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Sizing Small-Scale Renewable Energy Systems for the Navajo Nation and Rural Communities

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ABSTRACT

The Navajo Nation consists of about 55,000 residential homes spread across 27,000 square miles of trust land in the Southwest region of the United States. The Navajo Tribal Utility Authority (NTUA) reports that approximately 15,000 homes on the reservation do not have electricity due to the high costs of connecting rural homes located miles from utility distribution lines. In order to get these rural homeowners access electricity, NTUA and other Native owned companies are examining small-scale renewable energy systems to provide power for necessary usage such as lighting and refrigeration. The goal of this study is to evaluate the current renewable deployment efforts and provide additional considerations for photovoltaic (PV) systems that will optimize performance and improve efficiency to reduce costs. There are three case studies presented in different locations on the Navajo Nation with varying solar resource and energy load requirements. For each location, an assessment is completed that includes environmental parameters of the site-specific landscape and a system performance analysis of an off-grid residential PV system. The technical process, repeated for each location, demonstrates how the variance and uniqueness of each household can impact the system requirements after optimizations are applied. Therefore, the household variabilities and difference in locations must be considered. The differing results of each case study suggests additional analysis is needed for designing small-scale PV systems that takes a home-land-family specific approach to allow for better efficiency and more flexibility for future solar innovations to be considered for overall cost reductions.

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CONTENTS

1. Navajo Nation and Energy.....	9
1.1. Extractive Industry.....	9
1.2. Electricity Usage within the Home.....	10
1.3. Renewable Energy Future.....	10
2. Current Renewable Efforts on Navajo Nation.....	12
2.1. Utility Scale.....	12
2.1.1. Solar Energy Plants.....	12
2.2. Small-Scale.....	12
2.2.1. Navajo Tribal Utility Authority Renewable Deployment.....	13
2.2.2. Native-Owned Company Deployment.....	13
3. The Home and PV System Requirements.....	15
3.1. Incorporating the Home.....	15
3.2. Location and Solar Resource.....	15
3.3. Home Size and Loading Requirements.....	16
3.4. Three Home Case Study.....	17
4. Sizing Off-Grid PV Systems.....	19
4.1. Method.....	19
4.1.1. Determine Household Loading Requirements.....	19
4.1.2. Assess Environmental Parameters of the Land.....	20
4.1.3. Source Reliable System Components.....	21
4.1.4. Perform a System Analysis.....	23
4.2. Home 01.....	24
4.2.1. Loading Requirements.....	24
4.2.2. Environmental Parameters.....	25
4.2.3. System Performance Analysis.....	27
4.3. Home 02.....	28
4.3.1. Loading Requirements.....	28
4.3.2. Environmental Parameters.....	29
4.3.3. System Performance Analysis.....	30
4.4. Home 03.....	31
4.4.1. Loading Requirements.....	31
4.4.2. Environmental Parameters.....	32
4.4.3. System Performance Analysis.....	33
5. Process Discussion.....	34
5.1. Trends of the Environmental Parameters.....	34
5.2. Comparison of System Performance Analysis.....	35
6. CONCLUSION.....	37
6.1. Optimization.....	37
6.2. Flexibility.....	37
6.3. Choice.....	38

FIGURES

Figure 3-1. Direct Solar Normal Resource map of the Navajo Nation. The solar resource maps in Utah, Arizona, and New Mexico from the National Renewable Energy Laboratories data were combined to have a whole view of the solar resource within the Navajo Nation.....	16
Figure 3-2. Map of small-scale PV System deployment and potential on Navajo Nation. The NTUA systems recorded are from a Sandia National Laboratories archive from former student research on NTUA Electrification Demonstration Program that represents less than half of all NTUA PV systems. The non-NTUA systems are mainly from GRID Alternatives....	18
Figure 4-1. a. Graphic of the zenith and azimuth angles b. Graphic of GHI c. Graphic of DNI.....	21
Figure 4-2. Diagram of the connections between the different PV system components (Source https://solarcalculator.com.au/solar-power-systems/)	22
Figure 4-3. Analysis of the environmental parameters during spring equinox (March 17), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI.....	25
Figure 4-4. Analysis of the environmental parameters during summer solstice (June 17), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI	25
Figure 4-5. Analysis of the environmental parameters during fall equinox (September 17), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI.....	26
Figure 4-6. Analysis of the environmental parameters during winter solstice (December 17), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI	26
Figure 4-7. Module Power Output (W) at Solar Noon vs. Day of Year depending on the tilt angle of the solar modules (flat to the ground, at latitude angle of 36.43° and adding or subtracting 15° from latitude)	27
Figure 4-8. a. System DC and AC Power Output (W) vs. Hours of the Day of PV System b. Module DC Current (A) vs. Hours of the Day c. Module DC Voltage (V) vs. Hours of the Day	27
Figure 4-9. Analysis of the environmental parameters during spring equinox (March 16), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI.....	29
Figure 4-10. Analysis of the environmental parameters during winter solstice (December 16), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI	29
Figure 4-11. Module Power Output (W) at Solar Noon vs. Day of Year depending on the tilt angle of the solar modules (flat to the ground, at latitude angle of 36.43° and adding or subtracting 15° from latitude)	30
Figure 4-12. a. System DC and AC Power Output (W) vs. Hours of the Day of PV System b. Module DC Current (A) vs. Hours of the Day c. Module DC Voltage (V) vs. Hours of the Day	30
Figure 4-13. Analysis of the environmental parameters during spring equinox (March 18), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI.....	32
Figure 4-14. Analysis of the environmental parameters during winter solstice (December 18), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI	32
Figure 4-15. Module Power Output (W) at Solar Noon vs. Day of Year depending on the tilt angle of the solar modules (flat to the ground, at latitude angle of 36.43° and adding or subtracting 15° from latitude)	33

Figure 4-16. a. System DC and AC Power Output (W) vs. Hours of the Day of PV System b.
 Module DC Current (A) vs. Hours of the Day c. Module DC Voltage (V) vs. Hours of the
 Day33

TABLES

Table 3-1. Energy calculation chart common to determine the size of PV systems. Format is in
 reference to similar PV system handbooks17

Table 4-1. PV system array calculation to determine the total kW rating required to power a
 certain loading requirement. The amount of sun hours and factor for potential system loss is
 also considered.20

Table 4-2. Energy calculation chart for Home 01 to determine the size of PV system.....24

Table 4-3. Energy calculation chart for Home 02 to determine the size of PV system.....28

Table 4-4. Energy calculation chart for Home 03 to determine the size of PV system.....31

ACRONYMS

Acronym	Definition
AC	alternate current
DC	direct current
DHI	diffuse horizontal irradiation
DNI	direct normal irradiation
GHI	global horizontal irradiation
GW	gigawatt
kW	Kilowatt
MW	megawatt
NTUA	Navajo Tribal Utility Authority
O&M	operation and management
PPA	power purchase agreement
PV	photovoltaic
V	volts

1. NAVAJO NATION AND ENERGY

The landscape of infrastructure on the Navajo Nation has been defined by the production of energy. However, the facilities extracting power from Navajo land have not addressed the approximately 15,000 homes on the reservation that do not have access to electricity [1]. “Navajos [are] sitting beneath power lines that do not benefit their families” [2], and yet still face the negative consequences of extraction sites. There are also families who live too far from power lines to connect to electricity supplied by the distribution line infrastructure. Even those who live within the proximity of the power lines face the economic barrier to finance line extension, which can cost up to \$50,000 compared to the per-capita income of \$10,700 a year [3]. Navajo families often find alternative means of producing energy such as wood or kerosene, but at the cost of laborious transportation and high resource costs. The Navajo Nation has been economically dependent on extractive industries for fifty years and energy policy has focused on extracted resources that are not beneficial to Navajo families [4]. Recently, the proclamation Navajo Hayoolkaal, or Navajo Sunrise, was signed by the Navajo Nation president to “create a new economic vision for the Navajo people through healing the land, fostering clean energy development, and providing leadership for the energy market for the Navajo people,” [5]. Renewable energy systems have been identified as the future of the energy economy in the face of the decline of the extractive industry.

1.1. Extractive Industry

The coal industry is the main extractive industry on the Navajo Nation that is found on mining sites and generation stations. The Navajo Generating Station is the largest coal plant in the western United States and was built in the 1970s to supply power to California, Arizona, and Nevada [6]. However, there are thousands of Navajo families in close proximity to this plant without electricity. The Four Corners Generating Station was finished in 1970 as a coal fired power plant to extract its resource from the Navajo Coal Mine, however it has since been a major contributor to reduced air quality [7]. The pollutants—such as mercury, carbon, and smog—that affect the air translates into negative health effects ranging from asthma to cancer, all of which the Navajo families in the area suffer from [8].

The third major coal fired power plant impacting the Navajo Nation is the San Juan Generating Station. This plant is scheduled to be shut down in 2022 and the main concern of that shutdown is the loss of Navajo jobs which made up 60% of the workforce [9]. The dependence on the coal industry to supply jobs is demonstrated by just how many people will be without a job after the generating stations close. However, it is inevitable that the generating stations will face closure. Aforementioned, the air quality is negatively affected but it is protected by law which affects the future consideration for expensive additions to reduce the pollutants released or to be more competitive. Coal has also become the most expensive fuel for electricity production resulting in 268 coal fired power plants in the U.S. to close since 2010 [7]. The future of the extractive industries leads towards closures. However, the losses caused by the generating stations has already affected Navajo communities. On top of the economic dependency causing a major issue with job availability, Navajo households continues to face the environmental and health concerns of extractive industries.

1.2. Electricity Usage within the Home

The effect of the extractive industries on Navajo households is demonstrated by whether they are connected to the power lines for electricity or not. The families connected to the grid—that is, the larger power infrastructure that supplies the electricity—can be located at the end of the power line where reliability of power is reduced. This is due to larger loads, or power consumption, further up the line that use most of the electricity supply or simply due to the fact that the line is further from the main energy distribution centers. For the Navajo families living off the grid either due to the financial or location barrier to power line extension, the alternative means for producing energy are sourced from natural resources that take time to retrieve or have negative health effects associated with use in the home. The main electricity usage for the homes that use natural resources are lighting and heating. Kerosene is used for lighting, diesel generation is used for electricity, and wood or coal are used for heating [10]. The coal used within the home is often sourced from coal mines that are dispersed for household use [11], bringing health hazards within the home. Other resources such as kerosene pollute the inside of the household and cause respiratory issues and increased risk of fires [12]. The alternative means for producing energy within the home are dangerous to the wellness and safety of Navajo families.

1.3. Renewable Energy Future

Given the prospect of future closures of coal mining and generating sites, the Navajo Nation is faced with determining another solution for their energy production. The energy solutions must not only consider the economic dependency for jobs and revenue from the energy sector, but the growing concern of the health of the people and land. Renewable energy systems have been identified as a solution that is economically feasible, but more importantly, invokes values of the restoration of resources and correcting the imbalance previously caused by the extractive industries [8]. Navajo Hayoolkaal, or the Navajo Sunrise Proclamation, recognizes the necessity to separate from the coal industry as a means of exercising energy. The proclamation lists four base principles towards clean energy development: Navajo job creation through renewable energy development, restoration of land and water, rural electrification, and utility scale systems [5].

The principle basis of the proclamation is built on the efforts from Navajo-led initiatives in building renewable energy programs from the grass roots level projects to utility scale. The current landscape of renewable energy efforts on the Navajo Nation have provided a basis for future projects, but it has also demonstrated the issues that follow with new development. The main concern has been with following an energy development structure that does not reflect the same methods as the extraction industry. Brett Isaac of Navajo Power stated that “If we’re going to get renewable energy done in a way that isn’t reminiscent of what other energies have done to Navajo and other indigenous communities, we had to integrate a philosophy into the development process that would be fair and in tune with how development should occur on tribal land,” [13]. The Navajo Nation can be a leader in renewable energy development and define a new way to approach development on Native lands, however, determining that process is still in the planning stages. The Navajo Sunrise Proclamation reflects the work of many Navajo people working with renewable energy and it’s important to analyze the past Navajo led projects to determine a process plan for future implementation.

Although renewable energy has several drawbacks, the potential of its technologies to service a wide array of uses from utility to small-scale holds significance for Native communities. The promise of

renewable energy allows the Navajo Nation to separate from full dependency on the extraction industry to a more sustainable method. The current renewable landscape of the Navajo Nation offers hope for a cleaner energy future determined by the Navajo Nation.

2. CURRENT RENEWABLE EFFORTS ON NAVAJO NATION

The renewable energy projects on the Navajo Nation are on two different scales, either utility or small-scale, with different methodologies for energy development that range from utility company leadership to Native-grown companies in the photovoltaics (PV) or solar field. The market for solar is growing as costs for individual components are decreasing and the high potential of solar resources on the Navajo Nation contributes to greater considerations for solar technologies [13]. An overview of the current landscape of renewable projects is important to understand the reasons the Navajo people took the initiative to integrate renewables and to understand the successes and failures of energy development on Native land and communities.

2.1. Utility Scale

Utility scale PV systems generate solar power and feed it into the grid in order to supply a wholesale utility company with energy ranging from 1-400 megawatts (MW) of power. Generally, the solar facility and utility company decide on a power purchase agreement (PPA) that secures an energy market for 10-25 years [14].

2.1.1. Solar Energy Plants

The Kayenta Solar Project, also known as Kayenta I, located in Kayenta, Arizona, is the first solar energy production plant built and owned by the Navajo Nation. The 27.3 MW project is operated under the Navajo Nation's primary electricity service provider, the Navajo Tribal Utility Authority (NTUA), and sold to the Salt River Project for distribution [15]. In response to the closing of the Navajo Generating Station and interest in renewables, Kayenta I was meant to fill the gap while also beginning to power Navajo facilities such as significant buildings and some Navajo family homes. Kayenta I was NTUA's introduction to the successful development of large-scale renewable energy projects. The expansion into the Kayenta II phase will provide an additional 27.3 MW of power that has the potential to be sold off Navajo land as a new source of revenue generation for the nation. [16]. The additional revenue has also been suggested to fund line extensions for Navajo families, similar to the Light Up Navajo project in 2019 that extended electricity to 233 families [1]. Utility-scale solar projects benefit the Navajo Nation's energy economy and families near power lines; however, many Navajo families have little opportunity to access the energy from these large plants and their distribution networks.

2.2. Small-Scale

Small-scale PV systems produce solar power and supply it directly to the consumer host site rather than going through a utility company [17]. The small-scale systems considered are off-grid PV systems that are not connected to the power distribution lines.

2.2.1. Navajo Tribal Utility Authority Renewable Deployment

The NTUA began its first phase of the Navajo Electrification Demonstration Program in 1993. It installed 40 PV systems rated at 240/260W to power lighting in homes too far from the grid to be connected [18]. Since then, NTUA has reported a total of 220 off-grid PV system installations across the Navajo Nation with wattage rating of 680, 880, 1080, and 1800W [19]. The lower ratings are only able to generate power for lighting, while the higher ratings of 1080 and 1800W allow for a refrigerator to be connected. Lighting and refrigeration are the main power or loading requirements in the Navajo home that the solar programs have addressed. Lighting is necessary for nighttime activities, including light for children to do homework, adults to read, or other activities such as weaving. Refrigeration has been a main concern for health reasons such as medication storage or storing fresh food for longer periods of time. The electrification program prioritized homes that were too far from the power lines to have the possibility of future connection and where families requested electricity for their home.

The four different models of PV systems offered from NTUA are installed and maintained by NTUA for a monthly cost ranging from \$75-100 based on the model size [19]. The price is more affordable for some families who were originally paying high costs for generators that were unreliable [20]. The major inhibitor for future growth of the program is the source of funding that can purchase the PV systems. Also, upon consultation with NTUA renewable specialists, one other difficulty within the program is operation and maintenance (O&M). In larger utility scale projects, it is easier to control O&M procedures because of the scale and centralized locations of the solar fields, whereas small-scale projects are scattered across a large land area that takes more resources to perform maintenance. NTUA described how most of the maintenance requests are due to overloading the PV systems from excessive use within the household which causes the batteries to drain completely. NTUA's small-scale renewable energy deployments were an important first step in introducing these systems to the communities and showcasing their potential, however, greater technical analysis and upgrades to the PV systems should be considered for future models of the program.

2.2.2. Native-Owned Company Deployment

Other entities contributing to small-scale PV system programs on the Navajo Nation are the Native-owned companies that took initiative to begin installations in their own communities. Navajo Power and Native Renewables have been at the forefront of leading the deployment of renewables on the Navajo Nation. The founder of Navajo Power, Brett Isaac, formerly engaged in projects under Shonto Energy that installed over 200 off-grid systems—comparable to NTUA's programs [21]. Currently, Navajo Power has a goal of developing 10+ gigawatts (GW) of power on the Navajo Nation that will allow local communities to benefit from competitive clean energy projects [21]. During a conversation with Isaac, he mentioned the need to diversify after the closing of the Navajo Generating Station and the potential of small-scale PV systems to contribute to the new energy economy in renewables. Other than economic value, these systems also provide another avenue towards self-sufficiency of the Navajo individual or family over their household. Isaac talked about education towards independency where knowledge of the PV systems by the homeowners leads to system success and the goal of the homeowner being self-sufficient. This is one part of energy sovereignty that allows the Navajo homeowner to practice their own means of determination and decision making in the home.

Native Renewables follows a similar goal in their effort to “empower Native American families to achieve energy independence by growing renewable energy capacity and affordable access to off-grid power,” [22]. During a conversation with one of the founders, Suzanne Singer, she explained the extent of their technical assistance. They include building/maintaining energy systems, holding community solar education workshops, and assisting with PV system repairs. The focus is centered on building the capacity of the household to understand the benefits of renewables while using the founder’s own technical capacity to source low-cost components that are still efficient with a long lifetime. The community-based approach towards renewable energy deployments suggests another methodology to long-term energy projects. One other grass roots level group generating their own PV systems and education is Gallup Solar [23]. The importance of training on the technical operations of the PV system is an essential part of the individual user’s ability to care for the system. The education allowed the user to be more aware of their energy usage, leading to less need for maintenance. The last company researched working on the Navajo Nation was GRID Alternatives. They have worked with various chapter houses to implement or repair PV systems for individual homes. After speaking with their director, Adam C. Bad Wound, the relationship between sovereignty and the emerging energy projects on Native lands became clear. The small-scale deployments and community education are key to Navajo individuals exercising their choice in how their homes are powered.

3. THE HOME AND PV SYSTEM REQUIREMENTS

Native-owned company deployments of small-scale renewable energy systems have provided new methodologies for future installations that considers the needs of the families. They have modeled considerations for designing specific systems based on the household's requests and the necessity for the homeowner's understanding of solar energy in general terms. This report aims to amplify the methods of the Native-owned companies while also including considerations on household size and location in the technical analysis of the small-scale PV systems. This requires quantifying the home's size and location which will be calculated through loading requirements and solar resource. The method will be repeated for three different case study locations on the Navajo Nation to demonstrate the process and incorporation of the Navajo family and land into the equation.

3.1. Incorporating the Home

Many Navajo families live in the rural areas of the Navajo Nation that hold a traditional homestead, allowing for a self-sustaining lifestyle with many family members living in surrounding areas [24]. The significance in location of the home stems from the generations of family living in the area and connection to all relations of the land. The size of each home varies from an elder to the average Navajo family size of five people [25]. These two aspects of location and family size define the characteristics of the home that are necessary to determine the most efficient PV system design.

Other considerations of the home came from research of other Native communities deploying small-scale renewable energy. The close relationship between the building or home energy efficiency and its ability to best use the energy produced from PV systems became clear. In the Jicarilla Apache's plans for renewable energy development, one conclusion was that the "efficiency of electricity use is directly related to the efficiency of buildings, building systems, and appliances located inside buildings," [26]. Technically, the relationship between the home's load and efficiency in its appliances is an important consideration when sizing the PV system built for that specific home. Future developments on Native land have also considered the large amount of solar resources related to the location, especially on the Navajo Nation that has been identified as premium solar resource land in the West [27]. Location and home size alongside their calculated values is evaluated in the next sections for each of the three case studies.

3.2. Location and Solar Resource

Solar resource, or solar radiation, is the electromagnetic radiation emitted from the sun [28]. Solar irradiance is the rate at which the radiant energy hits a surface area during a specific time interval [29]. The National Renewable Energy Laboratory produces maps of the states providing the average daily solar resource over specific surface cells where its irradiance values represented the resource available [30]. The map information for the states of Utah, Arizona, and New Mexico were compiled together to show the solar resource on the Navajo Nation. When the maps were combined in Figure 3-1, the solar resource range was 6.0 – 7.5 kWh/m²/day. This is higher than most areas of the United States. The resource from the sun is abundant on the Navajo landscape.

Notice that the three different color regions represent a scale of solar resource with the lightest color being less irradiance and the darker being more. The central part of the Navajo Nation has a small strip with lower irradiance and increases as the distance moves out circularly to the edges of higher resource in areas like Cameron or Pueblo Pintado. The homes with higher solar resource and greater sun hours during the day will produce the most solar energy from the PV system. One variance in the case studies used for the technical analysis is the difference in solar resource based on location.

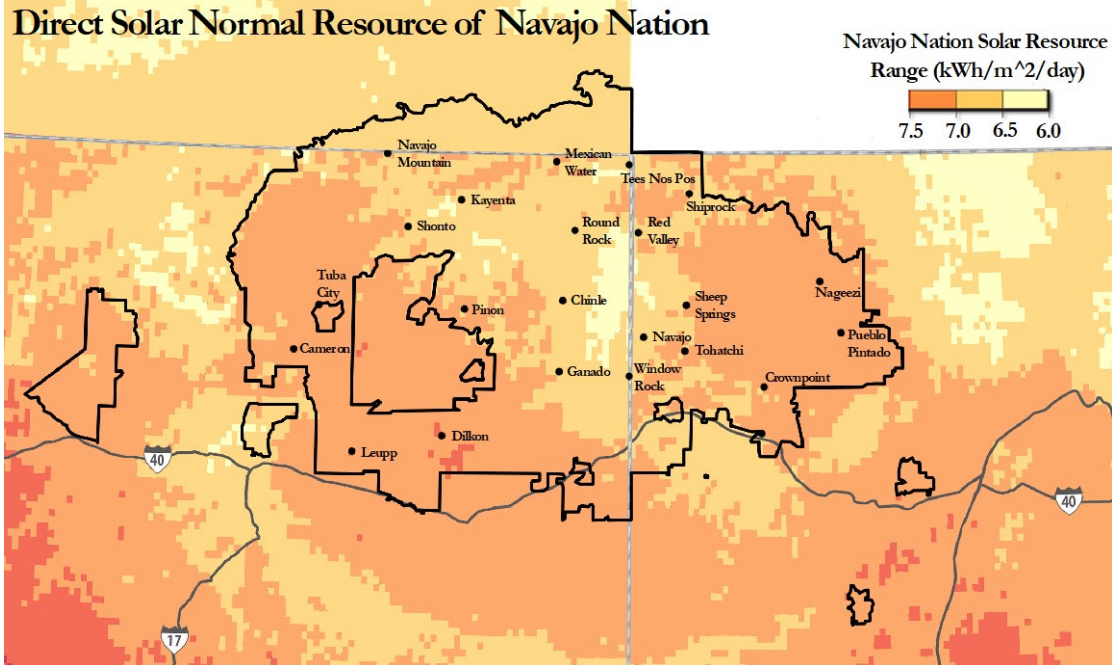


Figure 3-1. Direct Solar Normal Resource map of the Navajo Nation. The solar resource maps in Utah, Arizona, and New Mexico from the National Renewable Energy Laboratories data were combined to have a whole view of the solar resource within the Navajo Nation.

The solar radiance will be reflected in the environmental parameters section that shows how the sun position and its irradiance are tracked as a variable to change the power output of the PV system. Further information is described in the PV system sizing process with the addition of weather conditions that may interfere with solar radiance.

3.3. Home Size and Loading Requirements

The average Navajo household size is 4.8 or about five people in one home [25]. Based on the 2010 Census Data, it is reported that most homes have 4-5 rooms of which 2-3 are bedrooms [25]. However, there are still many homes with less people or less rooms. This report considers a range of different homes sizes to vary the loading requirements for those family types outside the reported averages. The size and type of family will determine what appliances are used and how many are in the home. For example, a home with an elder may not need as many light bulbs as a large family with school age children who have more nighttime activities.

In order to translate family size into a value that will affect the PV system design, the loading requirement for each family can be determined. The loading requirement will be calculated based on the highest load day in kWh/day. Under the guidance of educational materials from Native Renewables, Gallup Solar, and other similar PV system handbooks [31], the table in Table 3-1 was used to assess the daily loading requirement of different home sizes that was dependent on appliance ratings. The rated wattage of the appliances was multiplied by the number of hours used per day to get the Wh/day then divided by 1000 to convert to kWh/day. Each kWh/day rating associated with a certain appliance would all be added together to get the total loading requirement for the requested appliances of the household. There are other methods for calculating the kWh/day rating that require further evaluation of the specifications of the appliance.

The chart is one of many examples of the educational tools that can be provided to the homeowner, so they are able to calculate their own loading requirement. It allows them to choose what appliances they require and better understand the amount of energy required to power their appliances. It also allows for the number of appliances to be specified for each family type.

Table 3-1. Energy calculation chart commonly used to determine the size of PV systems. Format is in reference to similar PV system handbooks

Appliance	Wattage (W)	Time Used per Day (hours)	Wh/day	kWh/day
Appliance 1	x	=	÷ 1000	=
Appliance 2	x	=	÷ 1000	=
Appliance 3	x	=	÷ 1000	=
				= TOTAL

The chart also sets up the idea that the PV system is limited in energy supply. The appliances they list are the only loads that can be used under the PV system. Energy efficiency must be practiced in the home in order to avoid issues with overloading that both NTUA and the Native-owned companies reported as a major maintenance problem.

3.4. Three Home Case Study

In order to simulate the process of sizing PV systems, three different home case studies are performed. The choice of each location will be specified in their accommodating sections but the main difference between the three homes is solar resource and home size. The map in Figure 3-2 plots these three potential small-scale PV system sites to install alongside the partial mapping of the current off-grid systems deployed in Navajo Nation. The additional considerations for each home are also shown in Figure 3-2, including the proximity to transmission lines and type of PV systems deployed in the area. The following sizing process will be conducted for the three home case studies. The evaluation of the home-land-family specificities is an important aspect in the technical calculations necessary to determine the most flexible and optimized PV system design for the home.

Off-Grid PV System Deployment and Potential

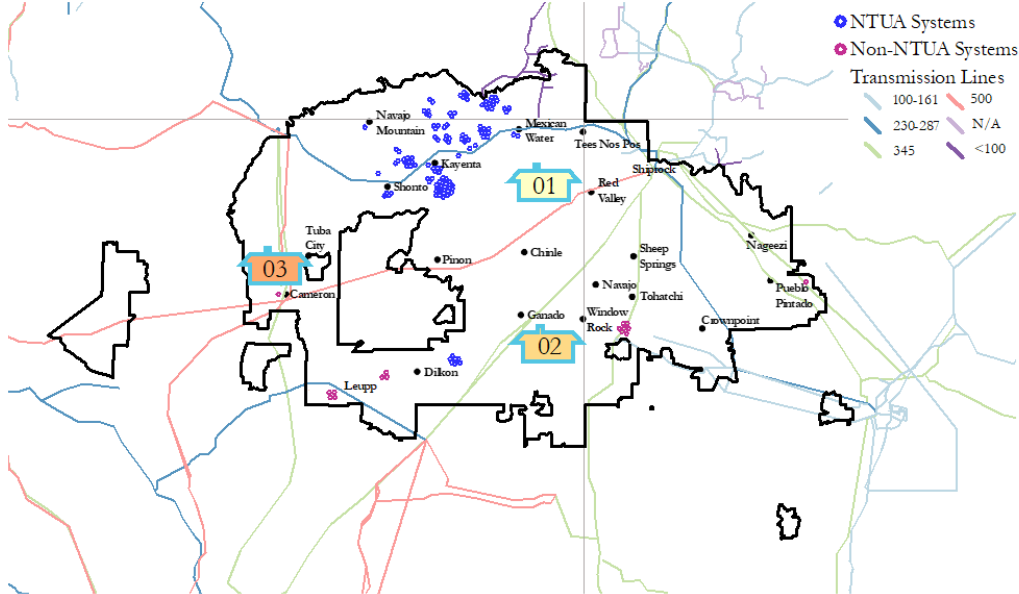


Figure 3-2. Map of small-scale PV System deployment and potential on Navajo Nation. The NTUA systems recorded are from a Sandia National Laboratories archive from former student research on NTUA Electrification Demonstration Program that represents less than half of all NTUA PV systems. The non-NTUA systems are mainly from GRID Alternatives.

4. SIZING OFF-GRID PV SYSTEMS

The technical steps for determining the best system design requires analysis of the site and the type of PV system components available. The process for sizing off-grid renewable energy systems has been documented in different manuals depending on the customer need. Both the process and component supply are focused on two main customer types of the small-scale energy sector: the do-it-yourself homeowner and the rural or “developing” communities. This is reflected in the scope of the manuals and the solar market of pre-packaged off-grid PV systems that contain all the necessary equipment for installation. The ease of installing PV systems has increased to accommodate the assumed lack of technical knowledge of the customer. However, these systems neglect to account for the home-land-family specificities that have been identified in the previous section that consider the values of the Navajo families. The report instead follows the guidance of PV system manuals created with the consideration of Native communities that are presented to be more accessible and readable to the families investing in their energy future with renewable technologies.

4.1. Method

With assistance from various manuals and publications on sizing small-scale off-grid PV systems on Native lands [31]-[36], the process for designing the system has been modified for this report into four major steps:

1. Determine household loading requirements,
2. Assess environmental parameters of the land,
3. Source reliable system components, and
4. Perform a system analysis.

The method will be repeated for each of the three case studies to show the difference in system design and performance. The process is explained in the following sections, but some of the technical expertise and resources necessary to perform certain areas of the sizing process is also highlighted. Many of the calculations and associated graphs were produced with Matlab codes provided by Sandia National Laboratories professionals. [37] These assisted this report’s analysis of the environmental parameters and PV system energy output made with Sandia’s PV Lib Matlab script [38]. The balance between the household input and technical skill allows for the home-land-family considerations to be recognized and implemented into reliable, efficient PV systems.

4.1.1. Determine Household Loading Requirements

The household loading requirement depends on the energy needs identified by the family. This requires an analysis of the appliances being used and the amount of time they are used during a day where the load is the greatest. Table 4-1 provides the framework for quantifying the home size into a kWh/day rating that will then be converted into kW rating for the PV system array. Figure 4-1 shows the additional equation to make the conversion that divides the kWh/day rating of the appliance usage by the total amount of sun hours for the location. Then, the kW rating is multiplied by a certain factor of potential system loss as a means to provide an overloading range before the system completely drains the batteries due to overuse.

Table 4-1. PV system array calculation to determine the total kW rating required to power a certain loading requirement. The amount of sun hours and factor for potential system loss is also considered.

	÷	=	x	1.2	=
kWh/day		Sun Hours	kW	Potential system loss	kW

In the following sections, each case study is given a certain household size that is also given a general appliance calculation to demonstrate the possible appliances available and the amount of each within the home. Their average daily energy demand is then converted into a kW rating that will identify the size of the PV array and the solar panels ratings/count necessary to sustain their daily demand. The “elder size load” is the lowest at 1.2 kW and then the “small family load” at about 2.0 kW followed by the “large family load” at 3 kW. At this stage, many companies ensure that the house has electrical wiring and an in-person load assessment can also be conducted.

4.1.2. Assess Environmental Parameters of the Land

The assessment of the environmental parameters is dependent on the sun’s position and irradiance. This information will tell the homeowner and technical designer at what times of the year the amount of solar resource is high and the specifics of the location of the sun relative to the land area. The sun parameters will also inform the optimal angle of the solar panels relative to the sun’s position at a certain time of year and the best practice for changing the angle. For the simplicity of this evaluation, the angle is at a fixed position at the latitude angle of the specific location, however, with greater technical expertise, the angle can be adjusted twice a year to a summer and winter angle [39].

There are four main graph considerations presented in this report to examine the environmental parameters associated with each home case study. They are based on the sun’s position and irradiance around the time of the four significant solar days of the year: Spring Equinox (March 17), Summer Solstice (June 17), Fall Equinox (September 17), and Winter Solstice (December 17). Home 01 contains all four days for comparison whereas Home 02 and 03 compare Spring Equinox and Winter Solstice as the two most extreme cases of irradiance and sun position. Also, note that the 12 value on the x axis marked under Hours of the Day is solar noon. Among the three home locations, the variables that change are the latitude/longitude/elevation values and the weather data input from cities that are close to the homes. The four graphs can be described as follows related to their day of assessment [38]:

- a) The Irradiance (W/m^2) versus Hours of the Day graph tracks the components of radiation: Eb or the beam component that is in direct line with the sun to receive more radiation and the diffuse components, EdiffSky and EdiffGround, that is scattered radiation
- b) The Angle of Incidence (degrees) versus Hours of the Day graph follows the angle between the direct beam from the sun to the array’s surface
- c) The Zenith and Azimuth Angles (degrees) versus the Hours of the Day graph tracks the zenith angle (angle between the sun and zenith/vertical) and azimuth angle (angle of the sun from due north in a clockwise direction). See Figure 4-1a.

- d) The second Irradiance (W/m^2) versus Hours of the Day graph follows the amount of solar radiation received by a surface: perpendicular to the sun rays (direct normal irradiation, DNI), not from direct path from the sun (diffuse horizontal irradiation, DHI), and horizontal to the ground (global horizontal irradiation, GHI). See Figure 4-1b/c.

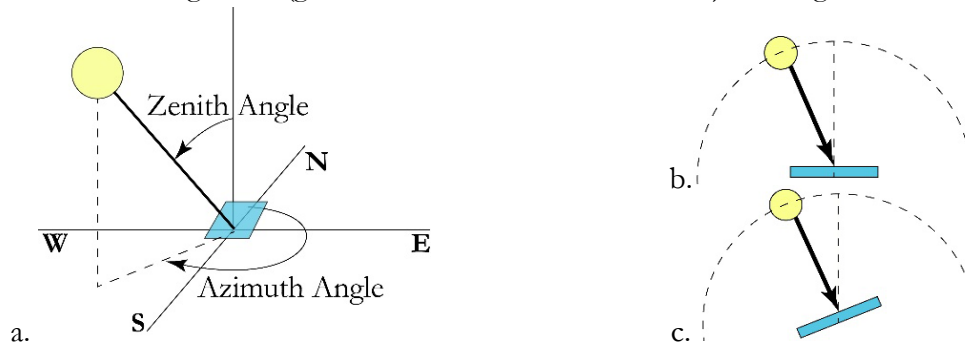


Figure 4-1. a. Graphic of the zenith and azimuth angles b. Graphic of GHI c. Graphic of DNI

Overall, the environmental parameters provide the analysis of the specifics of the land and the resource provided by the sun. Weather conditions are important to understand possibility of shading of the panels due to cloud coverage and the decline in the PV system's power output. The next section in sourcing reliable system components addresses any environmental factors that could reduce the energy system output and the technologies to protect against major losses.

4.1.3. Source Reliable System Components

The types of PV system components available is an important factor in designing the most reliable and efficient system. Many solar companies and suppliers offer pre-packaged, off-grid energy systems that include the major components such as the solar panels/modules, the inverter, racking system, and cabling. However, the system design process requires a more holistic view of the system that considers how all components work together. The main components and their functions are listed below and diagrammed in Figure 4-2:

- Individual Solar Modules to form the PV Array: absorbs sunlight as a source of energy to create direct current (DC) electricity; modules electrically connected in series form a string
- Combiner Box: brings together all the solar strings of the PV modules
- Charge Controller: controls the rate at which electric current is distributed to either the battery bank or inverter; prevents from overcharging the batteries
- Battery Bank: storage for the energy produced by the solar array for nighttime use or extra source during the daytime to draw energy from
- Inverter: converts the direct current (DC) from the PV array to alternate current (AC) that the appliances need to operate
- Back Up Power Source: such as a generator in case PV system goes down
- Racking Systems: mounting systems for the PV array and equipment to operate from

The choice of different components marks another point for additional technical expertise and consultation with solar suppliers. The efficiency and ability for various components to work together, especially when different manufactures are paired together, can cause some inefficiency. For simplicity in this report, the two major components, the solar modules and inverter, are considered and vary depending on the loading requirements and environmental parameters.

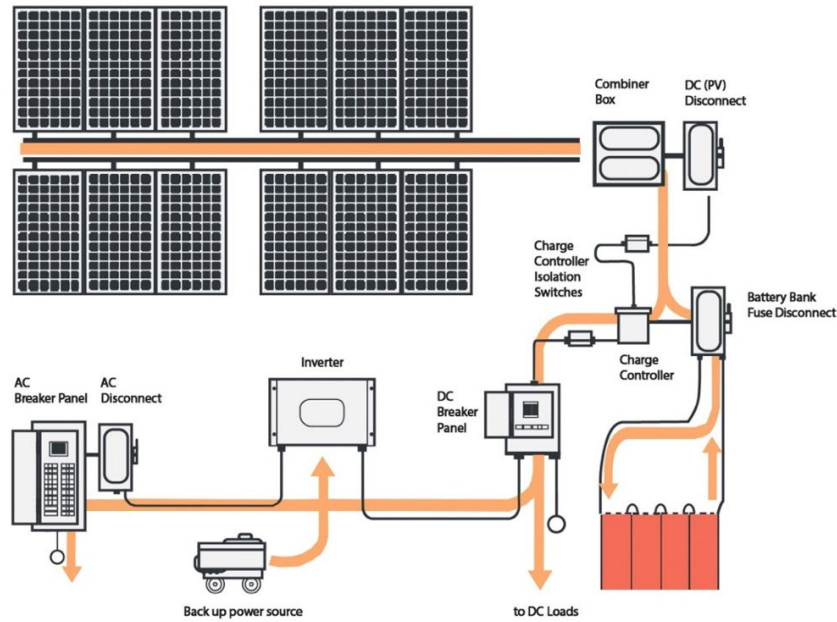
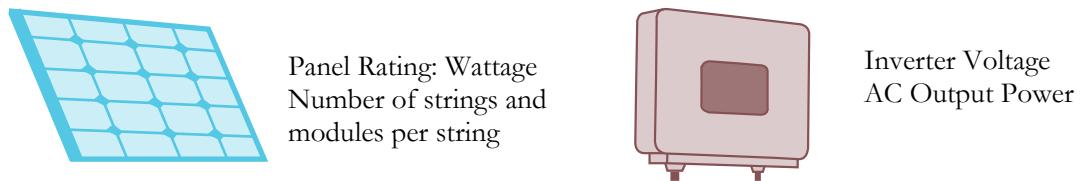


Figure 4-2. Diagram of the connections between the different PV system components (Source <https://solarcalculator.com.au/solar-power-systems/>)

Each home case study has a choice of panel and inverter that is determined by the kW rating found when determining the loading requirements, as seen in the following graphic.



The following criteria and calculations were used to determine the general specifications:

- Panel Rating: the panel rating ranges from 300, 345, 375W and paired with a kW rating
- Number of Strings/Modules Per String: first, the total number of modules was calculated by dividing the required kW rating of the whole system by the W rating of the individual panel. Then, the number of strings and modules per string was chosen based on the total number of modules that allowed for an even distribution.
- Inverter Voltage: all valued at 120 V that is common for household and off-grid usage
- AC Output Power: set to equal the PV array size in kW found in the loading requirements

With the new system component specifications identified, Sandia National Laboratories' database of solar modules and inverters was used to choose specific modules as input values to conduct the system analysis outlined in the next section [38].

4.1.4. Perform a System Analysis

The PV system performance analysis was used to understand the power output of the entire system and the individual modules. The PV Lib function [38] and code from Sandia National Laboratories' professionals [37] was used to generate the two main graphs describing the power output of the PV system designs. The input variables that changed for each home case study are as follows:

- Latitude/longitude/elevation values of the site
- Weather data from nearby cities in the TMYData format defined by the PV Lib function
- PV module with associated specifications and coefficients from Sandia's module database
- Inverter with associated specifications and coefficients from Sandia's inverter database
- The array configuration describing the number of modules in series and in parallel
- Additional array parameters (Array.a and Array.b) listed in Sandia's module database

The variance in environmental parameters and PV system components all contributed the difference in power output between each home. The two figures in the System Performance Analysis section describe the power output of the system based on solar module tilts during the year and specifics to the module/inverter combination:

- Single Panel Power Output (W) versus Day of the Year depending on the tilt of the solar modules was determined by compiling power production data from certain days of the year as the array tilt angle adjusted around the location's latitude degree value
 - a. System Power (W) versus Hours of the Day of both AC and DC. Power is equal to current times voltage ($P = I * V$) for the system during certain sun hours of the daytime
 - b. Module DC Current (A) versus Hours of the Day from the determined by the specifications and coefficients listed in the Sandia module database
 - c. Module DC Voltage (V) versus Hours of the Day from determined by the specifications and coefficients listed in the Sandia module database

Further evaluation of the graphs of the system performance analysis will determine the efficiency of the module/inverter combination as a product of its comparative DC and AC power output. The next sections will put into practice the sizing off-grid PV system method of three different homes on the Navajo Nation that will provide a framework for future renewable energy deployments.

4.2. Home 01

Lukachukai/Tsaile Chapters

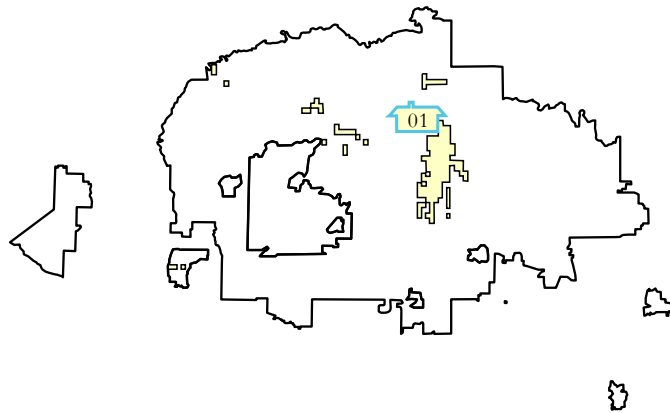
Solar Resource: 6.0-6.5 kWh/m²/day

Latitude: 36.43°

Longitude: -109.24°

Altitude: 1972 m

Other Considerations:



Close to Diné college that has people commuting from the general area of the shaded region. Lukachukai reports gaining population due to younger families moving back after college [40]. The area also reports their populations as progressive due to the younger generations that may be open to sustainable ways of living and opportunity to integrate renewable energy [41].

4.2.1. Loading Requirements

Large Family: 3 kW PV array

The Large Family load outlines one possible appliance arrangement and associated time usage that the average family size of around five people may consider. The 3 kW rating also reflects a model that NTUA explained they may implement for the next phase of their renewable deployments.

Table 4-2. Energy calculation chart for Home 01 to determine the size of PV system.

Appliance	Wattage (W)		Time Used per Day (hours)		Wh/day		kWh/day	
Large Refrigerator	800	x	10	=	8000	÷ 1000	= 8	
Washing Machine	500	x	1	=	500	÷ 1000	= 0.5	
Dryer	3000	x	1	=	3000	÷ 1000	= 3	
TV	250	x	5	=	1250	÷ 1000	= 1.25	
TV	200	x	2	=	400	÷ 1000	= 0.4	
10 LED Lights	100	x	8	=	800	÷ 1000	= .8	
Appliance	600	x	.5	=	300	÷ 1000	= .3	
Appliance	1100	x	.25	=	275	÷ 1000	= .275	
Appliance	300	x	.5	=	150	÷ 1000	= .15	
Chargers	5	x	2	=	10	÷ 1000	= 0.01	
							=	14.69

14.69	÷	6	=	2.448	x	1.2	=	2.937
kWh/day		Sun Hours		kW		Potential system loss		kW

4.2.2. Environmental Parameters

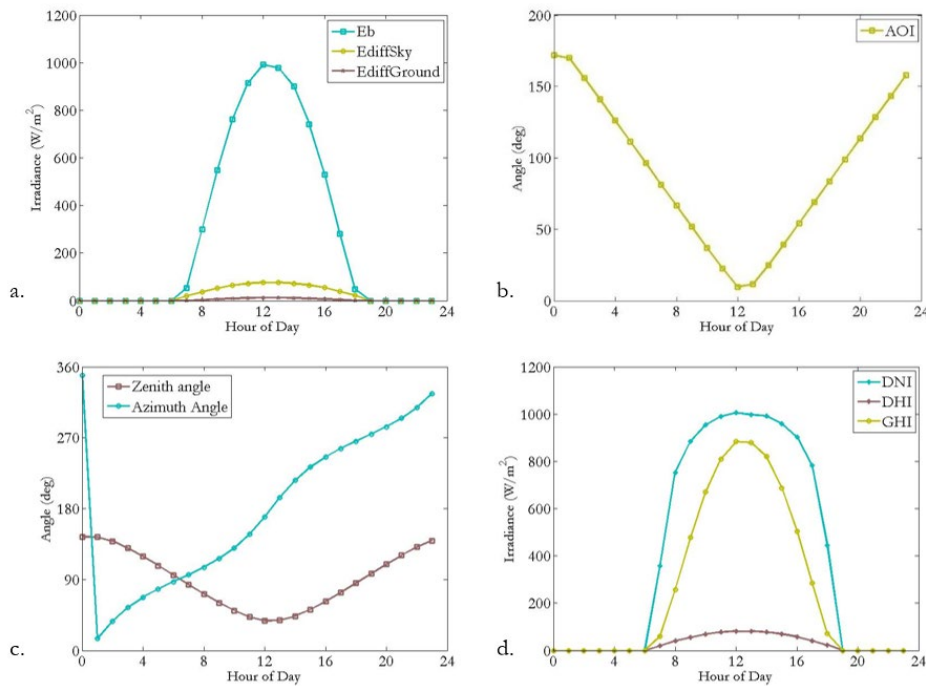


Figure 4-3. Analysis of the environmental parameters during spring equinox (March 17), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI

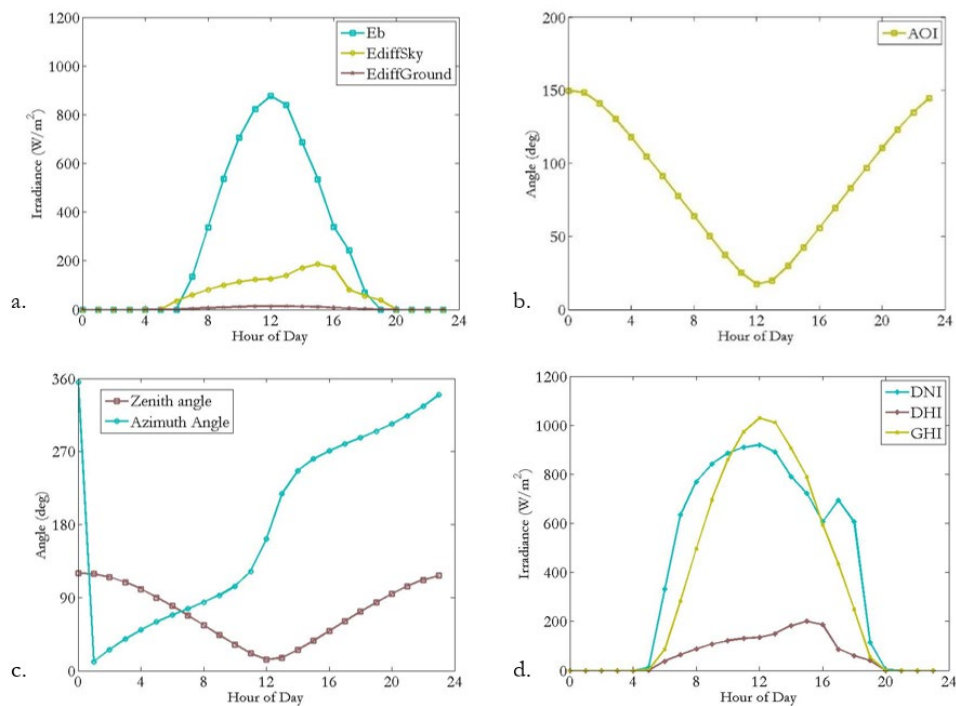


Figure 4-4. Analysis of the environmental parameters during summer solstice (June 17), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI

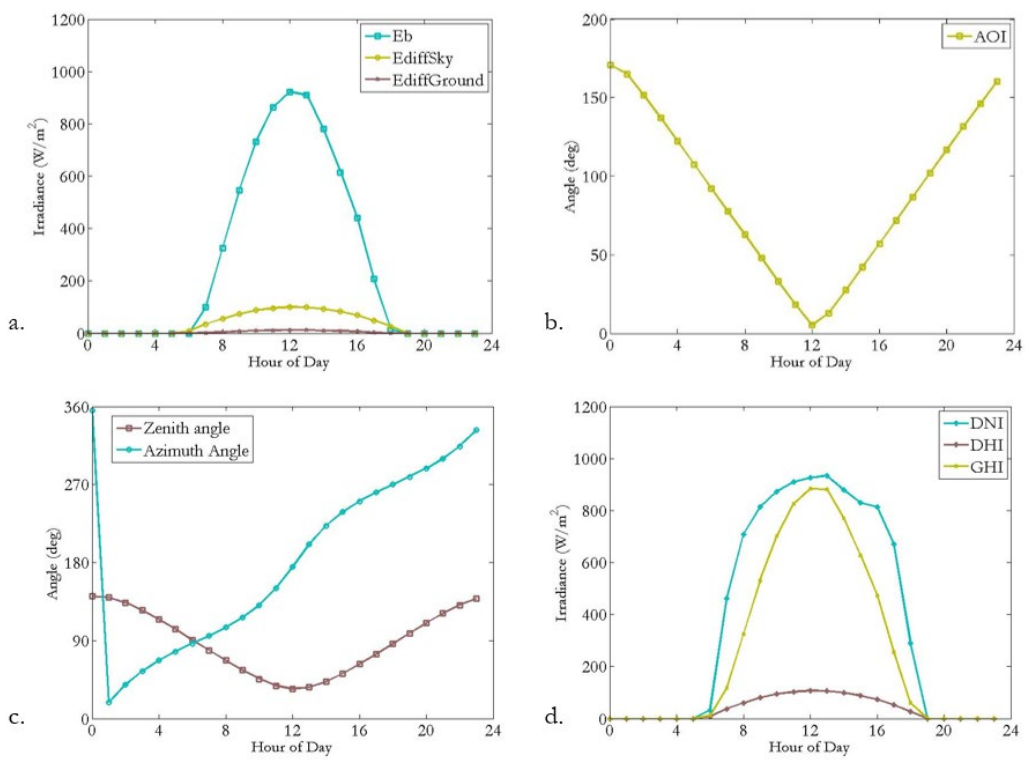


Figure 4-5. Analysis of the environmental parameters during fall equinox (September 17), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI

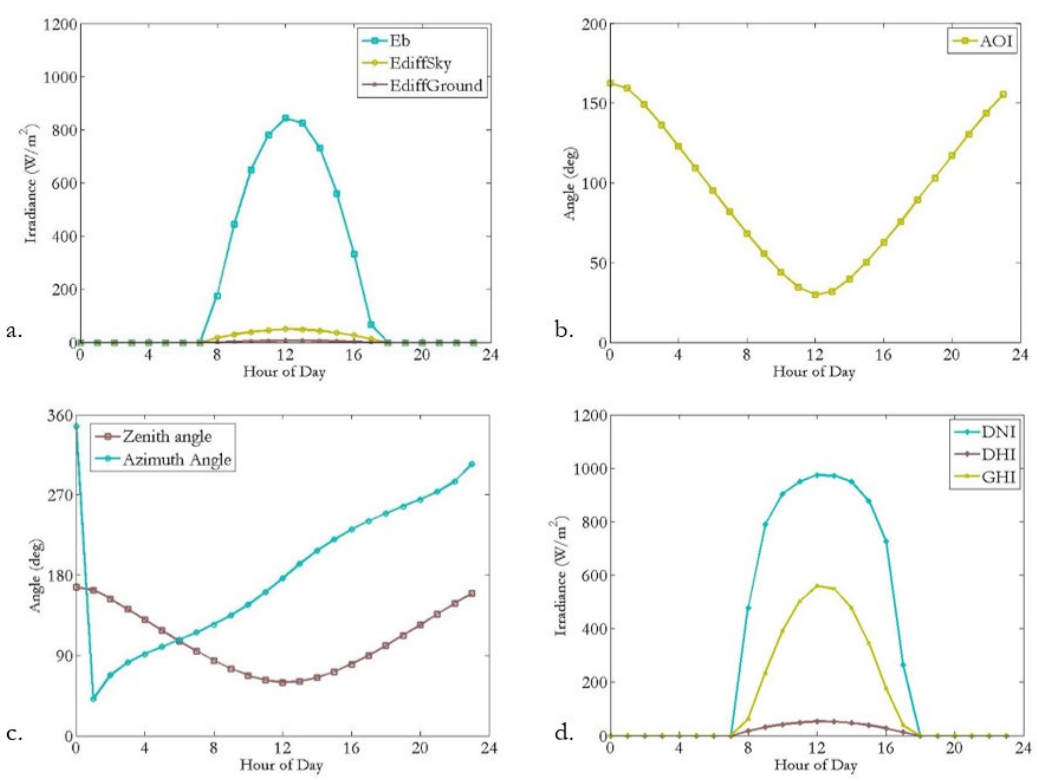


Figure 4-6. Analysis of the environmental parameters during winter solstice (December 17), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI

4.2.3. System Performance Analysis

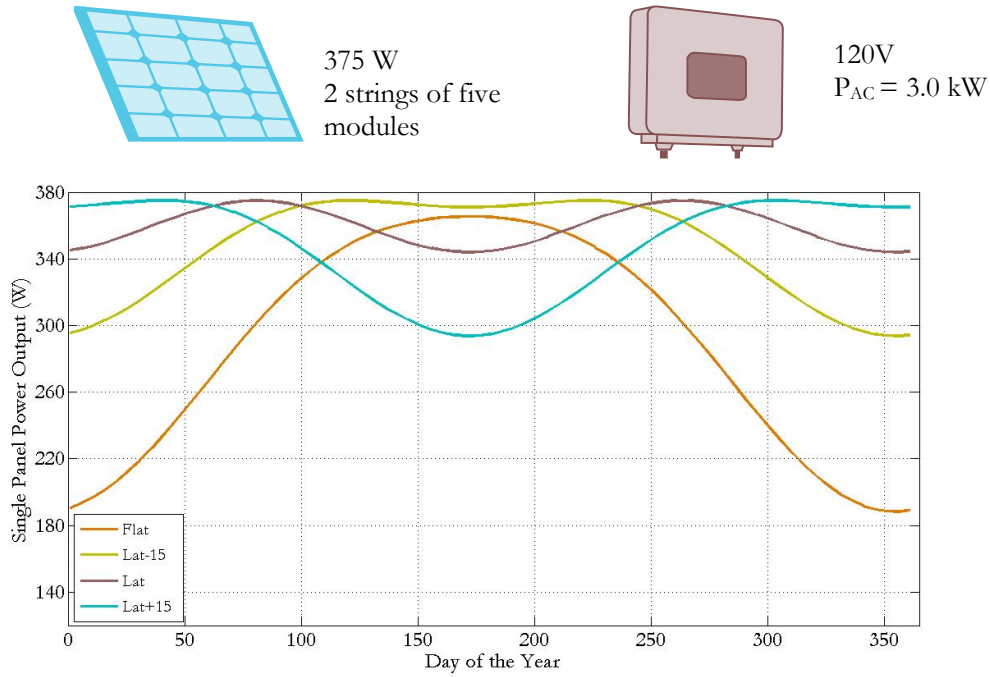


Figure 4-7. Module Power Output (W) at Solar Noon vs. Day of Year depending on the tilt angle of the solar modules (flat to the ground, at latitude angle of 36.43° and adding or subtracting 15° from latitude)

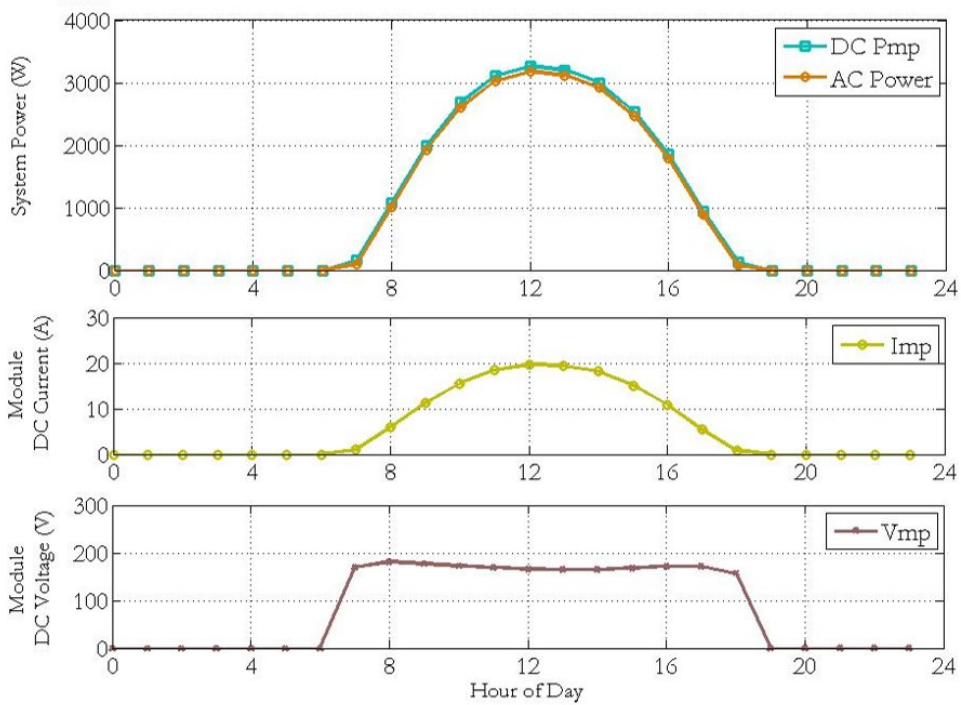


Figure 4-8. a. System DC and AC Power Output (W) vs. Hours of the Day of PV System, b. Module DC Current (A) vs. Hours of the Day, c. Module DC Voltage (V) vs. Hours of the Day

4.3. Home 02

Kinlichee Chapter

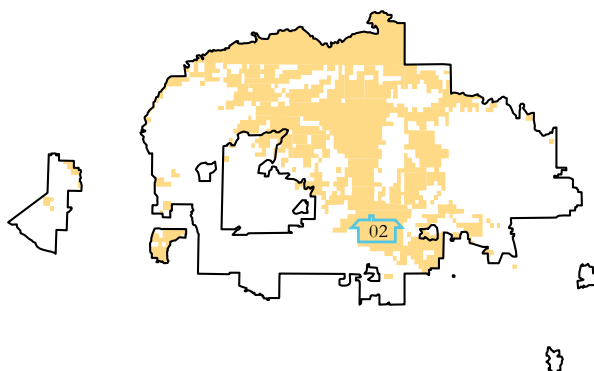
Solar Resource: 6.5-7.0 kWh/m²/day

Latitude: 35.56°

Longitude: -109.43°

Altitude: 2202 m

Other Considerations:



Further away from power lines shown in Figure 3-2. The chapter is also in an area that doesn't have a large number of small-scale PV deployments in the area whereas other locations within the solar resource range, such as Kayenta, have many projects in the area run under NTUA. There is greater potential to test new methods for the PV system sizing process.

4.3.1. Loading Requirements

Elder Load: 1.2kW

The Elder Load accommodates some of the appliances of the family size that includes an elder or other smaller size home living where large electricity usage is not necessary. Many of the current small-scale renewable deployments average around this size. They are also designed to work with a certain type of refrigerator since this tends to be the appliance with the most energy usage. However, one maintenance issue discussed among current deployments was overloading the system when other appliances were added or used for longer than the PV system could supply the required amount of energy. The energy calculation sheet below attempts to lower the possibility of overloading if the family understands how to distribute their appliances and how long to use them. It also suggests larger families to consider designs for larger systems if they know the current PV systems available are at risk for overloading under their energy requirements. The Elder Load size is meant for those with a small household size with minimal energy demand.

Table 4-3. Energy calculation chart for Home 02 to determine the size of PV system.

Appliance	Wattage (W)		Time Used per Day (hours)		Wh/day		kWh/day
Heater	1300	x	3	=	3900	÷ 1000	= 3.9
Small Refrigerator	220	x	8	=	1760	÷ 1000	= 1.76
3 LED Lights	30	x	4	=	120	÷ 1000	= .12
Appliance	600	x	.25	=	150	÷ 1000	= .15
							= 5.93

5.93	÷	6	=	0.988	x	1.2	=	1.186
kWh/day		Sun Hours		kW		Potential system loss		kW

4.3.2. Environmental Parameters

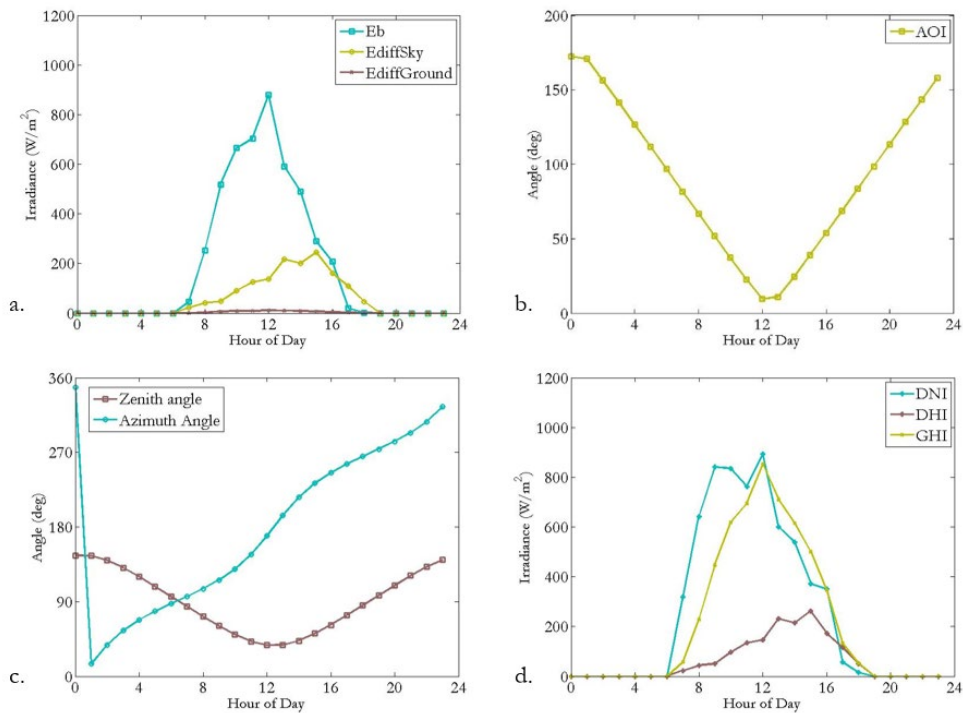


Figure 4-9. Analysis of the environmental parameters during spring equinox (March 16), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI

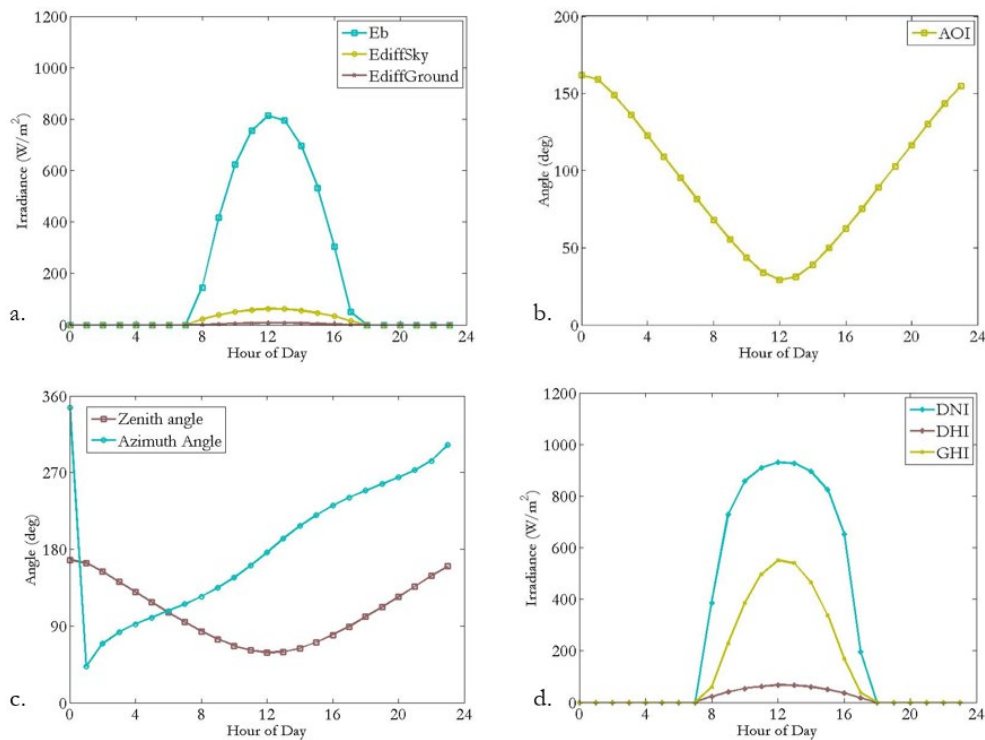


Figure 4-10. Analysis of the environmental parameters during winter solstice (December 16), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI

4.3.3. System Performance Analysis

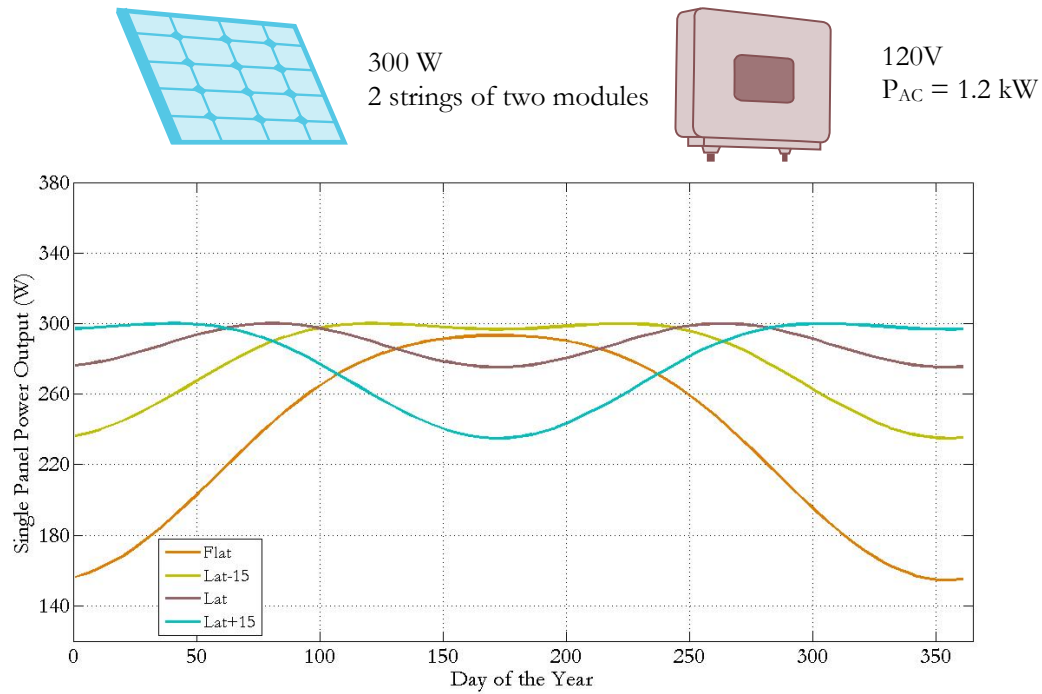


Figure 4-11. Module Power Output (W) at Solar Noon vs. Day of Year depending on the tilt angle of the solar modules (flat to the ground, at latitude angle of 36.43° and adding or subtracting 15° from latitude)

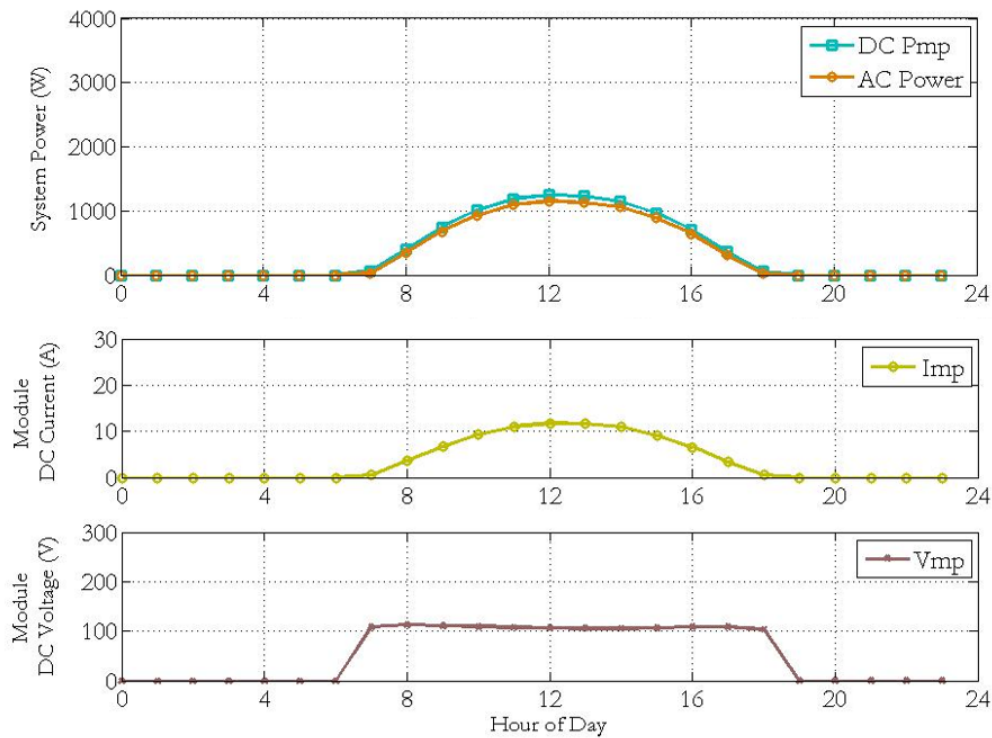


Figure 4-12. a. System DC and AC Power Output (W) vs. Hours of the Day of PV System, b. Module DC Current (A) vs. Hours of the Day, c. Module DC Voltage (V) vs. Hours of the Day

4.4. Home 03

Cameron/Coalmine Mesa Chapters

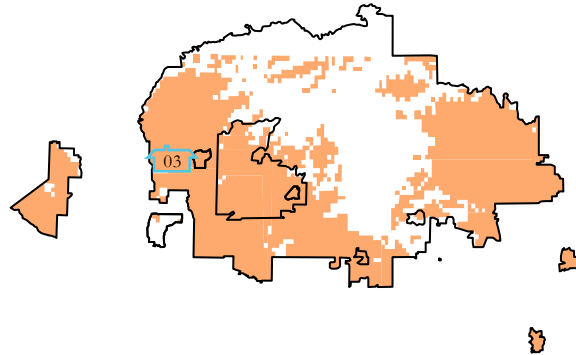
Solar Resource: 7.0-5.5 kWh/m²/day

Latitude: 35.86°

Longitude: -111.45°

Altitude: 1362 m

Other Considerations:



Possibility for chapter to approve a utility-scale solar field similar to the Kayenta project that has the possibility to generate revenue to fund local requests for small-scale PV systems [42]. Most NTUA units in the Kayenta area are showing a trend in utility-scale solar and the ability to use its revenue to fund local renewable projects. Cameron has a similar opportunity.

4.4.1. Loading Requirements

Small Family Load: 2.0 kW

The Small Family Load is meant for a family of three to four people. The middle size of the three case studies accommodates a larger refrigerator size and more appliances that are used for short periods of time such as microwaves and other kitchen appliances. When considering the types of appliances, the demographics of the family are considered. An older family may have more use for larger kitchen appliances whereas a younger family may have more electronics use. These considerations can be applied as each family expresses their energy usage through the calculations.

Table 4-4. Energy calculation chart for Home 03 to determine the size of PV system.

Appliance	Wattage (W)		Time Used per Day (hours)		Wh/day		kWh/day	
Large Refrigerator	800	x	10	=	8000	÷ 1000	= 8	
TV	250	x	3	=	750	÷ 1000	.75	
6 LED Lights	60	x	6	=	360	÷ 1000	.36	
Appliance	600	x	.5	=	300	÷ 1000	= .3	
Appliance	1100	x	.25	=	275	÷ 1000	.275	
Appliance	300	x	.5	=	150	÷ 1000	.15	
Chargers	5	x	.5	=	2.5	÷ 1000	0.0025	
							=	9.84

$$9.84 \div 6 = 1.640 \times 1.2 = \mathbf{1.968}$$

kWh/day	Sun Hours	kW	Potential system loss	kW
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4.4.2. Environmental Parameters

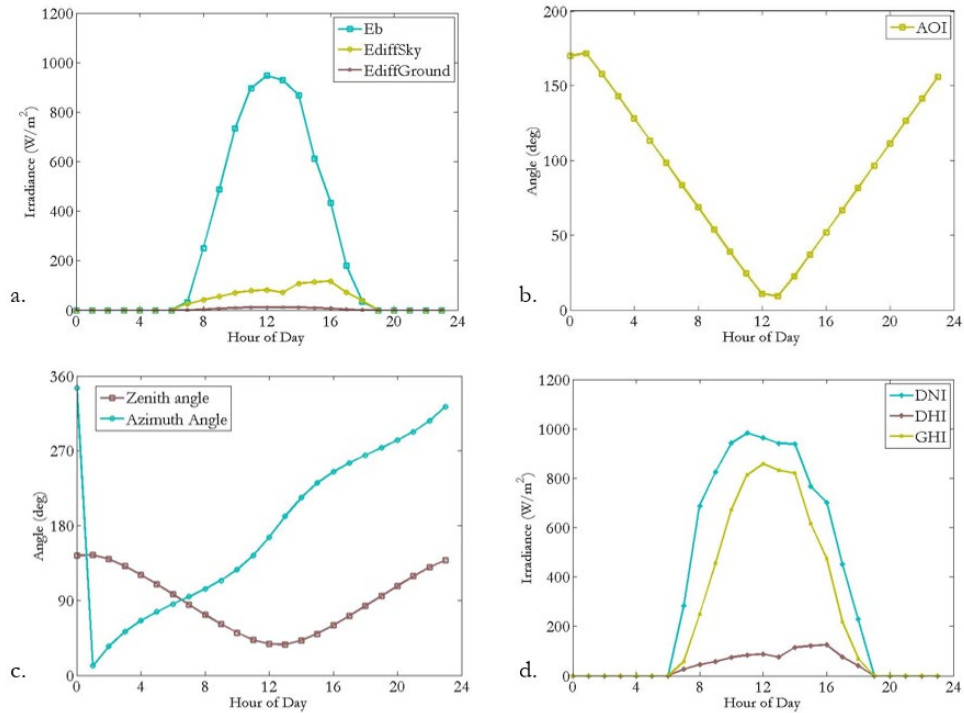


Figure 4-13. Analysis of the environmental parameters during spring equinox (March 18), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI

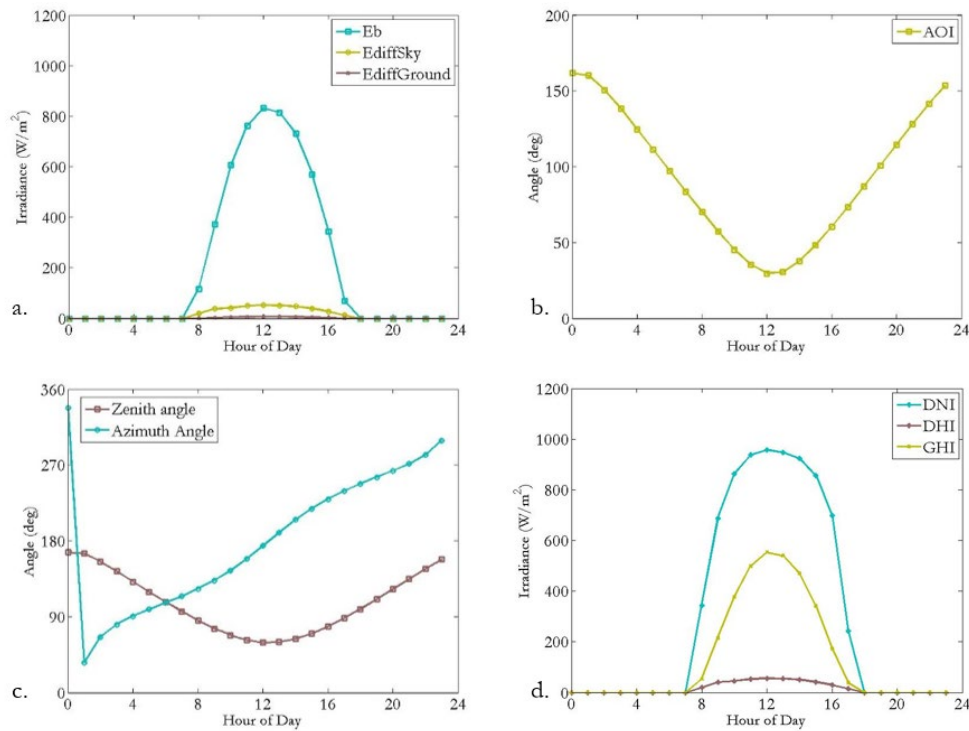


Figure 4-14. Analysis of the environmental parameters during winter solstice (December 18), related to a. Irradiance, b. Angle of Incidence, c. Zenith/Azimuth angles and d. DHI/GHI/DNI

4.4.3. System Performance Analysis

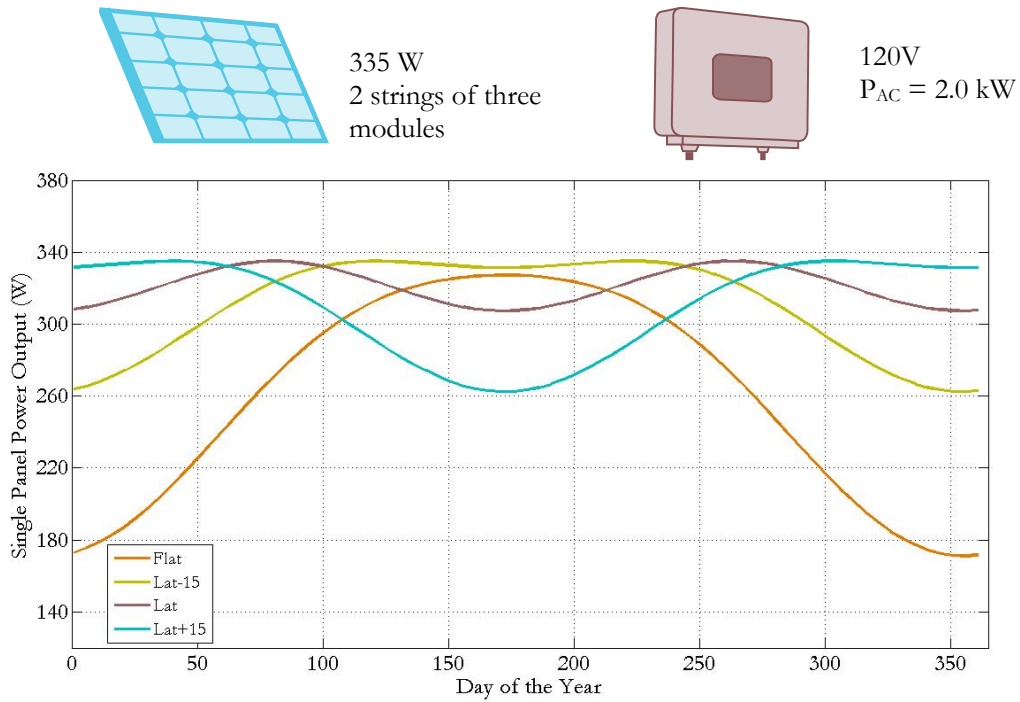


Figure 4-15. Module Power Output (W) at Solar Noon vs. Day of Year depending on the tilt angle of the solar modules (flat to the ground, at latitude angle of 36.43° and adding or subtracting 15° from latitude)

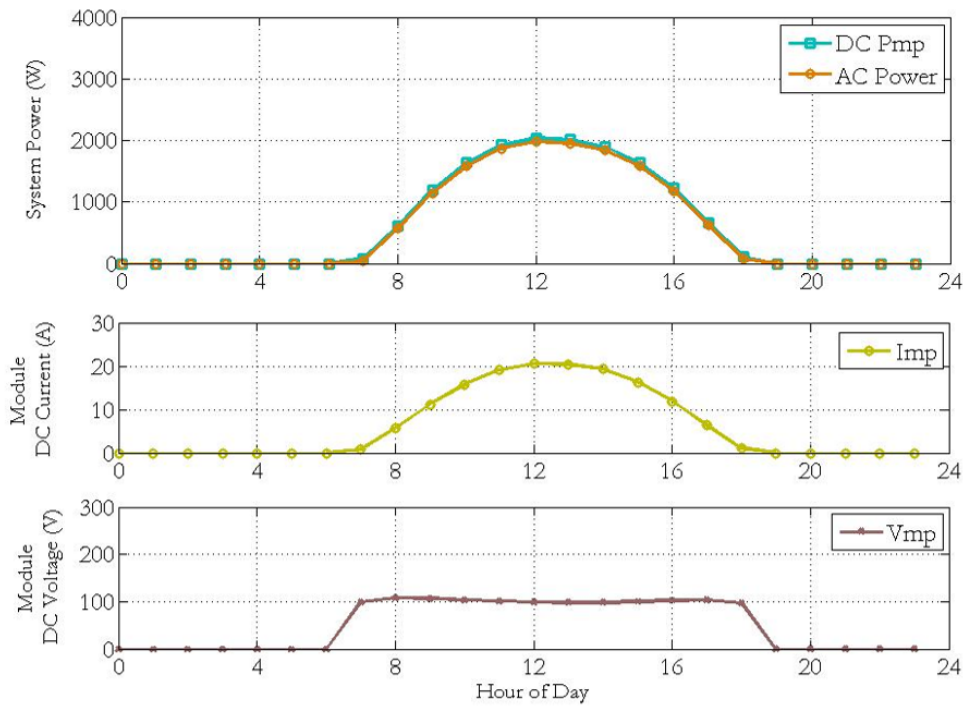


Figure 4-16. a. System DC and AC Power Output (W) vs. Hours of the Day of PV System, b. Module DC Current (A) vs. Hours of the Day, c. Module DC Voltage (V) vs. Hours of the Day

5. PROCESS DISCUSSION

By relating the location and size of the home to solar resource and loading requirements, the different case studies were able to inform the process of sizing the PV systems for each home. The two outputs of environmental parameters and system performance analysis are shown in the similar trends and important differences when all of the graphs in the previous sections are compared. The following paragraphs detail observations from conducting the sizing process and the considerations that are identified from the comparisons.

5.1. Trends of the Environmental Parameters

The graphs for each of the environmental parameters are similar amongst all the case studies, however, the main differences are between the various times of year each graph was observed. The main outcomes relate to the amount of distribution of irradiance and the position of the sun. The following analysis of each section will describe the common trends and their impact on the PV system design.

- a. Generally, the Eb irradiance is much higher than the scattered components of the irradiance. The irradiance is also higher during the Spring Equinox than Winter Solstice which is reflected in the sun's position (graphs b and c); in spring, the sun is higher in the sky for a longer period of time. The major shift in irradiance should be considered either in designing for Winter Solstice as the baseline irradiance value or communicating to the home that they should use less energy in the winter.
- b. The angle of incidence has a U-shaped graph where the lowest value at solar noon represents the sun ray being in line with the position of the module panel angle. This contributes to the high value of irradiance at solar noon as well since the sun rays are in direct line with the module cells to capture the most solar energy. The spring position of the sun is more likely to be at the same angle than the winter position. The angle of incidence can also determine the optimized tilt of the modules. In the region that the Navajo Nation is in, most solar panels are tilted southwards at latitude, but when considering how the angle of incidence changes throughout the year, a better angle can be determined which is further developed in the System Performance Analysis.
- c. The greater the zenith angle, the further the sun is away from the vertical from the ground which is typically reflected in the graph of the winter sun position. In the winter, the azimuth angle is less variable between 0 and 360° than in the spring. Both angles work together to position the sun in the sky relative to the ground and distinguishes a lower position during the winter time. This relates to less irradiance during the winter due to the visibility of the sun and how its rays hit the modules. All the angle outputs suggest for the tilt angle of the modules to be changed to accommodate the major differences in irradiance from Spring Equinox to Winter Solstice. It is suggested to adjust to the summer angle (closer to the ground) in March and the winter angle (further titled up from the ground) during September [39].

- d. The major difference between direct normal irradiance (DNI) and global horizontal irradiance (GHI) occurs in the winter where DNI is much greater. However, in the summer, the DNI and GHI values are closer together. This means that during the summer, the angle of the module perpendicular to the sun rays versus horizontal to the ground doesn't matter as much as it does in the winter time. The winter time is, again, identified as a baseline irradiance input value since it varies more depending on the module title angle and the homeowner should be aware that their energy usage in the winter should be less due to less solar resource.

The environmental parameters will help inform the tilt angle of the modules to produce the most optimal energy production. Another consideration should be the weather conditions reflected in the distorted graphs such as for Home 02 where the irradiance slopes are more jagged due to cloud coverage reported in the weather data from that day. Overall, the environmental parameters are similar for each of the home case studies, but the different reports of weather in those areas are different causing more variability in irradiance and therefore the energy production of the modules receiving less solar resource. Looking closer at these differences between each household location will provide more accurate data to better determine the efficiency of the solar modules and their energy production throughout the year.

5.2. Comparison of System Performance Analysis

The graphs for the system performance analysis reflect the relationship between the environmental parameters and the choice of system components to the power output of the entire PV system and its individual modules. The three parts of the analysis included the choice of system components, the power output related to module tilt, and the power output related to the modules and its array size.

The main two system components considered were the modules and inverter. The choice of each is outlined in the Source Reliable System Components section (4.1.3) and applied for each case study. Although the manufacturers are not listed, the technical analysis does consider the specifications of specific modules and inverters with coefficients produced by Sandia National Laboratories that are also unpublished but were used for the calculations. The choice of components is important in having the ability to predict system output to apply optimizations but also allows for greater flexibility for each individual system. Current renewable deployments often talked about systems that were given to homes from manufacturers or suppliers without the homeowners understanding the source or if they were efficient for their energy requirements. Designing the individual PV systems creates more flexibility to pick certain components and pair them with others to determine which has the best energy output. Also, knowing the specifications of each makes the calculations more accurate and specific to the home it will be powering.

The power output related to the module tilt is graphed in Figure 4-1 and considers the tilt at four different angles throughout the year. The conclusions from the environmental parameters related to the tilt angle are confirmed in the power output graph. During the winter days, the latitude + 15° has a higher energy output because it requires more tilt to account for the lower position of the sun. During the summer times, the latitude - 15° has the highest so adjusting the angle will produce the most power output. However, if the tilt angle is fixed, the consistency of the latitude slope on the graph represents an average tilt angle close to the highest power output. The technical analysis of the system performance confirms the more generalized ideas of the environmental parameters and assigns a number value in order to determine future optimizations.

The power output relating to the module types and its components is represented in Figure 4-2 in the three parts. Overall, the highest point of the power output reaches the wattage rating of the array size. The first graph shows the DC and AC power output. The DC power is slightly larger than the AC power output because once the DC is converted to AC within the inverter, there is some energy loss that is dependent on the inverter type. This graph also shows how the power output changes throughout the day where surrounding the solar noon time frame is the time where all the power is produced. It is important for the family to understand when their PV system array is producing energy versus when their battery supply is in use. The second graph relates to the specifications of the module that looks at the change in DC current throughout the day. The third graph looks at the DC voltage of the modules that is important to understand how the overall system power output is calculated. The values from the two lower graphs of current and voltage are multiplied to get the system power output for that hour of the day. The power output can be conducted for each module and inverter pair which was done for different configurations with the highest and optimal power output presented in the report. The system performance power output allows for the choice of components to be identified with a specific number value and can be compared for the highest power output for the home to choose from.

Comparing all the graphs, their shapes look similar, but the highest values and range of values vary where the lowest rated modules and loading requirement, the Elder Load, has the lowest values and the highest is the Large Family Load. They are all very different in the final outcome of PV system power output and reflect the important decision of designing individual systems rather than offering a single model.

6. CONCLUSION

The variation of all system performance analyses for each home size proves to be important in the significant differences between the three case studies presented. The final conclusions and next steps of the sizing renewables process are identified as increased optimizations, greater flexibility, and introducing choice to the individual households as they determine their energy futures.

6.1. Optimization

Both the environmental parameters and system performance analysis sections outlined some of the specific optimizations that can be made as far as the module tilt angle or the choice of specific components. With access to the resources and tests conducted at Sandia National Laboratories, observing where the PV system's power output peaks will determine which system design is working with the greatest efficiency. The performance analysis in this report is treated as a preliminary indicator of what components would work well together to produce the highest power output. It demonstrates the potential to perform closer analysis under those with greater technical expertise suggested for this type of system design. Further considerations would include relating power output to costs. The cost is another major factor that will determine how optimal a system is working relative to the initial expense of the PV system units or combined components. There is the possibility that higher cost components only provide a small change in efficiency which isn't worth the investment. Overall, evaluating the specific characteristics of each home provides more data for the performance to be analyzed for better optimizations of the PV system.

6.2. Flexibility

The individual PV designs allow for a home to have flexibility in its choice of system and how it may change in the future. During the initial step to determine the loading requirements, the family is allowed to choose their own appliance usage rather than be constricted to the wattage rating of previously designed systems. Rather than trying to fit their energy demand to the system, the system is designed for the energy demand that is valuable for their home. Within this, there is greater flexibility to consider growth of the system in the future. For example, a small family may have plans to expand their family or plan to expand their system once their finances allow which will change their energy demand. If communicated at the beginning of the sizing process, the PV system can be designed with future growth in mind to add additional modules or batteries. Flexibility is also observed in the choice of components. Solar technologies are constantly expanding and without being tied to a specific manufacturer or pre-packaged system, these technologies can be incorporated that also contribute to optimization. One additional consideration could be the use of microinverters that are connected to each module to protect the system against shading issues. These microinverters have mainly been used for grid-connected systems, but these off-grid systems offer the opportunity for new innovations. For all sizes of renewable efforts, Native communities have been identified as ideal landscapes for renewables in both solar resource and the potential to deploy new technologies. Flexibility allows for more variation and possibility to incorporate new innovations in the solar market.

6.3. Choice

The potential for renewable deployments on Native lands to enter the larger renewables market is high. In the effort to avoid following the same structures as extractive industries or solar companies trying to enter Native markets, the Native owned renewables market could add another source of economic development on the Navajo Nation that would have some benefit for its community members. Brett Isaac talks about planning Navajo Power's large-scale projects to generate revenue to fund smaller electrification projects or community development corporations [13]. The Navajo Nation has the opportunity to lead Native communities in energy production practices that resist past structures of harm and dependency. Renewables have been described as one method to achieve "a more self-reliant, financially and politically autonomous future," that contribute to notions of the expression of energy sovereignty [43]. Energy sovereignty for Native communities allows for more choice and self-determination in the sustainable projects they are creating and implementing themselves. This choice is also passed down to the individual household level through the ability to opt in.

The small-scale PV systems allow Navajo families to generate their own energy without being dependent on the grid system. It also allows access to electricity to those who are not financially able to connect to the grid. There are also the families in the situation where the PV systems are temporary while they wait for their homes to be connected to the grid. All three situations can be accommodated in the system design if the homeowners voice their intentions at the beginning. Navajo families have the ability to participate in deciding their energy future through the design process of the small-scale PV system. The technical application of choice has been integrated in the system design process to demonstrate the necessity to consider the decisions of the household as measured by increased optimization and flexibility. Without including the home, issues with overloading and failure of equipment will persist as previous unsuccessful renewable deployments may burden families. This report focuses on how the choice within the technical design can address the more mechanical issues, however, choice related to energy will always have its limitations due to the capacity of resource and material or the people planning its deployments. Future planning considerations are the next steps towards the implementation of these small-scale PV systems which has been a difficult operation to address as most companies have discussed. Programs to sustain basic maintenance or repair are in the process of being developed but have not been optimized for Native communities in rural areas with limited funding and onsite technical assistance. The future of this project is to expand from the technical application into the planning process.

In conclusion, to consider the families that the PV systems are servicing allows for system optimizations to be made specific to the home and flexibility for the futures of the families. By assigning home location and family size a number variable within the calculation process, home-land-family specificities can be integrated into the system design process. Previously, the sizing process has generalized these variables and run into issues with overloading the system or failure of its components. The system performance analyses prove higher values of system power output for the design specific to the characteristics of the home. The proposal for this home-land-family specific method for sizing small-scale PV systems provides an alternate approach with larger consideration for the land that will lead to greater optimizations and flexibility. Allowing the families to have greater participation in deciding their energy futures will result in better care for the PV systems at the individual level, but it also helps the Navajo Nation practice a cleaner means of producing energy. Integrating choice technically improves the design, but as a whole produces a more sustainable and self-sufficient opportunity to create a better energy future starting from the home.

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