PAN AMERICAN HEALTH ORGANIZATION

OFF-GRID PHOTOVOLTAIC SYSTEM
FOR SMALL HEALTH FACILITIES

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Abstract

This report was commissioned by the Pan American Health Organization and deals with the implementation of Off Grid PV Systems for small health facilities in the Caribbean. The initial section of the report touches on other renewable energy strategies and looks at the comparison of Grid-Tied and Off-Grid PV Systems. The body of the report focuses on the design guidelines for an Off Grid PV system. A typical small Health facility was used as a design example. While it is noted that Off Grid PV systems are applicable to facilities which are located in remote areas which do not have a Utility Supply, the Design Concepts that are detailed for the Health Facility in the example will be applicable to any remote health facility. The maintenance of PV Systems is also covered in the latter section of the report. It is anticipated that this report can be used as a guide to educate stakeholders and Engineers in the Caribbean so that they can be informed on the issues to be considered with implementing PV systems in Health Facilities under their control.

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GLOSSARY

Altitude Angle – The angle between the sun and a vertical line. Used to measure the elevation of the sun from the earth's surface.

Azimuth Angle – The horizontal angle measured clockwise from the north cardinal direction. Used to measure the angle of the sun from due north.

Battery – A device which stores electrical energy and provides power to electrical appliances

Critical Load – Any equipment or appliance that is deemed important and needs to be powered at all times

Days of Autonomy – The length of time the system will operate without any generation sources

Electrical Load – Any equipment or appliance that consumes electric power

Grid – An interconnected electrical network used to provide electricity from producers to consumers

Grid-tied – Enabling the use and supply of electricity to/from the local utilities provider.

Inverter – An electrical device that changes Direct Current (DC) to Alternating Current (AC)

Maximum Power Point Tracking (MPPT) Controller – An electronic DC to DC converter that optimizes the voltage match between the solar array and the battery bank.

Off-Grid – Not connected to any specific local utility for power use.

Photovoltaic (PV) – A method of generating electric power through the use of solar radiation.

Pulse Width Modulation (PWM) – A modulation technique used to control the supply of power to electrical devices.

Renewable sources – Resources that are naturally replenished on a human time scale

Solar Irradiation – The Power per unit area received from the sun

Solar Isolation – The amount of solar radiation incident on the earth's surface

Tilt Angle – The angle from the earth's surface and the face of a solar panel.

Winter Solstice – The day in the year with the shortest period of daylight. Designated as December 21^{st}.

Introduction

This document details guidelines for the implementation and maintenance of Off-Grid PV systems in small health facilities. While the implementation of Off-Grid systems is applicable to remote areas where there is no available supply of electricity from the Utility, many facilities with access to electricity utilize PV systems to reduce electricity cost. In such cases the PV system produces electricity for the facility and in cases where the demand is less than that which is generated by the PV system, the excess is sold to the Utility Company. This is known as a Grid-tied system and is beneficial in reducing energy costs while still contributing to the community and the environment. At this time most Utility companies in the Caribbean do not have facilities in place to facilitate paying back for electricity generated by PV systems. This is expected to change in the near future given the focus on alternative energy and reducing the carbon footprint in the world today. Most times, unreliable supply from Utility companies and the lack of policies and systems in place to facilitate pay back of electricity provided to the grid, result in the installation of Off-grid systems as opposed to Grid-tied systems. However, there are many advantages and disadvantages associated each one.

Grid-Tied Photovoltaic systems

The majority of projects that has access to a grid supply will use a Grid-tied system and will not consider Off-Grid due to the associated high cost. The storage of power to cater for twenty-four (24) hour operation and the space requirements for PV arrays all impact on the cost of Off-Grid systems. It is therefore important that an economic analysis be done when considering Off-Grid VS Grid-tied systems. The main issues that need to be considered are:

1. The Electricity Company's willingness to allow the public to provide power to their distribution networks through the use of PV systems.
2. Are there systems in place to provide compensation to clients who provide additional electricity to the grid?

When considering a grid-tied system, it is necessary to consult with the local utility company and discuss the procedure of implementing a grid-tied system. A representation of a Grid-Tied system is illustrated in Figure 1 below:

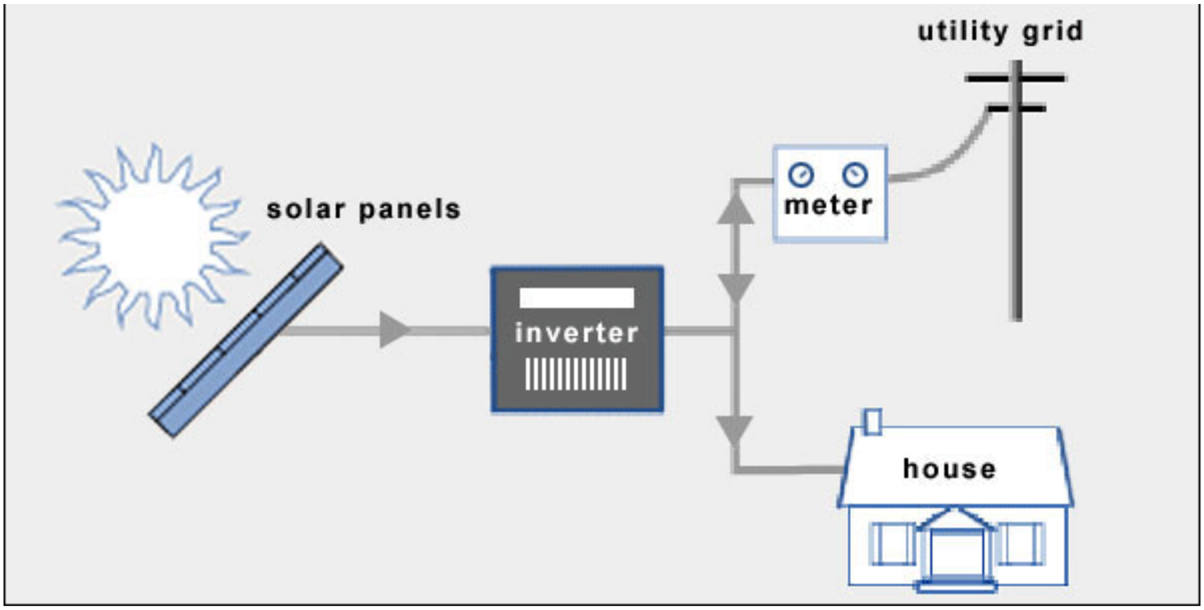

Figure 1 : Grid-Tied Photovoltaic System (Maehlum, 2013)

From the figure above, apart from the solar panels, the only equipment needed for a Grid-tied system is an Inverter and a Power Meter (which should be supplied by the Utility Company). Some of the advantages of this system include:

1. **Savings** - By having a grid connection, people are able to apply Net metering which allows for savings on the Electricity billing. In addition, the cost of a grid-tied system is much lower than that of an Off-Grid System. This is due to less equipment and installation costs. Some utility companies buy the excess electricity supplied at the same rate as they sell. This increases the feasibility of Grid-tied systems (Maehlum, 2013).
2. **Less Equipment needed** – Batteries and other stand-alone equipment needed for an off-grid system can be removed leading to a cheaper and simpler installation (Maehlum, 2013).
3. **Access to electricity** – Electricity, once it is generated, has to be used in real time or stored (batteries). This storage leads to losses due to battery efficiencies and leakages resulting in an increase in cost. With a Grid-tied system however, any extra unused

power is immediately sent back to the grid where it can be redistributed and used by other customers. Since Solar Energy is time and climate dependent (can only be utilized when there is sunlight) if storage is insufficient in an Off-grid system, then the building will lose power until there is sunlight to recharge the batteries. With Grid-tied systems, if your PV system fails or your usage outweighs generation, access to the grid allows for uninterrupted energy supply (Maehlum, 2013).

4. **Less change to lifestyle** – With Grid-tied systems, you are not required to change how you use electricity since the utility company can supply you with any excess power you may need (Intermountain Wind & Solar, 2017).

One of the disadvantages of Grid-tied systems however is that this system does not protect against power outages. Once the grid fails, the PV system will stop operating until the grid is back online. This means that Grid-tied PV systems do not allow for power generation and usage during a power outage. This disadvantage is often solved through the use of a Hybrid system (implementing battery storage into the system). This system will firstly store excess energy into the batteries until they are fully charged after which any excess energy is then fed back to the grid. Through this, if the Grid fails, energy can be supplied from the batteries to any critical loads within the building until the grid is restored (Anapode Solar, 2013).

Off-Grid Photovoltaic System

Off-Grid systems are more complex and rarely utilized, only in the severe cases where access to the grid is not possible. This system requires that the solar array produce all the electricity needed to meet the building's demand. For residential buildings, the evening and night times present with a higher electrical demand whereas for commercial buildings, the peak electrical demand is during the day. Batteries and a back-up source of energy (generator) is often used in this system to ensure that energy can be distributed at all times. Figure 2 below illustrates an Off-Grid system:

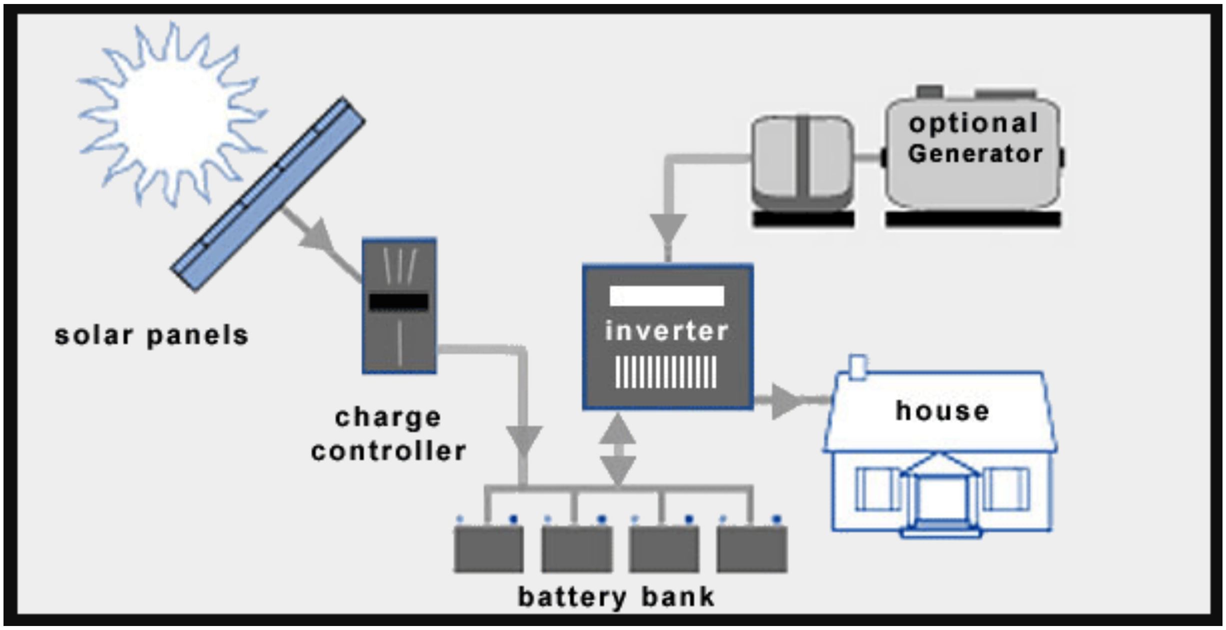

Figure 2 : Off-Grid Photovoltaic System (Maehlum, 2013)

From Figure 2 above, it can be seen that Off-Grid PV systems require much more equipment than Grid-Tied systems. This equipment includes: A Solar Charge Controller, Battery Bank, DC Disconnect Switch and an Off-Grid Inverter. It is also optional to include a Backup Generator in case the battery storage is not sufficient for meeting the energy demand of the building. Some advantages of this system are:

1. **Power Outage Protection –** For Off-Grid users, Power outages from the Utility do not affect electricity supply to the building. Since this is a standalone system, critical loads can still be supplied with electricity when the power grid is down (Maehlum, 2013).
2. **Energy Independence** – For Off-Grid systems, you are not tethered to any utility company or their policies. You will also not be subjected to any of their increasing rates for electricity (Intermountain Wind & Solar, 2017).

For this system, however, there exist many downfalls.

1. **Lifestyle change** – For Off-Grid systems, power conservation and management is extremely important in maximizing the energy generated. The energy generated by the solar system is finite and limited based on the number of panels and the size of the storage system. Depending on the budget of the client this makes supplying power to every load, at all times, difficult. To facilitate greater loads, more batteries and panels would be needed which would result in more costs.
2. **High Cost** – For Off-grid Systems, much more equipment is needed than for Grid-tied systems. This results in higher installation costs. Most Off-grid systems require a backup energy supply in the form of a generator or a battery bank, which at most times can be very expensive.
3. **Efficiency of Storage** – All Off-Grid systems utilize Battery banks to store excess energy. Batteries, however, are inefficient and a lot of the energy is lost due to heat.
4. **Power Demand** – For Off-grid systems, during none-generating periods (periods without sunlight), meeting the load of the building falls solely on the battery bank. Based on the budget of the client, the battery bank may or may not be able to provide power to the entire load of the building. In most cases due to the huge cost associated with battery storage, power is only supplied to what the user deems as "critical loads" forcing all other miscellaneous loads to be without power.

Renewable Energy

The rising cost of electricity in the Caribbean and the scarce and depleting resources in the traditional energy sector which includes; oil, gas and coal has forced many countries to resort to other means to meet their energy demand. The trust toward renewable sources of energy have been at the fore front for providing power to many countries worldwide. The advancements in technology over the decades have paved the way for a plethora of clean energy generation techniques. The most common sources of renewable energy are; Solar Power (Sunlight), Wind Power, Hydropower (flowing water), Tidal power (changing tides), Biomass (biological processes) and Geothermal Energy (taking heat from the earth's core). Though these processes

have an abundance of advantages which benefit the environment and secure a safer and cleaner future, they all have some disadvantages associated with them. For certain renewable energy processes, the efficiency of Power generation ranges from 10 – 95%.
A brief background on the three (3) most commonly used forms of renewable energy (Wind, Hydropower and Solar Energy) is given below.

Wind Energy

Wind energy is brought about by the uneven heating of the atmosphere by the sun. When harvested, this energy can be used to produce electricity through the use of a Wind Turbine. The speed of the wind is used to turn the blades of the turbine which generates mechanical power. Through the use of a generator, this mechanical power is then transformed into electrical power. Though they require large areas to install and can only operate at a minimum wind speed of approximately 8 km/h, wind energy is extremely viable for off-site power generation and has a relatively high efficiency of 35% (Level, 2017). Figure 4 below illustrates the process of utilizing wind energy to generate electrical energy.

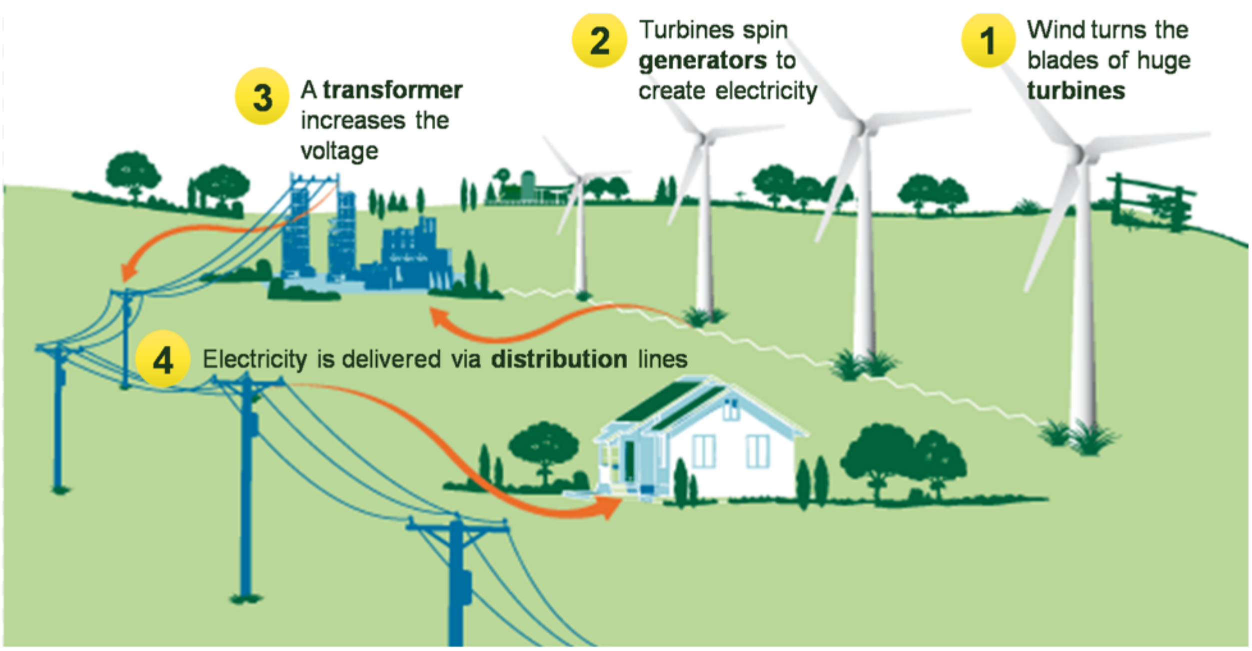

Figure 3 : Electricity generation using Wind Energy (US Department of Energy, 2014)

Hydropower

Hydropower is generated using the flow of water. Similar to Wind Energy, when water flows in a river, the kinetic energy generated by the moving water can be used to generate mechanical energy by turning a turbine which is then converted into electrical energy through the use of a generator. Hydropower is harvested by creating dams, which is used to create a reservoir. The water is then directed to flow through the dam by use of a control gate turning water turbines as it flows. There are many negative impacts associated with Hydropower, however, they can generate a great deal of energy at extremely low flow rates and has the highest efficiency than any other renewable technique (approximately 94%). Figure 5 below illustrates the process of utilizing flowing water to generate electricity.

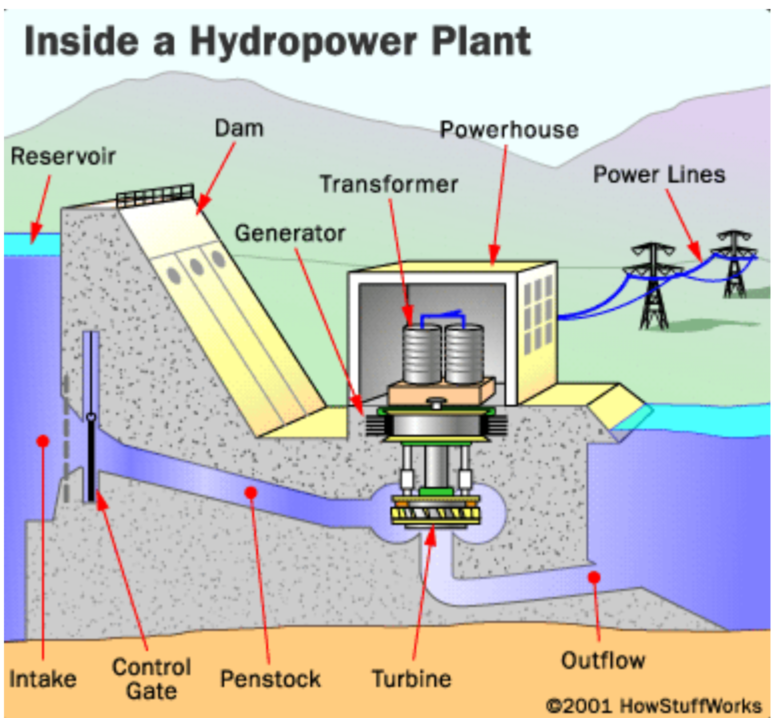

Figure 4 : Electricity Generation using Hydropower (Bonsor, 2001)

Solar Power

Solar Energy is one of the most abundant and unlimited energy resource that exists with the Sun being the primary generating source. In theory, the sun emits enough solar energy every hour to satisfy global energy needs for an entire year.

Solar energy is converted into Electricity through the use of Photovoltaic panels (PV panels). Photovoltaic panels are flat enclosures containing a special type of material (most commonly crystalline silicon) which, when hit by the sun's radiation, knocks electrons loose. When connected to a circuit, the electron travels creating an electrical current. That electrical current can either be stored, utilized or transferred to the electrical grid. Figure 6 below illustrates a standard Photovoltaic Panel.

Figure 5 : Roof-Mounted Photovoltaic Panel Array (Aggarwal, 2018)

The efficiency of solar panels ranges between 12 - 21 % depending on the conductive material used. There are three (3) types of Photovoltaic panels;

1) Polycrystalline Solar Panels
2) Monocrystalline Solar Panels
3) Thin-Film: Amorphous Silicon Solar Panel.

Table 1 below illustrates the differences between the three (3) types of panels mentioned above.

Table 1 : Comparison of Photovoltaic Panels

Solar Cell Type	Efficiency-Rate	Advantages	Disadvantages
Monocrystalline Solar Panels (Mono-SI)	~20%	High efficiency rate; optimised for commercial use; high life-time value	Expensive
Polycrystalline Solar Panels (p-Si)	~15%	Lower price	Sensitive to high temperatures; lower lifespan & slightly less space efficiency
Thin-Film: Amorphous Silicon Solar Panels (A-SI)	~7-10%	Relatively low costs; easy to produce & flexible	shorter warranties & lifespan

(GreenMatch, 2018)

From the table above, it can be seen in the case of tropical climates, Monocrystalline panels even though they are the most expensive are the most suitable since they tend to be slightly less affected by high temperatures than any of the other panels. They also have the highest efficiency and hence a high-power output whilst occupying minimal space. Figure 7 below shows a typical Photovoltaic system for generating electricity:

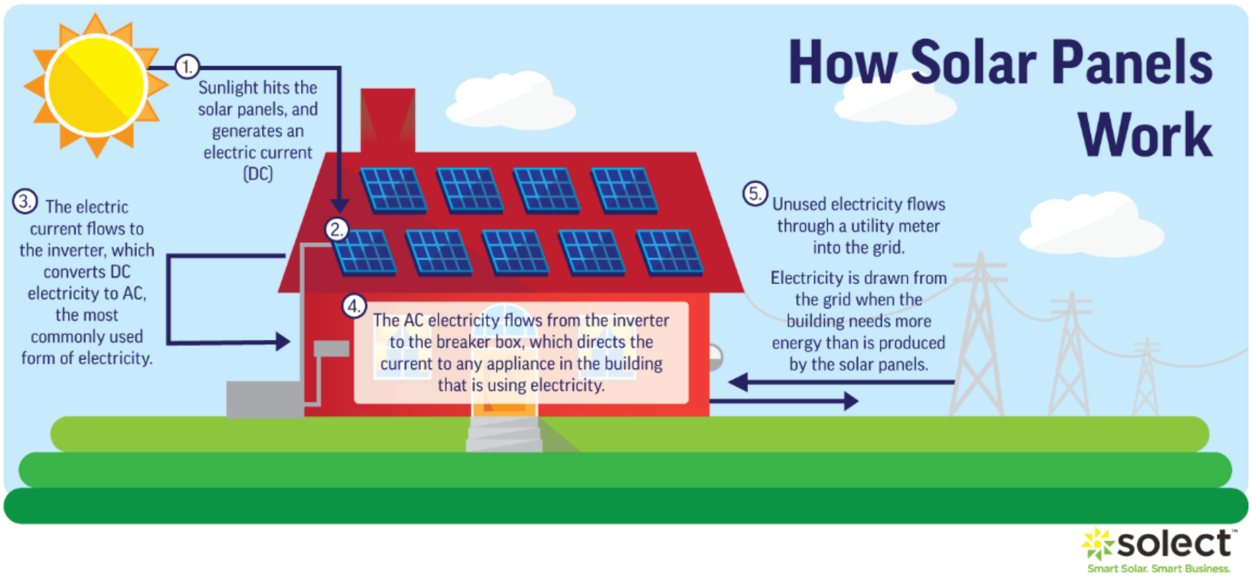

Figure 6 : Electricity Generation using a Photovoltaic System (Solect Energy)

Design Guide for Off-Grid Photovoltaic Systems

In designing any Photovoltaic system, there are many factors that need to be taken into consideration. The following information gives a step by step layout of a solar system installation process:

1. Determine the Power Consumption demands of the building
2. Decide whether the system is going to be grid-tied or an Off-grid system.
3. Size the PV Array
4. Size the Battery
5. Size the Charge Controller
6. Size the Inverter
7. Determine Tilt Angle and Spacing between Panel strings.

1. Power Consumption Demand

When calculating the Power consumption demand, all the electrical appliances within the building, being used on a daily basis, needs to be accounted for. From this, the Total Load of the building can be found. Once this is calculated, the energy consumption of the building per day can then be determined, taking into account the hours of operation of each appliance. A table illustrating all the information that must be known to calculate power consumption is shown below including some typical appliances found in buildings:

Table 2 : Format for calculating the Load for Small Health Facility

Appliance	**Total Amount**	**Power per Appliance (W)**	**Total Power (kW)**	**Hours of Operation (h)**	**Energy Consumption (kWh)**
Lights					
Outlets					
Refrigerator					
Air Condition					
Miscellaneous					
		Total Load		**Total Energy Consumption per day**	

2. Determining Type of Photovoltaic System

The earlier section of this report looked at the advantages and disadvantages of Grid-Tied VS Off-Grid Systems and listed the various considerations for each system. The decision however is made on an individual case by case basis.

Off-grid Photovoltaic systems are only utilized in cases where no connections can be made to the grid. Where utility companies do not facilitate the connection of Solar PV systems to their network an Off-grid system may be considered. The other factors in the analysis will be energy cost from the Utility company, equipment costs, payback period, cost of a continuous duty generator and fuel cost for full time service. When access to the grid is not possible and the decision is made for an Off-Grid system, most times the installation of a generator to bridge the energy gap is needed. The back-up generator acts as a failsafe in the event the panels cannot generate enough energy for daily operations. The other consideration for off-grid systems will be prioritizing loads in the building. Will the off-grid system be required to power all the loads all the time or will the system only power critical loads during off times?

There are many factors that will affect these decisions which include climate, usable surface area for PV array, types of available solar panels and peak sunlight. In most cases, the final decision depends on the motivation for the project. Is the aim solely to decrease Carbon footprint? Is maximizing your return on investment an important factor? Is saving as much money as possible the end goal? These questions would affect the decision that is made with regard to the type of Photovoltaic system that is implemented. In most cases, a focus on saving money is the primary motivator for implementing sustainable energy systems.

3. How to Size a Battery Bank

For Off-grid Systems, battery storage is as vital as the equipment generating power. Without proper storage, there would be no power during none-generating periods. Selecting the correct amount of storage is therefore very important. If storage is too big for the amount of power that can be generated this can lead to a waste of money, however, if storage is not sufficient, the building may run out of power and any power generated after the battery has been fully charged would be wasted. There are many types of batteries used for Solar applications (EnergySage, 2018):

1. Lead Acid – Relatively short life and lower Depth of Discharge than any other batteries. Not very expensive and is mostly popular in Off-grid connections for storage.
2. Lithium Ion – Are lighter and more compact than lead acid batteries. They also have a longer lifespan and higher Depth of Discharge, however, they are very expensive.
3. Saltwater – Not very common and relatively new. Not easily available but more environmentally friendly as they do not contain any heavy metals, relying instead on saltwater electrolytes.

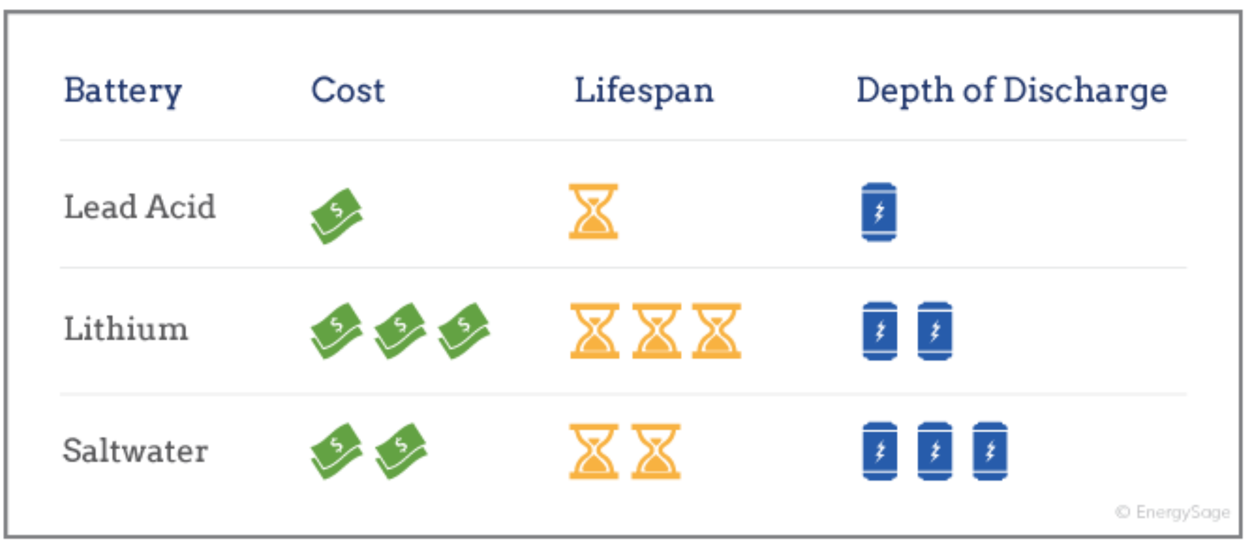

Figure 7 : Comparison of Batteries used in Solar Applications (EnergySage, 2018)

The best battery recommended for Solar PV systems however is a Deep Cycle Battery. A Deep Cycle Battery is a Lead Acid Battery which is specifically designed to be cycled (discharged and recharged) many times, lasting years. They are capable of providing steady power over a long period of time (Energy Matters, 2017). As stated above, ensuring that adequate storage is installed such that, the operation of appliances within the building during none-generating periods can be maintained, is imperative. The size of the battery can be calculated as such (LEONICS, 2018):

1. Calculate the Total Watt-hours per day used by the appliances (T_{Wh}).
2. Divide the Total Watt-hours per day used by 0.85 to account for battery losses.
3. Take into consideration Depth of Discharge. Divide value obtained in (2) by 0.6
4. Divide the answer obtained in (3) above by the nominal battery voltage available.
5. Multiply the value obtained in (4) by the amount of days of operation for the batteries (days of autonomy).

After following the above steps, the required ampere-hour capacity of the Deep cycle battery can be found.

$$\text{Battery Capacity (Ah)} = \frac{T_{Wh} \times Days\ of\ autonomy}{0.85 \times 0.6 \times Nominal\ Battery\ Voltage}$$

In some cases, it is important that the voltage on the battery bank matches that of the solar array. While considering the amount of power needed to be stored in the battery bank, the manner in which the batteries are connected affect its overall efficiency and lifespan. The amount of parallel strings used can negatively impact the life of the battery bank. Most professionals suggest not to connect more than two (2) strings, since the more parallel strings connected, the chance of uneven charging and discharging increases drastically.

$$\text{Minimum Battery Capacity per string (Ah)} = \frac{\text{Battery Bank Capacity (Ah)}}{\text{\# of strings}}$$

4. How to size the Photovoltaic Array

In order to determine the Size of the Photovoltaic array, the total amount of Kilowatt hours needed from the PV Array has to be determined. This can be done simply by multiplying the total amount of energy consumption per day by a factor of 1.3 to account for energy loss within the system (LEONICS, 2018). For fully Off-grid systems, the Photovoltaic system needs to be able to supply all the power to the building for regular operation.

4.1) **Calculating the total Watt-hours per day needed from the PV Array**

A listing of all the electrical loads in the building needs to be compiled using the table in section (1) as a guide and can be supplemented to include additional loads that may exist in the building. From this tabulation the Total Energy Consumption per day is obtained.

Total Energy needed from the PV Array per day = Energy Consumption per day (kWh) × 1.3

This calculation gives the total amount of power needed from the entire solar system per day in order to meet the buildings complete load demand.

The total peak watt produced by the panels is dependent on the size of the panel as well as the climate of the location. This can be calculated by taking into consideration, the Panel Generation Factor. **Panel Generation Factor (PGF)** represents the maximum Watt peak needed to meet the requirement of electricity from the panels. This factor varies depending on climate and location of the system. It is based on the quality of solar isolation (quantity of solar energy incident on the earth) and irradiation (Power per meter squared received from the sun) falling on the panels in that particular area. This can be found using the following map:

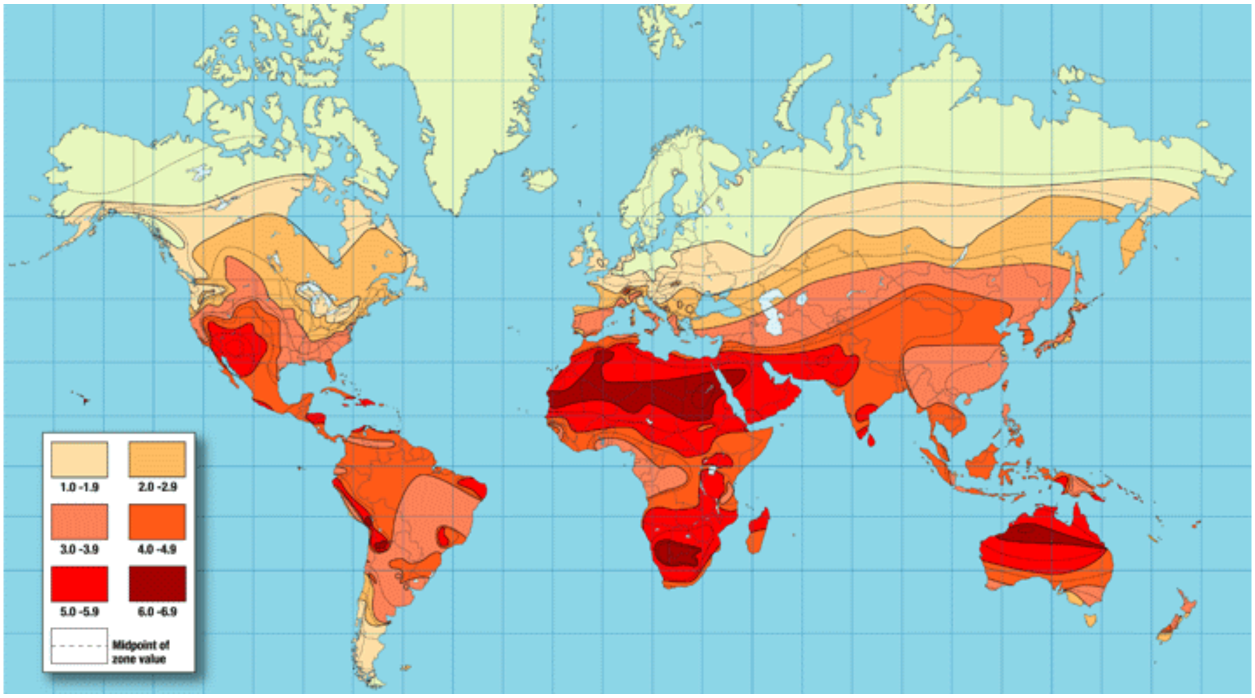

Figure 8 : Solar Isolation Map showing PGF (NASA)

From the above image, the PGF for the tropics can be seen to be on average 4.7.

4.2) **Calculate total watt peak ratings needed for the PV array.**

$$W_p \text{ rating of Array} = \frac{\text{Total Watt–hours needed from the PV array per day}}{PGF}$$

Once the watt peak rating of the PV array has been found, the amount of panels required to produce the daily load can be determined. It should be noted that this step can also be done in reverse if space constraints are a problem. Using the available space, the number of panels that can be set can be obtained and then the output Watt-peak of the PV array required can be calculated.

4.3) **Calculate the number of panels required for the system.**

$$\# \, of \, panels = \frac{Total \; required \; Watt{-}peak \; rating \; of \; the \; PV \; modules}{Rated \; output \; Watt{-}peak \; of \; PV \; Module}$$

This value indicates the minimum number of panels needed to sustain the building load. More panels can be used to improve the performance of the system and further enhance the battery life. It is important to note that the Nominal voltage of the PV array must be equal to or greater than the battery bank voltage.

$$\# \, of \, panels \; in \; series = \frac{System \; Voltage}{Panel \; Voltage}$$

5. How to select a Charge Controller

A Charge Controller regulates the amount of charge entering and exiting the battery and helps to provide the optimal and most efficient use of the battery. Charge Controllers help protect batteries from a variety of issues; overcharging, prevention of under-voltage and preventing current from flowing back to the PV Array at night (Dricus, 2015). Most Solar Charge Controllers are rated against Amperage and Voltage capabilities. It is important that the Charge Controller matches the voltage of the PV Array and batteries. There are three (3) main types of Charge Controllers:

1. **1 or 2 stage Controllers** – These controllers rely on relays to control the voltage. One of the first types of charge controllers to be used and are rarely implemented today. They are the most basic type of controller which simply disconnects the PV Array once a specific voltage on the battery is achieved. Due to the simplistic nature of this controller, it is very cheap but limited to its operation (North Arizona Wind and Sun, 2018).

2. **3-stage controllers with Pulse Width Modulation (PWM) –** This controller allows rapid charging for the battery until a designated voltage level is reached. Once this voltage level is reached, it toggles the connection between the Battery bank and the PV array on and off regulating the battery voltage (Phocos, 2015). These are most useful in areas with constant, steady and strong radiation (Smalley, 2015) and when cell temperatures are moderate, 45 -75°C (Vader, 2014). Figure 10 below shows the connection that is used for a PWM charge controller:

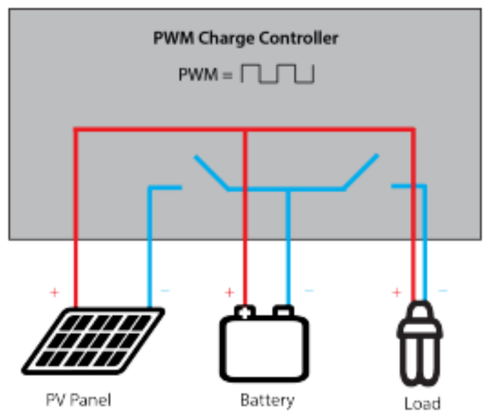

Figure 9 : Wiring diagram for a PWM Charge Controller (Phocos, 2015)

3. **Maximum Power Point Tracking (MPPT) Charge Controller** – These controllers possess an indirect connection between the PV array and the bank which includes a DC/DC voltage converter. This function allows the controller to reduce a higher voltage produced by the PV Array to a lower voltage with higher current at no Power loss to charge the batteries (Phocos, 2015). To maximize the efficiency of the controller, the PV array voltage should be slightly higher than the battery voltage. MPPT controllers are more efficient when solar cell temperatures are low (below 45°C) or high (above 75°C) or when solar radiance is very low (Vader, 2014). Figure 11 below shows the connection that is used for a MPPT charge controller:

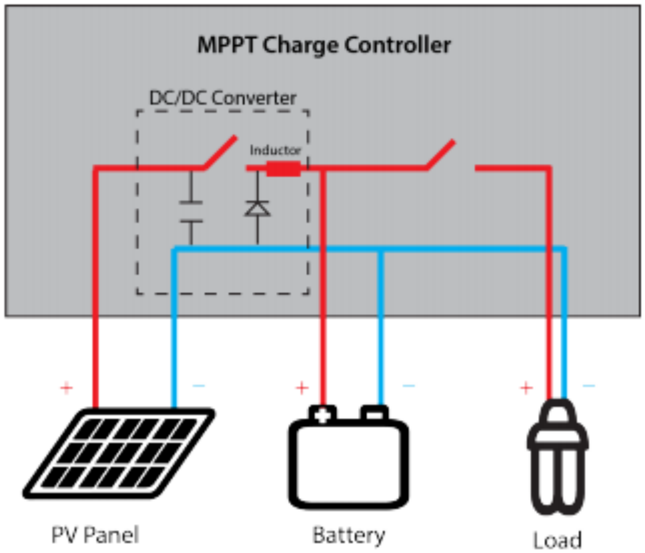

Figure 10 : Wiring Diagram for a MPPT Charge Controller (Phocos, 2015)

Given the above information, choosing the correct charge controller for the climate and region is very important. The advantages and disadvantages of each controller must be weighed before the most appropriate one can be selected. Figure 12 below helps to illustrate some of these advantages and compare the differences between the PWM and MPPT controller:

Table 3 : Comparison of PWM and MPPT Controller

	PWM	MPPT
Pros	1/3 – 1/2 the cost of a MPPT controller.	Highest charging efficiency (especially in cool climates).
	Longer expected lifespan due to fewer electronic components and less thermal stress.	Can be used with 60-cell panels.
	Smaller size	Possibility to oversize array to ensure sufficient charging in winter months.
Cons	PV arrays and battery banks must be sized more carefully and may require more design experience.	2-3 times more expensive than a comparable PWM controller.
	Cannot be used efficiently with 60-cell panels.	Shorter expected lifespan due to more electronic components and greater thermal stress.

(Phocos, 2015)

Once the type of controller has been selected, it is also important to ensure that it can handle the current from the PV Array.

5.1) Sizing a PWM Charge Controller

As a rule of thumb, the sizing of the PWM Solar Charge Controller is facilitated taking into consideration the short circuit current of the PV Array. A factor of 1.3 is used to account for safety.

$$\textit{PWM Solar Charge Controller Rating} = \textit{Total Short Circuit Current of PV Array} \times 1.3$$

Ensure the current rating of the charge controller selected is greater than the value calculated above.

5.2) Sizing a MPPT Charge Controller

For an MPPT Charge Controller the calculation is very similar but takes into account the total array wattage of the system

$$\textit{Total Array Wattage} = \textit{Rated Wattage of Panel} \times \#\ \textit{of Panels}$$

$$\textit{Current out} = \frac{\textit{Total Array Wattage}}{\textit{Battery Bank Voltage}}$$

Select a MPPT Charge Controller with the power and current rating calculated above at the battery bank voltage selected.

6. How to choose a Pure Sine Wave Inverters

For the inverter, the main rule is that the Input rating of the inverter should never be lower than the total wattage of the appliances and should have the same nominal voltage as the battery. For Off-Grid systems, the inverter needs to be large enough to handle the full load of the appliances being used within the building. For regular appliances, as a rule of thumb, the inverter should be **25-30% bigger** than the total load of the appliances. For compressors and motors, the inverter should be **3 times** the total load of the appliances and starting currents of the appliances need to be taken into consideration (LEONICS, 2018).

There are different steps that need to be taken when sizing an inverter. These steps depend on the type of system being installed. For an Off-grid system, there are two (2) parameters that need to be known:

1. The total load of the building.
2. The total surge power for all appliances that will be used simultaneously.

Once these two (2) parameters are known, an inverter which meets the power rating and surge rating of the building can be chosen.

For Grid-tied systems, the process of choosing an inverter is a more complex. During this calculation, the amount of panels that can be placed in a string and how many strings can be connected to a single inverter can also be found. This can be done through both Voltage and Current sizing of the inverter. In order to do this, some information needs to be known for the PV panels and the Inverter, as well as the climate information for the location of the system. It is important that all the aforementioned values used in these calculations be at Standard Temperature Conditions (STC). PV Module Information can be obtained from any PV panel supplier and is available on the Internet.

PV Module Information required:

1. Open Circuit Voltage (V_{OC})
2. Maximum Power Voltage (V_{MPP})
3. Short Circuit Current (I_{SC})
4. Temperature Coefficient of V_{oc} (TC_{OC})
5. Temperature Coefficient of I_{SC} (TC_{SC})

Inverter Information required:

1. Max Input Voltage (V_{max})
2. Max Input Current (I_{max})
3. MPPT Voltage Range, Min_{MPP} – Max_{MPP}

Climate Information required:

1. Highest Temperature throughout the year (T_H).
2. Lowest Temperature throughout the year (T_L).

Consider Voltage Sizing first in order to calculate the optimal number of panels in each string. From this calculation you will be able to determine a range for the amount of panels that can be placed on a string specific to the inverter being used (Power from Sunlight, 2017).

6.1) Voltage Sizing of the Inverter

a) Calculate the Open Circuit Voltage at the minimum temperature.

$$V_{OC\ (T.MIN)} = ((1- ((T_{STC} – T_L) * (TC_{OC} /100))) * V_{OC\ STC})$$

b) Calculate the Maximum number of panels (N) in each string.

$$N = \text{Max. input Voltage } (V_{max}) / V_{OC\ (T.MIN)}$$

For this calculation, the value obtained **must always be rounded down**.

c) Calculate the Maximum Power Voltage (V_{MPP}) at maximum temperature.

$$V_{MPP\ (T.MAX)} = ((1+ ((T_H – T_{STC})*(TC_{OC}/100))) * V_{MPP\ (STC)})$$

d) Calculate the Minimum number of Panels (M) in a string.

$$M = Min_{MPP} / V_{MPP\ (T.MAX)}$$

For this calculation, the value obtained **must always be rounded up.**

Consider Current Sizing of the inverter in order to determine the maximum number of strings that can be connected to the inverter. It is important that the Short Circuit Current of the PV array must not exceed the allowed maximum input current of the Inverter.

6.2) Current Sizing of the Inverter

a) Calculate the maximum short circuit current of the PV panel at maximum temperature.

$$I_{SC\ (T.MAX)} = ((1+ ((T_H - T_{STC})* (TC_{SC}/100))) * I_{SC})$$

b) Calculate the maximum number of Strings (P).

$$P = \text{Maximum input current } (I_{max}) / I_{SC\ (T.MAX)}$$

For this calculation, the value obtained **must always be rounded down**

7. How to select the Optimal Tilt Angle and Spacing between Panel Strings.

At this stage of the design, the following information should be known:

a. The daily power consumption of the building.
b. The configuration of the solar system.
c. The size of the panels being installed.
d. The amount of panels needed to meet the buildings energy demand.
e. The amount of panels connected in a string.
f. The amount of strings being installed.
g. The size and amount of inverters that would be needed for the system.
h. The size of the battery bank needed for storage of energy generated.
i. The size of the charge controller needed to protect the battery bank.

The next step in designing a PV Solar system is crucial in ensuring that the calculations compliment the actual data obtained after installation. This calculation operates under the assumption that the PV panels captures maximum radiation from the sun throughout the day. The placement of these panels play an important role in ensuring that this is actually true. The following gives information on selecting the appropriate parameters for installing roof mounted Photovoltaic panels:

a. The Tilt Angle of the panels

The geographic location of the panels greatly affects the angle at which they need to be placed for maximum efficiency. This angle varies greatly from 5° to 65° depending on the latitude of the area. Within North America, where the trajectory of the sun changes over the duration of the year, the ideal tilt angle also changes.
The following are rules of thumb for identifying tilt angles within North America:

For year round efficiency, Tilt angle = Latitude of area - 15°
For Winter, Tilt Angle = Latitude of area
For Summer, Tilt Angle = Latitude of Area – 30°

For more tropical climates, where the sun's trajectory is basically constant throughout the year, the above rules of thumb cannot always apply. This is also due to the fact that for most tropical countries, the latitude of the area falls between 25° to 0°. The panels should never be placed completely flat. This is due to a variety of reasons, some of which are:

1. The increased risk of dust accumulation on the panels – This would affect the panel's ability to capture the sun's radiation since the dust will block the surface of the panel.
2. The reduction in the cooling effect of natural ventilation – By having the panel flat, the movement of air below the panel will also be reduced. This would hinder the cooling of the panels, leading to a higher surface temperature and reduced efficiency.

It is for this reason that a minimal tilt angle of 5° is used. By having a tilt angle on the panels, its efficiency can drastically be increased and the maintenance cost of the system reduced. Tilting the panels allows for rain wash off which would clean the panel surface naturally and allow for better operation.

Due to the above reasoning, for Tropical climates, the rule of thumb for the tilt angle of solar arrays is as follows:

For year round Efficiency, Tilt Angle = Latitude of area ± 5°

b. Spacing between PV Array

Once the tilt angle has been obtained, the next step is to identify the spacing needed between each string of panels so as to ensure that the panel arrays do not cast shadows onto the other strings behind them. The calculation is strictly dependent on the following parameters:

1. The size of the panel
2. The trajectory of the sun (Azimuth and Altitude angle)
3. The tilt angle
4. The mounting height of the panel to the floor of the roof

Using a sun chart, the Altitude and Azimuth angle of the sun can be found. The worst case scenario (when the sun is at its lowest, during winter solstice on December 21st) must be found. This would allow us to know the longest length of shadow the panels would cast throughout the entire year. Since peak generation times occur between 9:00am and 4:00pm and this would be the lowest point of the sun for the generation period, the calculation needs to be done using the Altitude and Azimuth angle at either 9:00am or 4:00pm.

There is a variety of ways in which the Azimuth and Altitude angle can be found. A Sun chart is the simplest manner to acquire this information, however, for most tropical climates, this information is not available. The only other alternative is to use a 3D Sun Path Map. For this document, the AndrewMarsh 3D Sun Path mapping tool was used. The following figures shines some light on the process involved in finding the Azimuth and Altitude angle:

1. **Choose the location** – Within the program, you can use google maps to select the location in which the panels are being installed.

Figure 11: Google maps image to select location

Once this is completed, a visual representation of the path of the sun can be seen. This basically represents a 3D image of the Sun's path for the entire year. It indicates the exact trajectory of the sun at any time during the year. A visual representation of the shadows created by vertical objects can also be seen. Figure 13 below illustrates the Sun Path for Boe Vista, Brazil throughout the year. The light brown region indicates the entire trajectory of the sun over the year. The red line indicates the movement of the sun for a specific day and the blue line tracks the sun's movement based on time.

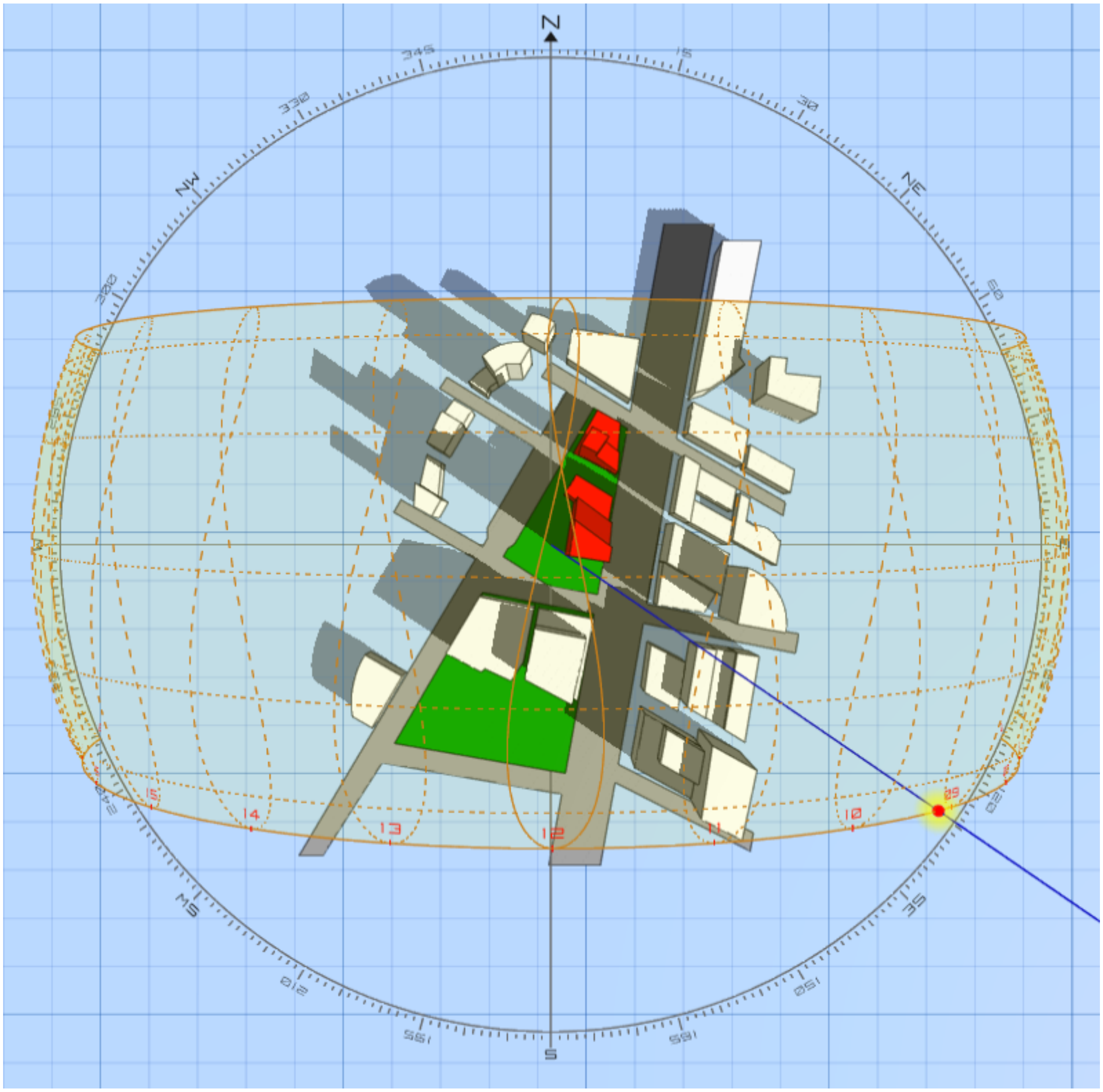

Figure 12 : Sun Path Diagram for Boe Vista, Brazil

Once the Sun Path has been generated, the last and final step in finding the solar Azimuth and Altitude is to identify the specific date and time for which the information is needed.

2. **Set the Date and time in which Solar Azimuth and Altitude is needed** – Using the table in the program, the date and time can be set and the corresponding Solar Azimuth and Altitude can be acquired. Figure 14 below illustrates the information obtained from the program for the sun's trajectory.

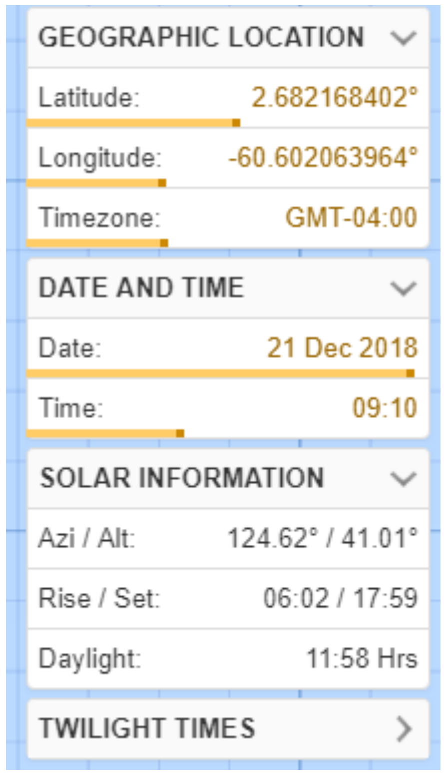

Figure 13 : Solar Azimuth and Altitude based on Date and time

As seen in Figure (14) above, under the section "Solar Information" on December 21st, 2018 at 9:10 am for Boe Vista, Brazil, the Solar Azimuth angle is 124.62° and the Solar Altitude angle is 41.01°. Finally, once this information has been gathered, the minimum spacing for the panel arrays can be found.

Figure 15 below illustrates a basic representation of the panel arrays and the important parameters needed.

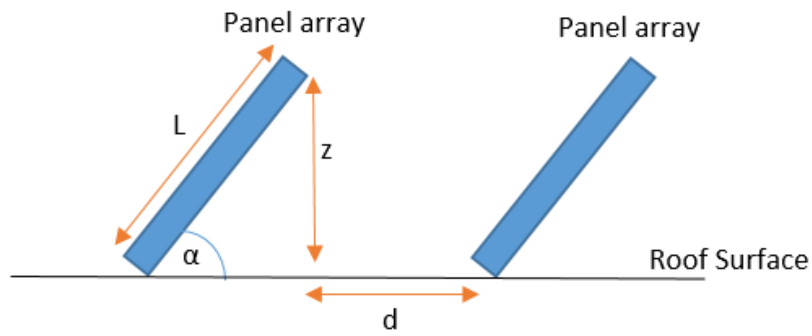

Figure 14 : Solar Panel Array

Using the following information; Tilt angle (α), length of panel (L), Solar Altitude (β) and Solar Azimuth (φ) the minimum spacing between the panel arrays (d) can be found as follows:

For a south facing panel, since the trajectory of the sun is from East to West, the shadow created by any vertical object is never directly north except when the sun is directly above. Therefore, most shadows will be casted in a diagonal manner from the object. We are not concerned about the diagonal length of the shadow (K) however; we need this value in order to calculate the minimal spacing for the panel arrays. In order to calculate the diagonal length (K), the vertical length of the mounted panel (z) needs to be calculated first. This length is based on the actual length of the panel (L) and the tilt angle (α).

$$z = L \times \sin\alpha$$

Once the vertical length of the panel has been found, the diagonal length of the shadow (K) can be found. This length is a factor of the vertical length of the mounted panel (z) and the Altitude angle (β).

$$\boldsymbol{K} = \frac{\boldsymbol{z}}{\boldsymbol{tan\,\beta}}$$

Using the Diagonal length of the shadow (K), the horizontal distance (d) of the shadow from the panel array can then be found. This distance would represent the minimal spacing between the panel arrays. This length is a factor of the vertical length of the mounted panel (K) and the Solar Azimuth (φ).

$$\boldsymbol{d} = \boldsymbol{K} \times \boldsymbol{sin}(\boldsymbol{\gamma})$$

where,

$$\gamma = 90 - \varphi \quad \text{for } \varphi < 90$$

$$\gamma = \varphi - 90 \quad \text{for } \varphi > 90$$

The minimum spacing is now known eliminating any shading created between the arrays.

Considerations for the Installation of Solar Panels on Buildings

In addition to properly sizing and designing a solar system, the design process must also consider the location of the solar array and the load bearing capacity of the roof structures and available area for panel installation. For solar panel installation on the roof, there are many factors that need to be taken to ensure the panels are safely secured to the roof surface. If the installation of solar arrays on the roof of a building is not done properly, many problems can occur which include leaking roof, mold growth due to moisture, and accidental damage to the roof and/or surrounding property due to wind load. The following are some factors which need to be taken into consideration before installation:

1. **The capacity for Loading on the roof** – Most roof structures are not built to handle the added weight of solar panels along with the added foot traffic associated with the installation and maintenance of the solar system. A Structural Engineer will need to be consulted to ensure that the roof can handle the load, as well as the wind lift of the solar array (BE Structural, 2018).
2. **The slope of the roof –** In most cases, the slope of the roof would not directly affect the installation of the solar system. Specialized racks can be placed to ensure the required tilt angle is achieved. These racks also securely fasten the panel array to the roof (BE Structural, 2018).
3. **Choice of adequate mounting** – Once the panels are mounted on the roof of the building, it is important to ensure that the mounting equipment is able to withstand any wind uplift loads. Wind speeds for the area should be obtained from local weather sources and the necessary calculations should be done to ensure that all necessary precautions are taken to prevent the solar panels from being blown away. Please consult a professional Structural Engineer to carry out the necessary design studies (BE Structural, 2018).
4. **Ceiling Life Expectancy** - Most solar panels have a life expectancy of 20 years on average. If the roof materials and structure has a lower life expectancy, installing solar panels would not be a smart choice. It is important to match the life expectancy of your roof and solar panels. This would prevent unnecessary costs in the future to

have the solar array removed and reinstalled on the new roof only to have to change the solar panels soon thereafter (BE Structural, 2018).

Mounting racks are used to fasten solar panels to a surface. These racks need to be connected directly onto the structural frame of the roof. Traditional racks include a rail system to support the solar panels and adjustable legs which secure the panels at a specific angle. These legs are then attached to feet which are bolted onto the rafters of the roof or of the roof surface. By bolting these racks onto your roof, a potential leaking point is made at each bolt location. It is therefore imperative that all holes made are resealed to prevent moisture damage (Fortified Roofing, 2017).

This can be done through the use of flashing. Flashing involves the use of a sheet of metal particularly aluminum or galvanized steel being positioned over the penetration point to divert any water from the bolt location and prevent leaking. This method varies depending on the orientation of the roof (flat or sloped). Polyurethane caulking can also be used around the bolt holes before the application of the flashing to aid in providing an extra layer of moisture protection. Regular sealant can also be used around the bolts, however, this method, though cheaper and faster, is not very reliable. It is important that for any installation of solar panels on the roof of the building, a professional roofing contractor be consulted to ensure no unnecessary problems occur (Fortified Roofing, 2017).

DESIGN EXAMPLE

Consider a small health facility in the remote areas of Guyana with a power layout as seen in Appendix A. The power layout drawing in Appendix A is used to determine the total power requirements of the building. For calculation purposes we have used the closest weather data which is available Boa Vista, Brazil on the Southern border of Guyana. The assumptions made during this example are:

a. The roof area is limited hence panels will be placed on the ground in an area next to the building.
b. The panels will be placed south facing.
c. In finding the optimal tilt angle and spacing of the panel arrays, historical weather data is used in order to anticipate what future weather conditions would be.
d. There are no other buildings or trees obstructing sunlight from hitting the panels (no external shading).
e. There are no space constraints for the placement of the panels.

Taking into consideration all of the aforementioned assumptions and the steps indicated above, we can now start designing our solar system.

Find the Power Consumption Demand and decide on the type of system.

Appendix A below depicts an electrical drawing for a small health facility. Utilizing the power layout for the facility, the peak load demand is determined. Taking into account all of the electrical appliances that would be used within the facility, the Energy Consumption per day of the facility was found. Table 4 below illustrates a basic example of how to calculate the power consumption of the building:

Table 4 : Electrical Load for Small Health Facility

Appliance	Total Amount	Power per Appliance (W)	Total Power (kW)	Hours of Operation (h)	Energy Consumption (kWh)
Lights					
Single bulb	5	37	0.185	8	1.48
Double bulb	16	74	1.184	8	9.472
Outlets	14	144	2.016	8	16.128
Refrigerator	3	400	1.2	24	28.8
		Total Load	4.585	**Total Energy Consumption per day**	55.88

Based on the above table, the instantaneous power needed for the building was found to be **4.585 KW**. Assuming the health facility is in operation for 8 hours in a day with exception for the refrigerators, the total Energy Consumption for the facility per day can be found to be **55.88 kWh.**

1. **Determining the type of Solar System.**

Since this report strictly deals with Off-Grid systems, the choice between Grid-tied and Off-grid has already been made. In an ideal case however, for any medical building, Grid Tied systems with the inclusion of a back-up generator are most often the best and safest choice.

Given that the building in question is a health facility, it is important that power be readily available and supplied at all times during the day. The use of a standalone Off-Grid system would not be able to guarantee constant supply of power, therefore, a back-up generator would also need to be implemented in the design. This back-up generator will act as a failsafe on days where weather does not allow for sufficient generation of power. In a tropical climate this is very possible, since some days are very overcast and rainy.

Sizing the Battery Bank

As stated previously, a deep cycle battery is the best battery which can be used for solar PV Systems. Once the type of battery is selected, the next step is to size of the battery. Assuming that the batteries would be in use for 2 days.

$$\text{Battery Capacity (Ah)} = \frac{T_{Wh} \times Days\ of\ autonomy}{0.85 \times 0.6 \times Nominal\ Battery\ Voltage}$$

$$\text{Battery Capacity (Ah)} = \frac{55880 \times 2}{0.85 \times 0.6 \times 48}$$

Battery Capacity (Ah) = **4.57 KAh**

$$\text{Minimum Battery Capacity per string} = \frac{Total\ Battery\ Capacity}{\#\ of\ strings}$$

$$\text{Minimum Battery Capacity per string} = \frac{4565\ Ah}{2} = \mathbf{2283\ Ah}$$

Utilizing a 12VDC, 2490Ah battery, the following arrangement can be used.

$$\text{Number of batteries connected in series} = \frac{DC\ System\ voltage}{Battery\ Voltage}$$

$$\text{Number of batteries connected in series} = \frac{48}{12} = 4\ \text{Batteries}$$

Since we know that we require 2 strings to be able to meet the required battery capacity of the load. The total number of batteries can be found.

Total Number of batteries = # of batteries per string × # of strings

Total Number of batteries = 4 × 2 = **8 Batteries**

Sizing the Photovoltaic Panels.

1) Calculating the total Watt-hours per day needed from the panels

Total Energy needed from the PV Array per day = Energy Consumption per day (kWh) × 1.3

Total power consumption per day = 55.88 kWh

Total energy needed from the PV Array per day = 55.88 × 1.3 = **72.64 kWh**

2) Calculating the total Watt peak ratings needed for the PV Array

Using Figure (8) above, the Panel Generation Factor (PGF) can be determined For Brazil/ Guyana , it can be seen to be between 4.0 – 4.9. For the city of Boe Vista, the Panel Generation factor is noted to be approximately 4.7 (Assuncao & Schutze, 2017).

$$\text{Total } W_p \text{ rating of panel} = \frac{Total\ Watt{-}hours\ needed\ from\ the\ PV\ modules}{PGF}$$

$$\text{Total } W_p \text{ rating of panel} = \frac{72644}{4.7} = \mathbf{15.456\ kW_p}$$

3) Calculating the number of panels required for the system.

Consider a Solar panel with a rating of 190 W, 24 V.

$$\text{\# of panels required} = \frac{Total\ required\ Watt{-}peak\ rating\ of\ the\ PV\ modules}{Rated\ output\ Watt{-}peak\ of\ PV\ Module}$$

$$\text{\# of panels required} = \frac{15456}{190} = 81.3 = \underline{\textbf{82 panels}}$$

$$\text{\# of panels connected in series} = \frac{System\ Voltage}{Panel\ Voltage} = \frac{48}{24} = \textbf{2 panels}$$

This would mean that 41 strings of 2 panels each will allow us to generate the required power needed for the building. Due to the fact that the floor area of the roof as seen in Appendix A is (25' x 52'), it is obvious that the required panels would not be able to fit on the roof of the building. As a result, the panels will be placed on the ground next to the building. For a small building this may seem like a lot of panels to be installed. In the case of Off-grid systems the quantity of panels required are far more than Grid-tied systems. This is due to the fact that the panels need to generate all the power for the building at any given time since no power can be acquired from the grid. Most grid tied systems are installed simply to offset energy costs and reduce carbon footprint rather than to provide full power to the building at all times.

Sizing the Solar Charge Controller

Based on the aforementioned information, a MPPT Controller would be more suitable for implementation in a tropical climate. Even though this controller is more expensive than the PWM controller, it would be more efficient for use in this system. The size of the Charge controller, however, needs to be calculated. Connecting 41 strings with 2 panels in series will amount to 82 panels which will meet the desired demand. For this configuration, the MPPT Charge controller can be sized as follows:

$$\text{Total array Wattage} = \text{Wattage of panel} \times \#\ \text{in array}$$

$$\text{Total array Wattage} = 190 \times 82 = \mathbf{15580\ W}$$

$$\text{Current out} = \frac{Total\ Array\ Wattage}{Battery\ Bank\ Voltage}$$

$$\text{Current out} = \frac{15580}{48} = 324\ \text{A}$$

Since this system is large, multiple charge controllers will need to be installed. Each charge controller will be responsible for a sub-set of panels connected in series. For this example, four (4) charge controllers will be installed, each connected to 22 panels. The calculation can now be altered as follows:

$$\text{Total array Wattage} = \text{Wattage of panel} \times \#\ \text{in array}$$

$$\text{Total array Wattage} = 190 \times 22 = \mathbf{4180\ W}$$

$$\text{Current out} = \frac{Total\ Array\ Wattage}{Battery\ Bank\ Voltage}$$

$$\text{Current out} = \frac{4180}{48} = 87\ \text{A}$$

From the calculation above, four (4) Outback Power FlexMax Charge Controller rated at 100A, 48V can be used. It should be noted that in order to connect four controllers evenly, 88 panels would be installed.

Sizing the Pure Sine Wave Inverter

Utilizing the table completed in section (1) above, the maximum power load of the building can be obtained. For all the appliances, a surge load also needs to be acquired through the specifications sheet on the appliance. For this building, the total load is found to be 4585 W. Assuming a surge wattage of 2.5 times the total load (11462.5W) an inverter that meets these parameters need to be chosen.

Calculating the Optimal Tilt Angle.

In order to find the optimal Tilt angle of the PV arrays, all the aforementioned factors need to be taken into consideration. This value cannot be calculated or deduced, however, at a basic level the rule of thumb can apply to get an idea of what the optimal tilt angle will be. The best way to acquire optimal tilt angle is by using simulation tools to deduce the performance of the PV system over the course of one (1) year for varying tilt angles. One such tool that facilitates this is the System Advisor Model (SAM), which is a free software that can be used to simulate sustainable systems and indicate optimal design parameters. For this example, based on the location (Boe Vista, Brazil), using SAM the **optimal tilt angle** which produced the maximum amount of energy was found to be **7°**.

This tilt angle is based on an ideal situation, using historical weather data as a basis for measurement. It is important to note that even though this value may seem to be optimal in simulation, in reality, this may not be true due to external factors that cannot be accounted (dust accumulation, lack of maintenance of the panels and unknown weather changes). In practice however, this is the closest to the optimal tilt angle that can be found.

a. Calculating the Spacing between PV Arrays

Using the SunPath program stated above, the Solar Azimuth and Solar Altitude angle for Boe Vista, Brazil was found to be 124.62° and 41.01° respectively. Given the length of the panels are 1.5 meters and the optimal tilt angle found was 7°, the minimal spacing between the PV arrays can now be found.

Vertical length of mounted panel

$$z = L \times \sin\alpha$$

$$z = 1.5 \times \sin 7$$

$$z = 0.183 \text{ m}$$

Diagonal length of shadow created

$$K = \frac{z}{\tan\beta}$$

$$K = \frac{0.183}{\tan 41.01}$$

$$K = 0.279 \text{ m}$$

Minimal Spacing between Panel arrays

$$d = K \times \sin(\gamma)$$

$$d = 0.279 \times \sin(124.62 - 90)$$

d = 0.16 m

The minimum spacing between the panel arrays required to prevent any internal shading was found to be 0.16 meters. This is extremely small and is only due to the fact that the panels are almost completely horizontal. For this example, due to how the panels are situated, internal shading will never be an issue since a minimum of 1 meter would be required between the panel arrays to facilitate maintenance.

Wiring Configurations

After designing the complete PV system and sizing all the necessary components, deciding how to connect the system to the building's power layout is the next and last step. In this report, three (3) wiring configurations are discussed:

1. Off-Grid PV Supply with Full Back-up Generator on Full Load
2. Off-Grid PV Supply Full Load with Back-up Generator on Critical Loads only
3. Off-Grid PV Supply with PV only and Load Shedding of Non-Critical Loads

Off-Grid PV Supply with Full Back-up Generator and Full Load

This first configuration is the standard Off-grid configuration used in most buildings. All loads within the building are protected in the event that the battery bank is depleted. The bank-up generator will supply power to the entire building, once the battery storage of the PV system is unable to. A typical configuration is as follows:

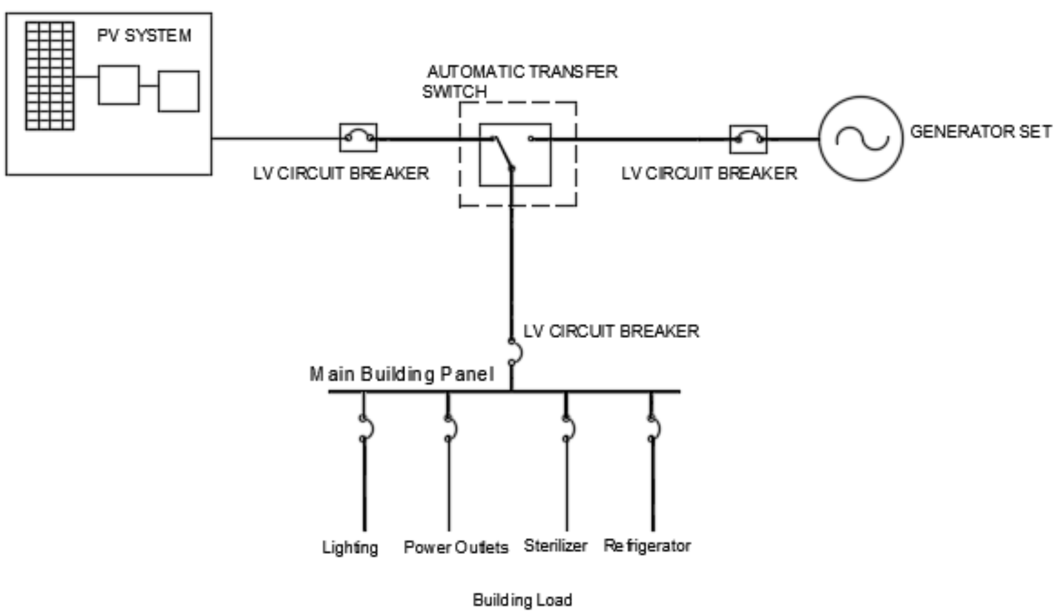

Figure 15 : Distribution Diagram of PV Wiring Configuration with Full Back-up Generator

As seen in figure 15 above, the PV system is supported by a Generator. In the event the PV system cannot supply the load of the building, the Automatic Transfer Switch (ATS) will immediately switch the supply from PV to generator resulting in minimal disruption of power to the building lasting approximately twenty (20) seconds for generator start up and transfer.

Off-Grid PV Supply Full Load with Back-up Generator on Critical Loads only

In some instances, depending on the budget of the client, the generator is sized to only handle critical loads of the building .This will allow critical functions of the building to continue while non essential loads are turned off. The generator is connected such that in the event of power loss from the PV system, power is only supplied to critical loads within the building. A typical configuration is as follows:

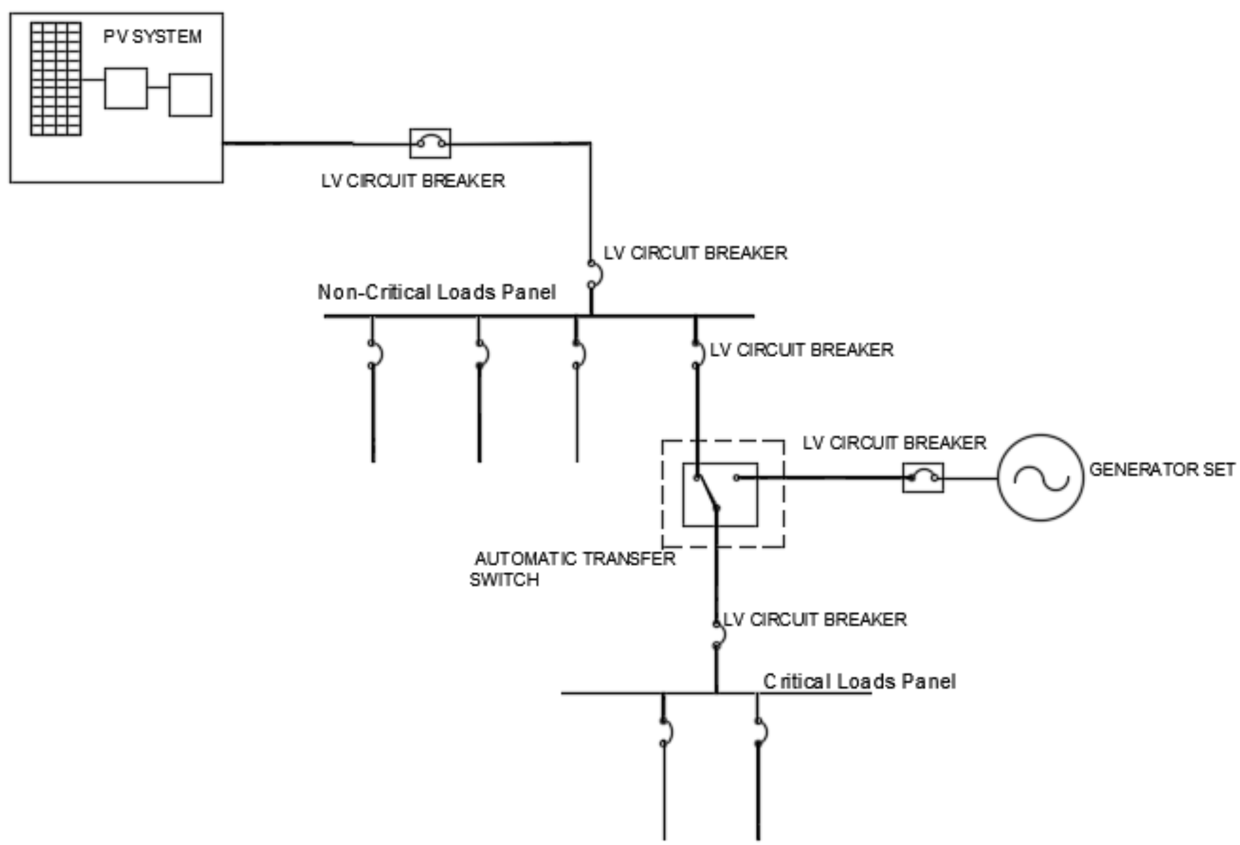

Figure 16 : Distribution Diagram of PV Wiring Configuration with Partial Back-up Generator

As seen in Figure 16 above, the Critical load panel is connected to an ATS, which is connected to the generator. In the event that the battery power on the PV system is depleted, the ATS will automatically switch the connection to the Generator which will provide power to the Critical loads panel. Again in this configuration there will be a 20 second disruption for generator start up and transfer.

Off-Grid PV Supply Full Load with PV only and Load Shedding of Non-Critical Loads only

In the scenario, where a Generator is not included in the system, it is imperative that the PV Supply be monitored and all power stored be used efficiently. For this design, Load shedding is utilized. Load shedding involves the removal of Non-Critical Loads from the PV System. This is done to conserve remaining stored battery power for critical loads only. This is facilitated through the use of magnetic contacts to remove part of the buildings load once the PV system has reached a specific battery threshold. A typical configuration is as follows:

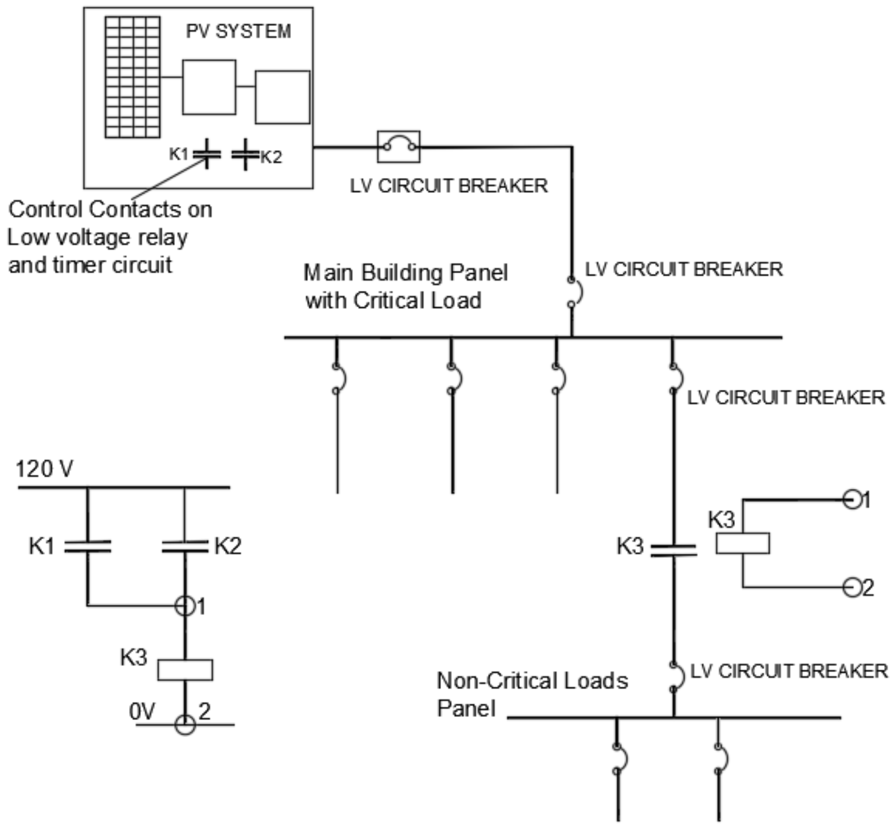

Figure 17 : Distribution Diagram of PV Wiring Configuration with Load Shedding of Non-Critical Loads

As seen in Figure 17 above, the Critical load panel is connected to a control contact (K3), which would open in the event that the timer relay (K1) or the low voltage relay (K2) is energized. K1 and K2 are both located within the PV system and will activate once the battery storage of the PV system reaches a fixed level of depletion. Once this is achieved, K3 will open disconnecting the Non-critical load panel. This panel will remain disconnected until the battery storage in the PV system is recharged above the threshold level. In this case, if the battery bank on the PV system is depleted fully there is no back-up power supply to the building.

Maintenance of Photovoltaic Systems

Once the design of the system has been completed, the steps to ensuring maximum efficiency does not end. Maintenance of electrical and mechanical systems are equally as important as the design phase itself. Proper maintenance practices allow the system to operate at maximum efficiency for the entire duration of its lifecycle. This also lengthens the lifespan of the system, limiting any technical problems that may occur. Even though, over time, some wear and tear is expected, maintenance of the system limits the effect normal wear and tear has on the performance of the system.

When discussing a Solar System, there are many key components that require maintenance. The following section discusses some key maintenance steps that need to be taken for the respective sections of a solar system:

1. Solar Panels
2. Inverter
3. Charge Controller
4. Battery bank
5. Main wiring and connectors

Before any maintenance can be done, each component of the PV system should be isolated and disconnected. Any and all circuit breakers should be opened and all loads disconnected to prevent any electrical accidents from occurring. It is also important to note that before carrying out any maintenance procedures, proper personal protective equipment (PPE) must be worn.

Solar Panel Maintenance

There is a misconception that solar panels are maintenance free systems, however, this is not true. Though Photovoltaic panels require far less maintenance than most other electrical and mechanical systems, some manner of maintenance is still important. Maintenance of Solar panels exist in a variety of capacities (Tetra Tech Inc., 2013):

a. **Removing excess dust accumulation on the panel surface** – Over time, due to wind, the surface of the panels become covered with a thin layer of dust. This layer of dust hinders the ability of the panel to generate energy by blocking radiation from falling on the surface. This can be easily fixed by simply washing the panels with water and if needed, rubbing with a sponge. Refrain from using any material that may scratch the surface of the panel as well as the use of any detergents.
b. **Weekly Inspection of the panels for damages** – This is an important precursor to ensuring limited interruptions in power generation. By inspecting the panels on a weekly basis to identify any cracks, de-lamination, water leaks or discoloration, measures can be made to replace faulty panels before further deterioration compromises the panel's output.
c. **Inspect the array's mounting frame and joint connections** – The mounting frame of the panel holds the panel in place at the designed tilt angle and orientation. If the support of the panels is compromised, the panels may shift or fall, resulting in damages. Inspect the mounting frame and joints to ensure no rusting or cracks are seen. The panels should be securely fastened to the mount in a rigid manner to prevent any possible accidents.

Inverter and Charge Controller

The maintenance of the Inverter and Charge controller is mainly carried out through visual inspection. Though it is important to minimize dust accumulation on these equipment, the major priority for these components is in ensuring that all LED indicators are functional and working correctly. Ensuring that there are no loose or exposed wires is also imperative (Tetra Tech Inc., 2013). Using tamperproof covers to protect these equipment is also suggested to prevent any unnecessary complications with unauthorized people interfering with it.

Battery Bank

The battery bank is one of the main components of an Off-grid solar system. Without the battery bank, the building would not have any power during none-generating periods. Proper maintenance of the batteries allows for extended lifecycles and efficient storage. There are three (3) steps in maintaining batteries (Tetra Tech Inc., 2013):

1. **Visual Inspection and cleaning** – A visual inspection should be done at least once a month to check for any electrolyte leaks, cracks or corrosion of the terminals. Any liquids or residue seen on the batteries should be removed. A damp wet cloth should be used to wipe away any dust. Care must be taken for any acidic residue that is seen and should be dealt with accordingly, taking the necessary precautions.
2. **Checking the Electrolyte levels** – Checking the cell electrolyte level for correct acid volume once a month is also important. The standard required level is between ¼ to ½" below the bottom of the vent. ONLY distilled water should be used when topping up the batteries. Measuring the electrolyte specific gravity is also an accurate means of checking the state of charge of each individual cell in the battery but special equipment is required to undergo this procedure and should only be done by a professional.

3. **Ensuring the battery is in a high stage of charge** – The most common manner in measuring a battery's charge is through the use of a volt meter. The charge of the battery should always be checked on a weekly basis and a record should be kept to monitor the charging potential of the battery over time. Most solar systems have an indicator to identify when the charge on the battery bank is low. Ensuring that these indicators are functional is important in monitoring the condition of the battery.

Main Wiring and Connectors

Visual Inspections of the panel boxes and conduits is also important. In most situations, the main cause of wiring failures is due to rodents and insects eating away the insulation and coating. For this reason, it is imperative that all conduits and panel boxes be inspecting to ensure no rodents have taken up refuge in them. The other important factor in this inspection is to ensure that all ground wires are connected and not loose (Tetra Tech Inc., 2013).

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Appendix A – Electrical Layout of Health Facility