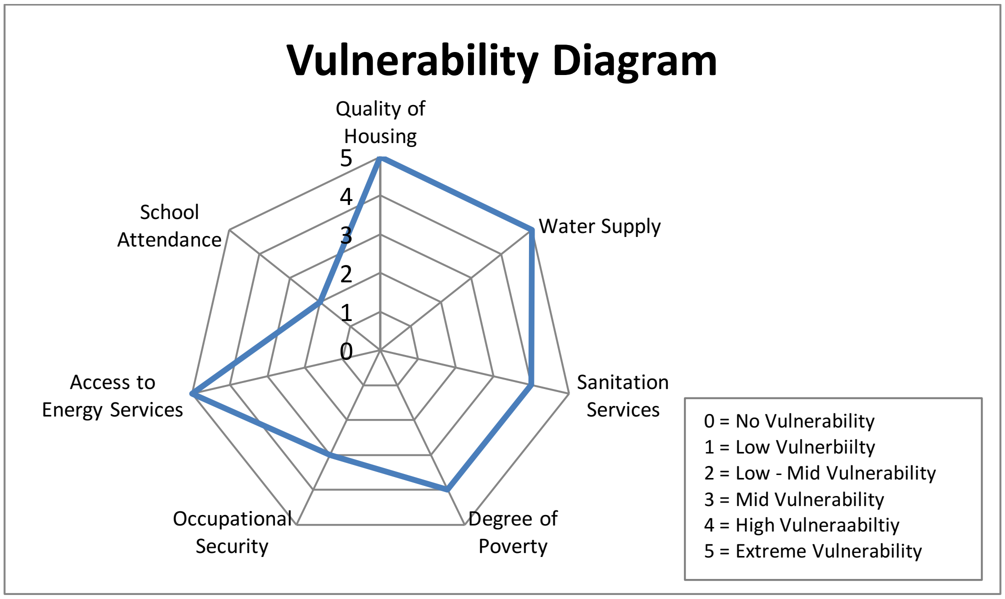

Figure 8: Vulnerability of Residents

In underdeveloped communities the terms capacity and vulnerability are used to describe the lack of security and level of resilience a community has (Amadei, 2013). Capacity is the ability of individuals, organizations, or systems to perform appropriate functions effectively, efficiently and sustainably. Most of the time developing communities have high vulnerability and low capacity (Amadei, 2013). In this report energy capacity refers to the ability of the community to provide adequate energy services to residents taking into account natural, social, and economic crises. For example, if the price of wood dramatically increases due to a shortage, will residents still be able to afford enough wood to heat their homes? If the answer is a small number of residents will still be able to heat their homes, than the community has low energy capacity. An example of high vulnerability would be if a forest fire occurs and the local wood supply is decimated, will residents still be able to heat their homes from some other source? If the answer is no or probably not, than the community has high vulnerability in the area of energy services.

The figures above show that the residents living in the Bennett Freeze area are vulnerable to outside disasters both economic and environmental. If a natural disaster were to occur, such as a wildfire, the affected household would have a very difficult time recovering. The high degree of poverty in the region, along with the poor quality of housing, would make it difficult for the household to find other adequate housing. This would result in the family having to rely on other community members to help them or face becoming homeless. If wood or coal, their main heating sources, were to become more expensive, families would be cold during the harsh winters which could lead to an increase in health problems. Water supply is a concern within the community. Due to the limited freshwater resources in the area and a lack of piped water, the community's water supply is vulnerable.

Clean and safe drinking water is essential to maintain health and cleanliness. This community suffers from uranium contaminated groundwater in many places, making drinking water wells a health liability. The high cost of drilling a well also makes the option unfeasible for the average household in the area. Without access to piped water the community members are forced to drive for miles and truck in water from wells that may or may not be safe. The capacity diagram shows that the community has low capacity in almost all areas of their lives.

The economy in the area is not strong and the unemployment rate is high, around 42% (Navajo Nation Division of Economic Development, 2013). Energy capacity of the area is also low, with most households finding it difficult to afford fuel that will not be harmful to their health. Wood is expensive, as shown by table 3. Peabody Coal provides some residents living in the area with free coal to burn in their homes for heat. For these families it is economically feasible to obtain fuel, but there is indoor air pollution associated with this type of fuel. The burning of coal indoors can cause many health problems that occur due to indoor air pollution. The lack of access to electricity as well as the prevalence of coal burning indoors, results in low energy capacity. Due to low water, sanitation and shelter capacity, which is strongly related to the low financial capacity, families that live in this area are subjected to a life of poverty. The cycle of poverty is hard to break and requires outside help, from either NGOs or the federal government. This coupled with high vulnerability in all aspects of their lifestyles, makes finding a solution to their plight all the more important.

4.3 Overall Needs of the Community

This community is facing many issues that have to be addressed, but certain ones are more important than other since they are essential for the health and well-being of the residents. In my opinion, the issues that have to be resolved immediately are:

- Absence of electricity
- Lack of adequate housing
- Absence of piped water
- Sanitation system deficiencies

There are many ways to mitigate the problems plaguing this community. Policy and technical solutions need to be implemented simultaneously to achieve the best results. Without policy changes and action, the technical solutions may not be realized due to the high cost of technology implementation and home construction.

5. Policy Considerations

5.1 Current Policy Situation

In 2006 a settlement was approved between the Hopi and Navajo tribes, and most of the 1.5 million acres was returned to the Navajo (Donovan, 2009). Finally on May 8, 2009, the Bennett Freeze was officially lifted when President Obama signed a law repealing the ban. This action allowed Navajos the ability to seek federal funding to begin the reconstruction process. On December 15, 2010, the Former Bennett Freeze Area Development Act was introduced in congress under the bill title H.R. 6525 (US Congress, 2010). This act sought to establish the Former Bennett Freeze Area Rehabilitation Trust Fund so that funding would be available for the improvement of economic, housing, infrastructure, health and educational conditions within the Navajo communities affected by the freeze (US Congress, 2010). The act specified that the United States had to be reimbursed for the funds that were given to the Navajo Rehabilitation Fund before it was terminated. It also stated that the income from certain Navajo surface and mineral estates in New Mexico could be used to reimburse the General Fund of the United States Treasury (US Congress, 2010).

Currently Bennett Freeze Area residents have not received any compensation for the decades of unjust treatment. The only construction projects, including energy systems, water systems and new housing, that have been built in the area have been funded and built by NGOs. These NGOs are few and include; the Forgotten People, Project Pueblo, Eagle Energy and the Grand Canyon Trust. There are a few specifications within the bill described above that may be contributing to the lack of progress in reconstruction efforts. The bill states that the Navajo Nation will need to pay back the U.S. Treasury for money it contributes to rehabilitation. The Navajo Nation does not have a lot of money to begin with, and paying back money that is loaned could be a problem. The bill also states that income from mineral resources could be used to pay back the loans. It is not very likely that the Navajo Nation will use part of its main income source to rehabilitate an area if Navajo Nation government is already economically stressed.

5.2 Potential Policy Solutions

For money to become available for reconstruction, new policies with less restrictive conditions need to be introduced and signed into law. The United States federal government needs set aside a certain amount for reconstruction that does not need to be repaid. In this economically stressed area, more loans will only worsen the financial situation. If the Navajo Nation takes money from the U.S. federal government under the conditions specified in H.R. 6525, they run the risk of never being able to pay back the loan. This fact will continue to discourage the Navajo Nation government from putting money into reconstruction. Once the U.S. treasury sets aside an amount for reconstruction, they need to be specific about it can be used for. They also have to implement monitoring and evaluation procedures to make sure the money is being used for the projects it is supposed to be used for. There is corruption within the Navajo Nation government and sometimes money “magically disappears” and communities do not see any benefit from the funds. Another way to ensure that the money set aside is used for its purpose is to put it in the hands of businesses and NGOs, who would be subject to the same monitoring and evaluation methods.

6. Technical Solutions

The lack of electricity in the area can be addressed through the use of many technologies, but the most environmentally friendly technology that uses the areas abundant solar resource, is solar photovoltaics (PV). Northern Arizona receives a large amount of solar radiation which makes the Navajo reservation a great place to put off grid solar systems. The ability of solar PV to provide electricity without needing access to a transmission line makes it an ideal technology to solve the lack of electricity problem.

6.1 Solar Photovoltaics

Implementation of small scale solar energy systems will be very beneficial for the community. Solar PV systems can provide a much needed source of electricity without polluting the surrounding community. Initial costs are high but with no other practical options for electricity, solar PV is the best solution available (Dreveskracht, 2013). Solar PV can provide many benefits to households in the area including electricity for refrigeration, lighting, charging small devices, and powering kitchen appliances. Figure 9 shows the solar radiation in the area. Since solar radiation is high on the Navajo Nation, from 5.0 – 7.0 kWh/m^2/day, power output from a small solar system will most likely reach its full capacity year round (Acker, 2013). Solar PV systems can be installed directly onto roofs or the can be mounted on the ground if the roof in not able to support the weight of the PV system. To be able to install these systems outside funding will need to be secured because the families who need these systems cannot afford them. Labor and material costs could be kept low if student groups and NGOs helped with installations. Working with local contractors and companies would help spur economic development in the area, and help to get residents interested in solar energy and its applications.

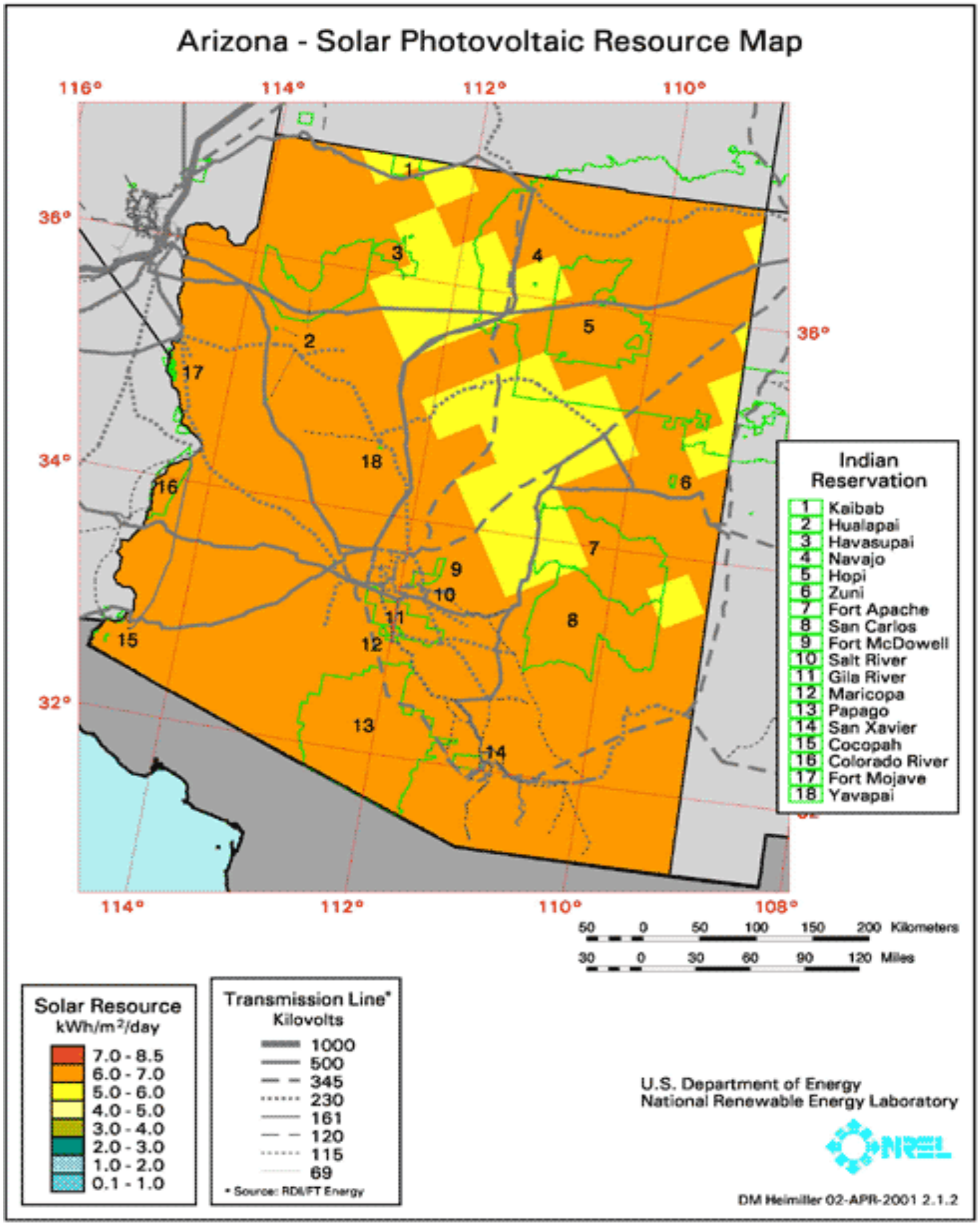

Figure 9: Solar Resource of the Navajo Nation (4)
Source: http://www.azsolarcenter.org/solar-in-arizona/resource-maps.html, courtesy of Tom Acker

7. Proposed Off Grid Solar Photovoltaic Design

Throughout the design process I made many assumptions about what appliances the residents might purchase, (if they had the money) based on the survey data taken in March 2013. In reality, there could be many differences between my assumptions and the actual appliances residents use and buy. For example I assumed that families would purchase an efficient, low wattage DC Sun Frost refrigerator. This may not always be the case, either due to economic or availability constraints. Also I did not take into account air conditioning needs or electric heating needs. This would have resulted in a power demand too high to put in an affordable practical system without backup grid electricity.

For the appliance voltage and wattage specifications, I used data taken from literature [(Hankins, 2010), (Masters, 2004)] for simplicity. Finally I assumed that each family had access to a groundwater well so this created a need for electricity to power a water pump. This is currently not the case but having the electrical capacity for well water makes it possible to install a well in the future if the groundwater is not contaminated. Lack of water availability is an issue in the area, and hopefully at some point these residents will have access to either piped water or wells.

7.1 Load Calculation and System Voltage Selection [(Hankins, 2010), (Masters, 2004)]

The first step in determining how large of a photovoltaic system you need is to estimate how much power you are going to need. Below is a list of appliance that may be used in the average Navajo home. I chose to include some DC appliances so the inverter would be able to have a lower power rating. I chose the overall system voltage based on guidelines found in Gilbert Masters's Renewable and Efficient Electric Power Systems, pg. 556. From this information, along with estimated hours of use for each appliance, I calculated the approximate daily energy use for all AC and DC appliances, as well as the total energy demand.

Appliance	Voltage (V)	Power (W)	Daily Use (hr.)	Daily Energy Use - AC (Wh)	Daily Energy Use - DC (Wh)
AC Appliances					
Microwave Oven: (AC)	110	900	0.25	225	0
TV: 20" Color, active, (AC)	240	68	2	136	0
TV: 20" Color, standby, (AC)	240	5.1	22	112.2	0
Stereo: active (AC)	240	22	3	66	0
Stereo: standby (AC)	240	9.8	21	205.8	0
Total Power Needed (W)		1004.9			
DC Appliances					
Refrigerator: dc Sun Frost 12 cu ft. (DC)	12	58	9	0	522
Water Pump: 24 Vdc 100 ft @1.6 gpm (DC)	12	100	2	0	200
Compact Fluorescent Light 16W: 4 per home (AC)	12	64	5	0	320
Total Power Needed (W)		222			
Total Daily AC Energy Demand				745	
Total Daily DC Energy Demand				1042	
AC Losses				260.75	
DC Losses				208.4	
Total Daily System Energy Requirement (Wh)	**2256.15**				
System Voltage (V)	**12**				
Daily System Charge Requirement (Ah)	**188.01**				

Table 4: Load Calculations and Daily Energy Requirements

7.2 Selection of PV modules and Solar Resource Assessment

For the positioning of the PV array, I decided to place the modules south facing at latitude with no tracking. Flat plate collectors at a fixed position are much cheaper than tracking (1 or 2 axis) systems. I used Flagstaff, AZ solar insolation data because there is no data available for Tuba City, AZ or the Navajo Nation (Marion & Wilcox, 1994). For implementation, the solar resource needs to be measured on site to provide an accurate assessment. I decided on a PV module based on where they are manufactured to lower shipping costs. Kyocera PV modules are manufactured in Scottsdale, AZ so I thought this was a good choice. The total price of the PV modules is estimated to be $325.00 each, which would cost the installer a total of $1625. This estimate was based off of prices of other solar PV panels of similar wattage since I could not find the exact price of the KD 250. I used December as the design month because this is the month in which the average peak sun hours is the least.

Solar Radiation for Flat Plat Collectors Facing South at a Fixed Tilt (Marion & Wilcox, 1994)

Flagstaff, AZ Latitude and Longitude: 35.13° N, 111.67° W

Month	Peak Sun Hours
January	5.2
February	5.8
March	6.2
April	6.7
May	6.7
June	6.7
July	5.8
August	5.9
September	6.3
October	6.1
November	5.4
December	4.9

Table 5: Peak Sun Hours for Flagstaff, AZ

Module Specifications (Hankins, 2010),

Module Type	Number of Modules	Daily System Charge Requirement (Ah)
Kyocera KD 250, 60 cells	5	188.0
Peak Sun Hrs (Dec.)	**Charging Current (A)**	**Max Power Current (A)**
4.9	38.4	8.39
Max Power (W)	**Max System Voltage (V)**	**OC Voltage**
250	600	36.9
SC Voltage	**Length (m)**	**Width (m)**
9.09	1.66	0.99
Area (m)	**Module Price ($)**	
1.64	325.00	

Table 6: PV Module Specifications

7.3 Sizing and Selection of Battery [(Hankins, 2010)]

For the battery(s) I decided to choose the Absorbed Glass Mat: Universal Battery Sealed 200 Ah capacity. Since I need a battery system that can provide power for 752 Ah I designed a battery bank that could provide up to 800 Ah if needed. The need for a minimum of 752 Ah of battery storage was estimated from multiplying the daily system charge requirement of 188.00 Ah by the number of reserve days that the battery power would be needed for. I chose two reserve days because it is very unlikely that the array would be without sun exposure for longer than that, due to the local climate. I calculated the number of strings in parallel I divided the required battery capacity of the system by the Ah capacity of each battery. I need four parallel strings of batteries with one battery per string to support the power demand if the modules are not working or if the sun is not shining. The total cost of the battery bank is approximately $1372.00. To make sure that the family will have enough power even if they increase their demand for electricity, I decided to add a backup generator to the system. I chose the Powermate PC0103007 3000 W Portable Generator because it was not very expensive, $385.00, and exceeded the wattage use of the system.

Type of Battery	**Voltage**	**Capacity (Ah)**	**Recommended Daily DoD (%)**	**Recommended Max DoD (%)**	**Price ($)**	**Cycle Life @ DoD**
AGM: Universal Battery Sealed	12	200	30	50	343.00	1200
Required Battery Capacity (Ah)	**Number of Batteries in String**	**Number of Strings – Parallel**	**Actual Battery Capacity (Ah)**			
752	1	3.76	800			

Table 7: Battery Specifications

7.4 Sizing and Selection of Inverter and Charge Controller [(Hankins, 2010)]

To size the charge controller I first calculated the size by determining the amps needed. I calculated the short circuit current and multiplied it by 1.25 to account for efficiency, 56.8A. Then I calculated the power rating for all DC loads and multiplied it by 1.25 to account for efficiency, 23.1A. The larger of the two values determined the minimum size of the charge controller. I chose a charge controller that could handle 80A of current in case the loads were increased. The Outback Power FLEXmax 80A was the logical choice because it can be purchased in Flagstaff, AZ for $565.00, and could accommodate the 56.8A minimum charge requirement. To size the inverter I added all of the AC loads and multiplied by 1.25 to account for efficiency. The total AC load is 1005W and the minimum inverter rating is 1256W. I chose the Outback 2000W, 24VDC International 50 Hz 55 Amp Charger because it was cheaper than other models at $1309.00, and provided an AC voltage large enough for all AC appliances.

Controller Specification		Rating		
Rated Voltage	V	12		
Maximum Array ISC Input	A	56.8		
Max Load Ouput	A	23.1		
Min Controller Size (A)	**SC Current of Module (A)**	**SC of Array**		
56.8125	9.09	45.45		
Total Power of DC Loads (W)	**Max DC Load**	**Charge Controller, A (56.81 >23.13)**	**Charge Controller**	**Price ($)**
222	23.125	56.8	12V and 56.8 A min. : Outback Power FLEXmax 80 MPPT Solar	565.00
Total AC Load (W)	**Recommended Inverter Rating**	**Inverter**	**Price ($)**	
1005	1256.25	Outback 2000 Watt, 24 VDC International 50Hz Inverter with 55 Amp Charger	1309.00	

Table 8: Controller and Inverter Calculations and Specifications

8. Design Analysis Using HOMER

HOMER is a micropower optimization model that evaluates both small off grid and grid connected energy systems (National Renewable Energy Laboratory, 2011). I am using HOMER to compare the cost of using the PV system described above versus a hybrid PV and generator system versus a generator only system. I am using the components described above and details regarding them can be found in Appendix D.

8.1 Daily Load Curve and Solar Resource Assessment

Below is a daily load curve reflecting the design month of December to make sure that the peak load can be accommodated when the peak sun hours are the least. I have broken it down into AC and DC load curves to provide more detail.

Hour	Load Total (kW)	Load (AC - kW)	Load (DC – kW)	Appliances Running *Assumed stereo is unplugged after use*
00:00 - 1:00	0.0631	0.0051	0.058	Refrig, TV standby
1:00 - 2:00	0.0631	0.0051	0.058	Refrig, TV standby
2:00 - 3:00	0.0631	0.0051	0.058	Refrig, TV standby
3:00 - 4:00	0.0631	0.0051	0.058	Refrig, TV standby
4:00 - 5:00	0.0631	0.0051	0.058	Refrig, TV standby
5:00 - 6:00	0.0631	0.0051	0.058	Refrig, TV standby
6:00 - 7:00	0.9951	0.9051	0.09	Refrig, Micro, 2 lights, TV standby

7:00 - 8:00	0.9951	0.9051	0.09	Refrig, Micro, 2 lights, TV standby
8:00 - 9:00	0.195	0.005	0.19	Refrig, 2 lights, TV standby, water pump
9:00 - 10:00	0.095	0.005	0.09	Refrig, 2 lights, TV standby
10:00 - 11:00	0.095	0.005	0.09	Refrig, 2 lights, TV standby
11:00 - 12:00	0.158	0.068	0.09	Refrig, 2 lights, TV
12:00 - 13:00	0.158	0.068	0.09	Refrig, 2 lights, TV
13:00 - 14:00	0.117	0.027	0.09	Refrig, 2 lights, Stereo, TV standby
14:00 - 15:00	0.117	0.027	0.09	Refrig, 2 lights, Stereo, TV standby
15:00 - 16:00	0.095	0.005	0.09	Refrig, 2 lights, TV standby
16:00 - 17:00	0.095	0.005	0.09	Refrig, 2 lights, TV standby
17:00 - 18:00	1.058	0.968	0.09	Refrig, 2 lights, TV, Micro
18:00 - 19:00	1.058	0.968	0.09	Refrig, 2 lights, TV, Micro
19:00 - 20:00	0.19	0.068	0.122	Refrig, 4 lights, TV
20:00 -21:00	0.29	0.068	0.222	Refrig, 4 lights, TV, water pump
21:00 - 22:00	0.106	0	0.106	Refrig, 3 lights
22:00 - 23:00	0.0631	0.0051	0.058	Refrig, TV standby
23:00 - 24:00	0.0631	0.0051	0.058	Refrig, TV standby

Table 9: Assumed Daily Load Profile of a Household

Below are the assumed daily load profiles for a typical Navajo Hogan. In reality these profiles will vary according to the day of the week and time of the year. For example, during the summer the TV may be run more often when children are home from school Also if the family size grows, microwave use might increase resulting in an increased power demand. The DC load profile will most likely not change at much since the only DC loads that have the potential to increase are the lights and possibly the water pump. From the load curves one can conclude that the greatest power demand is in the morning and evening.

AC Daily Load Profile

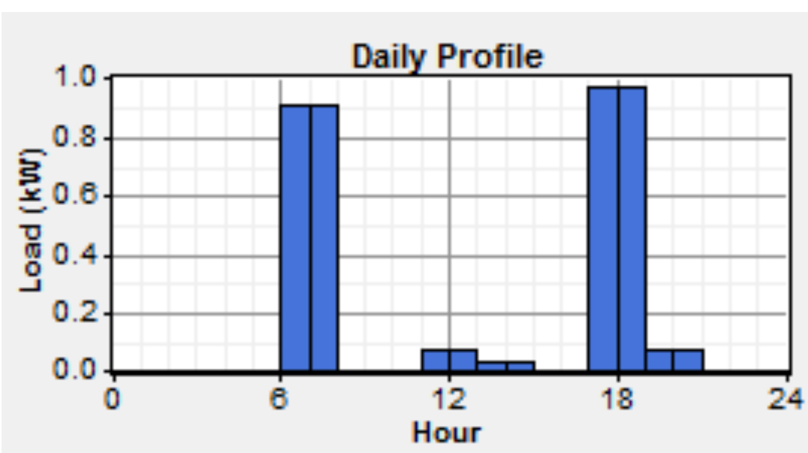

Figure 11: Daily AC Load Profile

DC Daily Load Profile

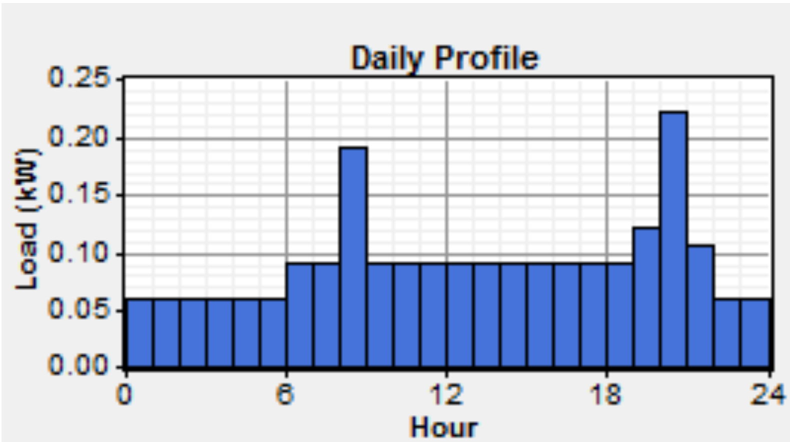

Figure 12: Daily DC Load Profile

Solar Resource

The annual solar resource was calculated using Flagstaff, AZ solar radiation values due to lack of data for the Navajo Reservation (Marion & Wilcox, 1994).

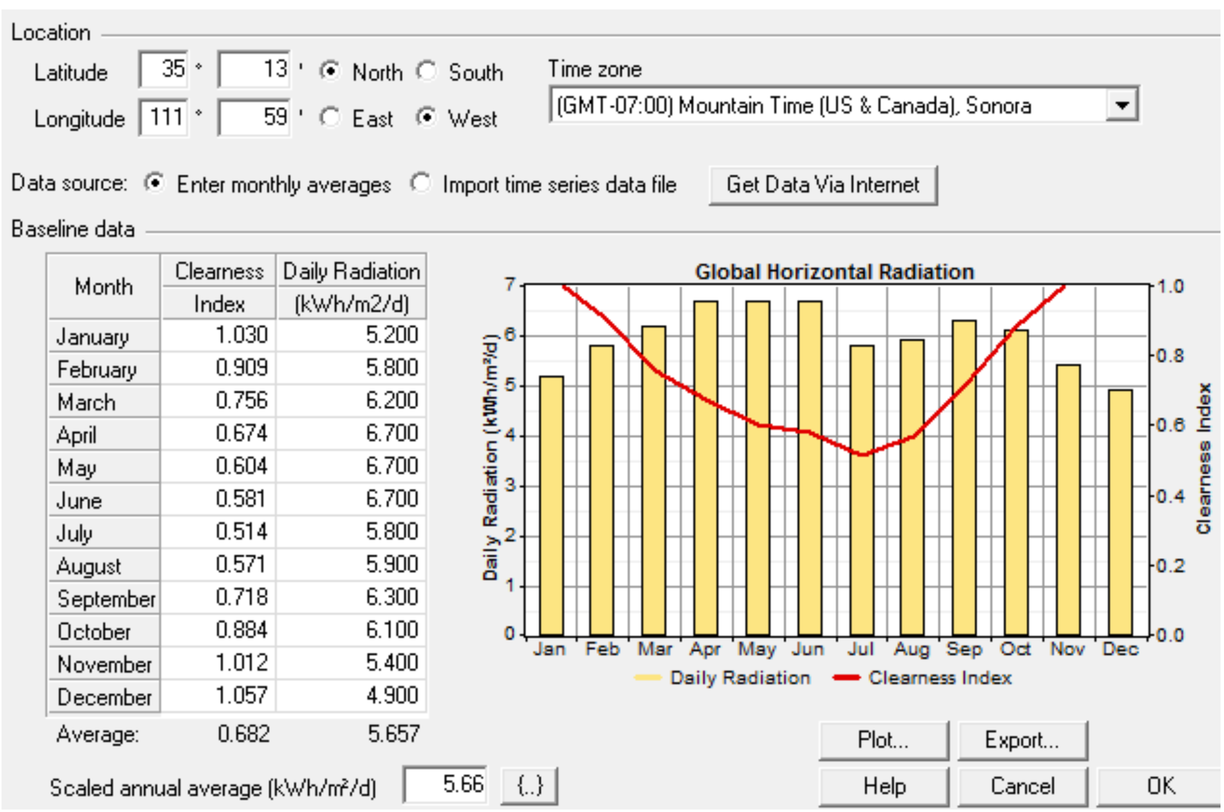

Figure 13: Annual Solar Radiation for Flagstaff, AZ

8.2 Optimization Results

Since this system is off grid, I decided to model the system allowing a 20% maximum annual capacity shortage of electricity. This allowed me to compare a scenario without the use of a generator. Also for the battery component inputs I used a similar battery since the one I am using was not available in the list. I did not have all the specs needed to create a new battery in the menu.

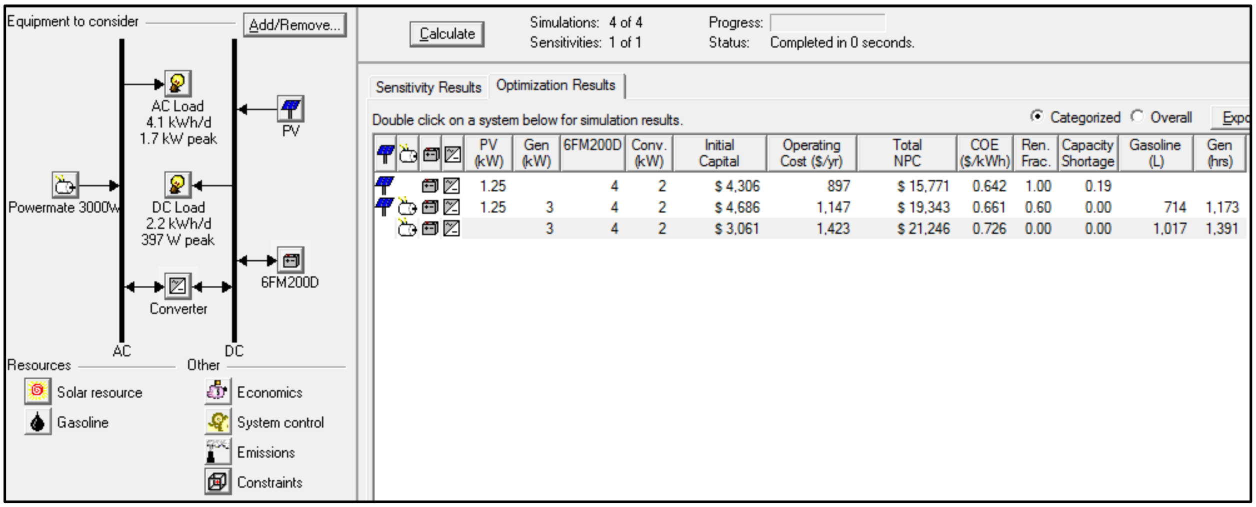

Figure 14: Optimization Results for Potential System Configurations1

From the optimization results, it can be concluded that the most cost effective option is the stand alone PV system with no generator. In HOMER the most cost effective solution is listed at the top followed by other options. The list is based off of the total net present cost column in the optimization model. The PV system with no generator costs less over the life of the system then both the PV and generator option and generator alone option. This is a great result to have when advocating for PV systems. One thing to keep in mind is the capacity shortage. Even though the PV alone system is low cost, on average annually 19% of the time the system will not be able to keep up with demand. In some cases it might be more beneficial to use the second system. If the family in question already has a generator it is worth using the hybrid system to avoid any potential capacity shortages.

8.3 Sensitivity Analysis Results

HOMER has the capability of running a sensitivity analysis to see at which point one system is more beneficial than another. The sensitivity analysis below compares a system with just a PV array, a hybrid system with a PV array and a gasoline generator, and a gasoline generator only. If the solar radiation goes below 5.6 $kWh/m^2/d$ and gasoline prices stay above $0.25/L, then the PV/Generator system will be the best option. If the solar radiation is at or above 5.6 $kWh/m^2/d$, then the preferred system is the PV array only. Finally if the gasoline price is below $0.25/L then the generator only system is favored. These results lead me to conclude that the amount of solar radiation an area receives is a much better indicator of whether or not a PV system will be cost effective than local gasoline price because it will be very rare that gasoline will cost below $0.80/L since the current average gasoline price is $0.97/L (World Bank, 2012).

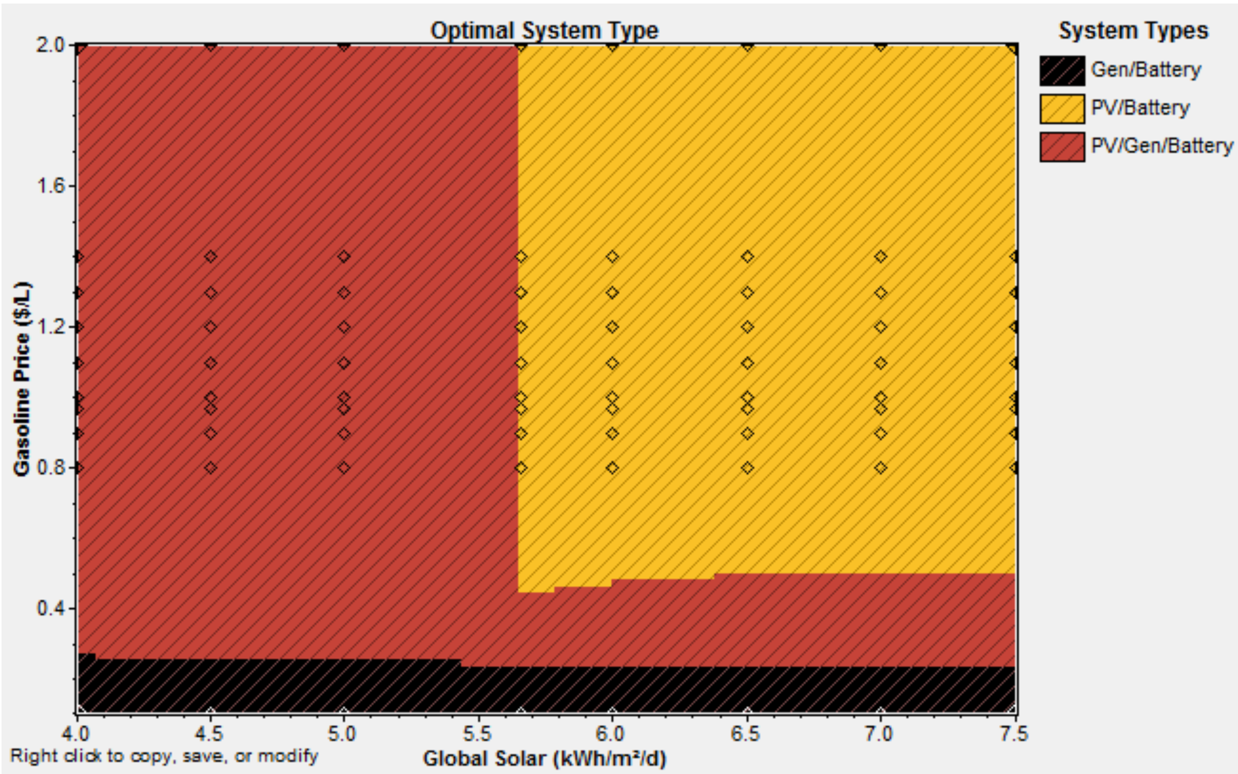

Figure 15: Resource Requirements for System Comparison

9. Feasibility of Sustainable Energy System Implementation

The solar resource in the region is more than sufficient to justify a solar energy project(s). Engineering expertise, labor, and materials are relatively easy to obtain when compared to other underdeveloped areas, but to successfully carry out a project of this type; trust must be established between community members and project leaders. To do this, contacts within the community must be made. This will be one of the more difficult tasks that will be faced during the project. Potential community members who can help outside researchers could be found through NGOs already working in the area, such as Eagle Energy or Forgotten People. Once trust is established with individual families and project members, installations can begin. It will be necessary to have a translator present during all project work in case some of the community members do not speak English. Another important factor to remember is that not of this will be possible without funding. Before a research plan can be carried out, a grant writing team must secure a federal grant to carry out a project. The families are extremely poor and cannot afford to pay installers or engineers so their salaries must be paid through grants or donations.

10. Further Research

This community is suffering from many problems, ranging from socioeconomic concerns to basic infrastructure issues, which makes the opportunities for future research endless. There are numerous topics that could be investigated. Below is a comprehensive outline of possible topics.

- Sustainable water supply solutions
- Climate change and how it affects the community
- Appropriate technologies for improved sanitation systems
- Microenterprise solutions to encourage economic development
- Sustainable construction
- Effects of educational workshops to improve the capacity of the community
- Other sustainable energy solutions that could electrify the area (wind, geothermal etc.)

The situation in this region is very dire, and more people need to become aware of what is happening to this community. Any research that is undertaken should have objectives that seek to improve the living standards for the residents living in the former Bennett Freeze area. As researchers we must remember to never bring harm to a group of vulnerable people. We must keep the well-being of the community the top priority when carrying out our investigation.

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