UNIVERSITY OF NAIROBI

FEE 560: FINAL YEAR PROJECT

SOLAR PV SYSTEM SIZING

PROJECT 101

DONE BY:

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DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING

DEDICATION

This project is dedicated to my dad and mum, Ephraim and Edith, my sister Susan , my brother Amos and the Muritu's (dad, mom, Shiro, Muthoni and Brian) who have been my second family. Your love, care and support throughout my life means the world to me.

ACKNOWLEDGEMENT

First and foremost I would like to thank God for bringing me this far. I would be nowhere without Him.

I extend my heartfelt gratitude to Dr. Cyrus Wekesa, my supervisor.

My most heartfelt appreciation to the staff at Botto-Solar Ltd for their support during my project and for availing all the information necessary for the successful completion of this project.

I would like to take to this opportunity to give special thanks to all my classmates. Your continual support and trust in my abilities has not gone unnoticed.

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ABSTRACT

Stand-alone PV (Photovoltaic System) systems operate reliably and are the best option for many remote applications around the world. Obtaining reliable long-term performance from a PV system requires consistent sizing calculations and knowledge of PV performance, use of good engineering practices when installing equipment and developing and following a complete operation and maintenance plan.

This document presents recommended design practices for Stand-Alone photovoltaic (PV) systems. The different components which comprise the PV systems are described and their characteristics enumerated. This information provides a base for the design.

The solar PV design technique takes into consideration estimated load requirements as the basis for sizing the system. The design technique is done through Worksheets. The calculations are simple and straight-forward. A practical sample sizing problem is presented and is completed through the worksheets. System component parameters have been obtained from manufacturer's data sheets which have been documented.

It is important to note that the solar radiation plays a great role in determining the system size. As seen from the result section, locations with low solar radiation require bigger system size to compensate for low sun hours.

CHAPTER 1

1.1 INTRODUCTION

Photovoltaic (PV) energy generating systems (or PV systems) convert the sun’s energy directly into electricity using state-of-the-art semiconductor materials. PV systems produce clean, reliable energy without consuming fossil fuels and are used in a wide variety of applications. Some are called a “stand-alone or off-grid” system, which means they are the sole source of power to a home, water pump or other load. Stand-alone systems can be designed to run with or without battery backup. Remote water pumps are often designed to run without battery backup, since water pumped out of the ground during daylight hours can be stored in a holding tank for use anytime. In contrast, stand-alone home power systems often store energy generated during the day in a battery bank for use at night. Stand-alone systems are often cost-effective when compared to alternatives such as utility line extensions.

Other PV systems are called “grid-connected “systems. These work to supplement existing electric service from a utility company. When the amount of energy generated by a grid-connected PV system exceeds the customer’s loads, excess energy is exported to the utility, turning the customer’s electric meter backward. Conversely, the customer can draw needed power from the utility when energy from the PV system is insufficient to power the building’s loads. Under this arrangement, the customer’s monthly electric utility bill reflects only the net amount of energy received from the electric utility.

The high initial costs of PV installation calls for a means of sizing these systems to be able to match projected loads and applications. Sizing matches the user’s energy needs with the appropriate solar systems components.

Typical applications of PV in use today include;

- Stand-alone power systems for cottages and remote residences,
- Remote telecommunication sites for utilities and the military,

- Water pumping for farmers,
- Emergency call boxes for highways and college campuses,
- Street Lighting
- Grid Connected supply of Electricity
- Navigational aides for the Coast Guard

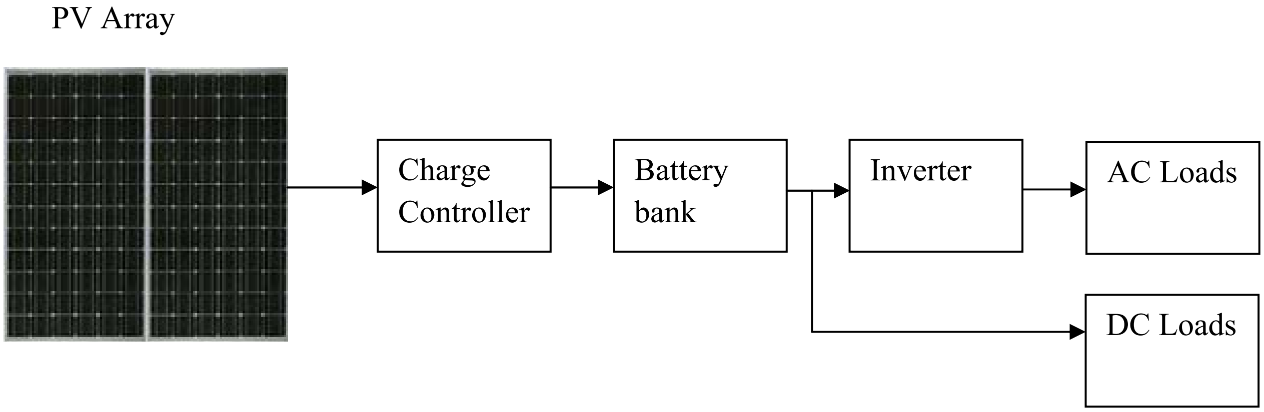


Figure 1.1 Stand-Alone PV System

1.2 Objectives

The main objective of this project is to provide a means of sizing Photovoltaic Systems supplying Stand Alone AC and DC loads. The sizing includes components which comprise the photovoltaic system, namely;

- Photovoltaic Module
- Charge Controller
- Battery Storage
- Inverter

1.3 Project overview

The Solar PV design has been split up into four chapters consisting of Literature review, System Design, Results and Recommendations.

- Chapter 2 details any relevant theory which is crucial in further understanding of the design sections.
- Chapter 3 details the design and steps involved in sizing the PV components.
- Chapter 4 presents a practical sizing sample problem.
- Finally Chapter 5 includes recommendations and conclusion for the design technique presented

The project report aims at providing an in-depth and accurate analysis and of PV system design and relevant theory. It is hoped that enough detail has been provided to allow a good understanding of the design.

CHAPTER 2: LITERATURE REVIEW

2.1 Photovoltaic module

A photovoltaic module is a group of cells, wired in series. The electrical output from a single cell is small; so multiple cells are connected in series and encapsulated (usually behind glass) to form a module. PV modules are thus the principle building blocks of a PV system, and any number of modules can be connected to give the desired electrical output in a PV array or system. This modular structure is a considerable advantage of PV systems, because new panels can be added to an existing system as and when required. [1]

Figure 2.1 Solar Cell

There are four advanced thin film technologies for making PV modules. Their names are derived from the active cell materials:

1. Cadmium telluride (CdTe),
2. Copper indium diselenide (CIS),
3. Amorphous silicon (a-Si)
4. Thin film silicon (thin film-Si).

Amorphous silicon is in commercial production while the other three technologies are slowly reaching the market. Thin film modules are made directly on the substrate, without the need for the intermediate solar cell fabrication step.

2.1.1 Photovoltaic module performance

The total energy output wattage of a photovoltaic module equals its output voltage multiplied by its operating current. Unlike voltage sources such as batteries which produce current at relatively constant voltage, photovoltaic modules may produce current over a wide range of voltages.

The output characteristics of a module are characterized by a performance curve called an I-V Curve which shows the relation between current and voltage output. An example is shown in Fig.2.2. Voltage (V) is plotted along the horizontal axis while Current (I) is plotted along the vertical axis. Typical I-V curves are given for the conditions of 1000 watts per square meter of sunlight and 25degrees C (77 degrees F) cell temperature. 1000 watts per square meter is often referred to as one 'Peak Sun.' There are three significant points of interest on the I-V curve;

1. **Maximum Power Point (MPP)** - is labelled Vmp, Imp on the I-V curve. This is the operating point at which the maximum output will be produced by the module at operating conditions indicated above.
2. **The Open circuit Voltage, (Voc)** - is the maximum potential voltage achieved when no current is being drawn from the module. As shown by the figure the open circuit voltage (V_{OC}) occurs when there is no current passing through the cell.

   $$V \text{ (at } I=0) = V_{OC}$$

   V_{OC} is also the maximum voltage difference across the cell for a forward-bias sweep in the power quadrant.

   $$V_{OC} = V_{MAX} \text{ for forward-bias power quadrant}$$

3. **The Short Circuit Current, (Isc)** - Is the maximum current output which could be reached by the module under the conditions of a circuit with no resistance. The short circuit current I_{SC} corresponds to the short circuit condition when the impedance is low and is calculated when the voltage equals 0.

   $$I \text{ (at } V=0) = I_{SC}$$

I_{SC} occurs at the beginning of the forward-bias sweep and is the maximum current value in the power quadrant. For an ideal cell, this maximum current value is the total current produced in the solar cell by photon excitation.

$I_{SC} = I_{MAX} = I_{\ell}$ for forward-bias power quadrant

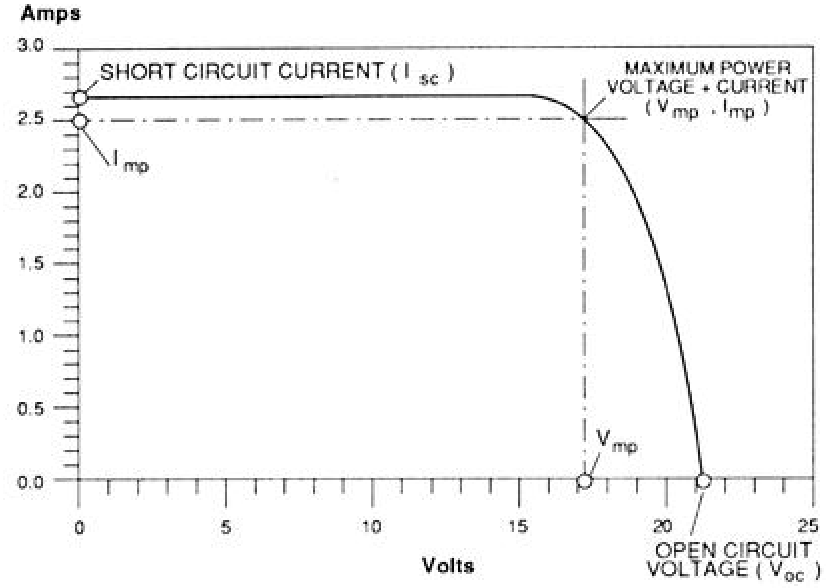


Figure 2.2 Typical Current Voltage Curve of a Photovoltaic Module

2.1.2 Factors affecting photovoltaic module performance

1. **Load Resistance-** A load or battery will determine at what voltage the module will operate. For example, in a nominal 12 volt battery system, the battery voltage is usually between 11.5 and 14 volts. In order for the battery to charge, the modules must operate at slightly higher voltage than the battery.

   If a load's resistance is well matched to a module's I-V curve, the module will operate at or near the maximum power point, resulting in the highest possible efficiency. As the load resistance increases, causing the photovoltaic module to operate at a voltage higher than the maximum power point, module efficiency decreases. Efficiency also decreases at voltages less than at the maximum power point.

2. **Intensity of Sunlight**- a photovoltaic module's output is proportionally affected by the intensity of solar radiation to which it is exposed. More intense sunlight will result in greater module output. Lower sunlight levels result in lower current output. Voltage is not changed appreciably by variations of sunlight intensity.

3. **Cell Temperature**- Photovoltaic modules operate less efficiently at higher cell temperatures. The operating voltage drops with increasing cell temperature. Heat, in this case may be thought of as an electrical resistance to flow of electrons. Effective current output may be significantly reduced decreased if the maximum power point of a module or array shifts to a much lower voltage than the operating voltage of the load. Generally a module will lose approximately ½% efficiency per degree centigrade of temperature rise between 80 and 90 degrees C. [1]

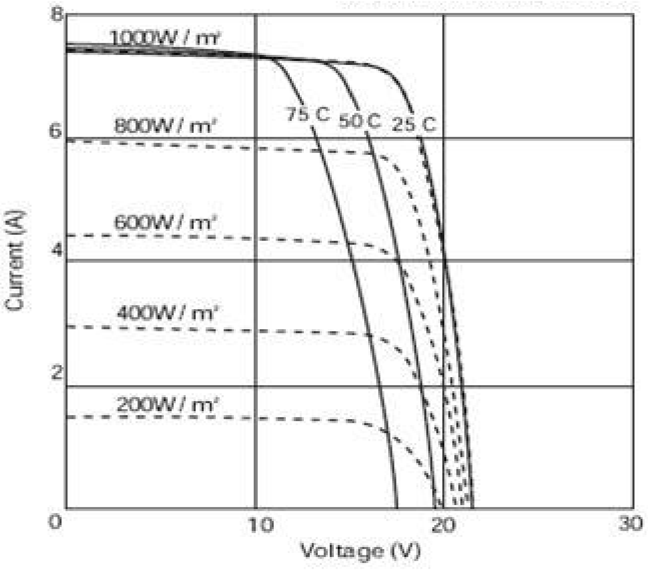


Figure 2.3 Effects of Decreased Insolation Effect and Cell Temperature

4. **Shading-** Even partial shading of photovoltaic modules will result in dramatic reduction of module's output. One completely shaded cell can reduce this module's output by as much as 80%. The effect of partial shading of three cells cuts the modules output in half when operating at 15 volts.

2.1.3 The photovoltaic effect

The basic unit of a photovoltaic system is the photovoltaic cell. It generates electricity because the cell's materials give it an electric potential and are sensitive to sunlight. The photovoltaic cell consists of thin layers of semi conducting material, prepared as wafers or films, most commonly made from silicon cells which are one of the earth's most abundant elements. Silicon's natural properties as a semiconductor of electricity make it an ideal material for photovoltaic cells. Its electric properties are modified by two other elements, boron and phosphorus, to create a permanent imbalance in the molecular charge of the material.

A solar cell is made up of two layers of semiconductor material. Two regions are created, a positively charged region and a negatively charged region. These layers create an electric potential within the cell. Light energy striking the cells free electrons from some of the atoms in the cell material. The cell's internal potential pushes these free electrons toward one of the layers. When one end of a wire is attached to this layer and the other end is attached to the second layer, the free electrons will flow through the wire, creating an electric current. [2]

2.1.4 Photovoltaic array

A photovoltaic array is a linked collection of photovoltaic modules, which are in turn made of multiple interconnected solar cells. The power that one module can produce is seldom enough to meet requirements of a home or a business, so the modules are linked together to form an array. Most PV arrays use an inverter to convert the DC power produced by the modules into alternating current that can plug into the existing infrastructure to power lights, motors, and other loads. The modules in a PV array are usually first connected in series to obtain the desired voltage; the individual strings are then connected in parallel to allow the system to produce more current. Solar arrays are typically measured by the electrical power they produce, in watts, kilowatts, or even megawatts.

2.1.5 Electrical characteristics of PV modules

The industry standard against which all PV modules are rated and can be compared is called Standard Test Conditions (STC). STC is a defined set of laboratory test conditions which approximate conditions under which PV modules might be used. The same standard is also used to evaluate potential installation locations, since it is the basis for Insolation values. STC includes three factors:

1. ***Irradiance*** (sunlight intensity or power), in Watts per square meter falling on a flat surface. The measurement standard is 1 kW per sq. m. (1,000 Watts/m2)
2. ***Air Mass,*** refers to “thickness” and clarity of the air through which the sunlight passes to reach the modules (sun angle affects this value). The standard is 1.5.
3. ***Cell temperature,*** which will differ from ambient air temperature. STC defines cell testing temperature as 25 degrees C. [2]

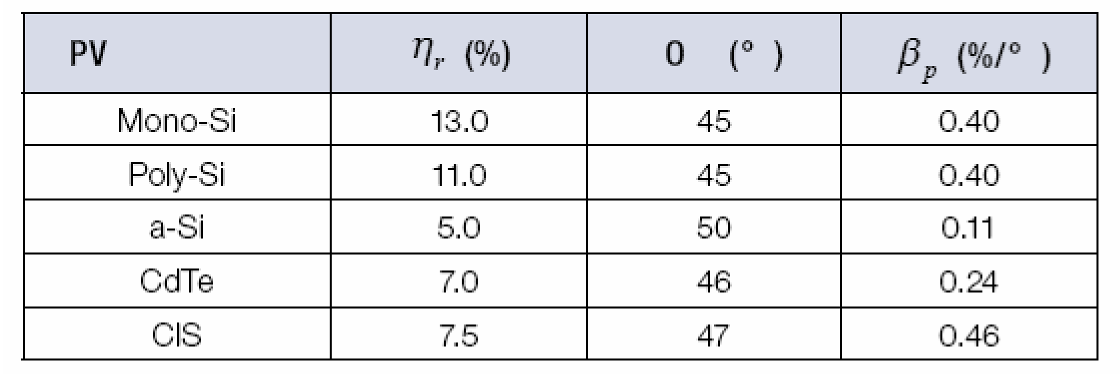
2.1.6 Efficiency (*η)*

Efficiency is the ratio of the electrical power output P_{out}, compared to the solar power input, P_{in}, into the PV cell. P_{out} can be taken to be P_{MAX} since the solar cell can be operated up to its maximum power output to get the maximum efficiency.

$$\eta = \frac{P_{out}}{P_{in}} \Rightarrow \eta_{MAX} = \frac{P_{MAX}}{P_{in}}$$

P_{in} is taken as the product of the irradiance of the incident light, measured in W/m^2 or in suns ($1000\ W/m^2$), with the surface area of the solar cell [m^2]. The maximum efficiency (η_{MAX}) found from a light test is not only an indication of the performance of the device under test, but, like all of the I-V parameters, can also be affected by ambient conditions such as temperature and the intensity and spectrum of the incident light. For this reason, it is recommended to test and compare PV cells using similar lighting and temperature conditions.

Table2.1 PV Module Characteristics for Standard Technologies



PV	η_r (%)	0 (°)	β_p (%/°)
Mono-Si	13.0	45	0.40
Poly-Si	11.0	45	0.40
a-Si	5.0	50	0.11
CdTe	7.0	46	0.24
CIS	7.5	47	0.46

2.1.7 Advantages and disadvantages of using photovoltaic systems

Advantages

Reliability-Even in harsh climates, photovoltaic systems have proven their reliability. Often, photovoltaic systems are chosen for systems that must remain operational at all times. Photovoltaic systems may prevent costly or dangerous power failures in situation where continuous operation is critical

Low Maintenance Cost- It is expensive to transport materials and personnel to remote areas for equipment maintenance. Since photovoltaic systems require only periodic inspection and occasional maintenance, these costs are usually less than with conventionally fuelled equipment alternatives.

Scaleable and modular- From providing milliwatts to power a calculator to acres of panels providing megawatts for grid connected supply on a commercial building roof or field, solar power products can be deployed in many sizes and configurations and can be installed quickly and almost anywhere in the world. As a distributed generation option, transmission and distribution costs are reduced.

Universal Applications- Solar PV is the only renewable energy technology that can be installed on a truly global scale because of its versatility and because it generates power under virtually all conditions, i.e. even in overcast light conditions

Peak Shaving- The output of solar systems typically correlates with periods of high electricity demand where air conditioning systems create peak demands during hot sunny days. PV can shave peak-load demand, when energy is most constrained and expensive and therefore can move the load off the grid and alleviate the need to build new peak generating capacity.

Reliability- With no fuel supply required and no moving parts, solar power systems are among the most reliable electric power generators, capable of powering the most sensitive applications, from space satellites to microwave stations in the mountains and other remote harsh environments. Solar panels typically carry warranties of 20 years or more.

Dual use- Solar panels are expected to increasingly serve as both a power generator and the skin of the building. Like architectural glass, solar panels can be installed on the roofs or facades of residential and commercial buildings.

Environmentally safe- Solar power systems produce no air or water emissions or greenhouse gases and produce no noise. Solar systems are generally far safer than other distributed energy systems, such as diesel generators and as such are the most suitable technology for urban on-site generation. PV is the only commercially available renewable technology generation option for urban areas.

Disadvantages

Cost- Photovoltaic systems have a high initial cost. Each installation must be evaluated from an economic perspective and compared to existing alternatives. If the initial cost of the photovoltaic systems decreases and the cost of conventional fuel sources increases, photovoltaic systems will become more economically competitive.

Variability of Available Solar Radiation- Weather can adversely affect the power output of any PV system. If there is no sunshine there is no power.

Energy Storage- Some photovoltaic systems use batteries for storing energy which will be used at a later time. The battery increases the system's size and cost can make the system more complex.

Education- Photovoltaic systems use a new technology with which many people are unfamiliar. Few people understand its applicability. This lack of information slows market and technological growth.

2.2 Batteries

Batteries chemically store direct current electrical energy for later use, during periods of cloudy weather and when a portable power source is desired. Since a photovoltaic system‘s power output varies throughout any given day, the battery storage system can provide a relatively constant power source, even when the photovoltaic system is disconnected for repair and maintenance or producing minimal power in periods of reduced insolation.

2.2.1 Battery Types and Classifications

Many types and classifications of batteries are manufactured today, each with specific design and performance characteristics suited for particular applications. Each battery type or design has its individual strengths and weaknesses. In PV systems, *lead-acid* batteries are most common due to their wide availability in many sizes, low cost and well understood performance characteristics. In a few critical, low temperature applications *nickel-cadmium* cells are used, but their high initial cost limits their use in most PV systems. There is no “perfect battery” and it is the task of the PV system designer to decide which battery type is most appropriate for each application.

In general, electrical storage batteries can be divided into two major categories, *primary* and *secondary* batteries.

- **Primary Batteries-** Primary batteries can store and deliver electrical energy, but *cannot be recharged*. Typical carbon-zinc and lithium batteries commonly used in consumer electronic devices are primary batteries. Primary batteries are not used in PV systems because they cannot be recharged.
- **Secondary Batteries-** A secondary battery can store and deliver electrical energy, and *can also be recharged* by passing a current through it in an opposite direction to the discharge current. Common *lead-acid* batteries used in automobiles and PV systems are secondary batteries. Table 1 lists common secondary battery types and their characteristics which are of importance to PV system designers. A detailed discussion of each battery type follows.

2.2.2 Lead-Acid Batteries

There are several types of lead-acid batteries manufactured. The following sections describe the types of Lead-acid batteries commonly used in PV systems;

Lead-Antimony Batteries

Lead-antimony batteries are a type of lead-acid battery which use antimony (Sb) as the primary alloying element with lead in the plate grids. The use of lead-antimony alloys in the grids has both advantages and disadvantages. Advantages include providing greater *mechanical strength* than pure lead grids, and excellent *deep discharge* and *high discharge rate* performance. Lead-antimony grids also limit the shedding of active material and have better lifetime than lead-calcium batteries when operated at higher temperatures.

Disadvantages of lead-antimony batteries are a *high self-discharge rate*, and as the result of necessary overcharge, require frequent water additions depending on the temperature and amount of overcharge. Most lead-antimony batteries are flooded, open vent types with removable caps to permit water additions. They are well suited to application in PV systems due to their deep cycle capability and ability to take abuse, however they do require periodic water additions. The frequency of water additions can be minimized by the use of *catalytic recombination caps* or battery designs with excess electrolyte reservoirs. The health of flooded, open vent lead-antimony batteries can be easily checked by measuring the *specific gravity* of the electrolyte with a *hydrometer*. Lead-antimony batteries with thick plates and robust design are generally classified as motive power or traction type batteries, are widely available and are typically used in electrically operated vehicles where deep cycle long-life performance is required.

Lead-Calcium Batteries

Lead-calcium batteries are a type of lead-acid battery which uses calcium (Ca) as the primary alloying element with lead in the plate grids. Like lead-antimony, the use of lead-calcium alloys in the grids has both advantages and disadvantages. Advantages include providing greater *mechanical strength* than pure lead grids, a *low self-discharge rate*, and *reduced gassing* resulting in lower water loss and lower maintenance requirements than for lead-antimony batteries. Disadvantages of lead-calcium batteries include *poor charge acceptance* after deep discharges and shortened battery life at higher operating temperatures and if discharged to greater than 25% *depth of discharge* repeatedly.

- Flooded Lead-Calcium, Open Vent- Often classified as stationary batteries, these batteries are typically supplied as individual 2 volt cells in capacity ranges up to and over 1000 ampere-hours. Flooded lead-calcium batteries have the advantages of low self discharge and low water loss, and may last as long as 20 years in stand-by or float service. In PV applications, these batteries usually experience short lifetimes due to sulfation and stratification of the electrolyte unless they are charged properly.

- Flooded Lead-Calcium, Sealed Vent- Primarily developed as 'maintenance free' automotive starting batteries, the capacity for these batteries is typically in the range of 50 to 120 ampere-hours, in a nominal 12 volt unit. Like all lead-calcium designs, they are intolerant of overcharging, high operating temperatures and deep discharge cycles. They are “maintenance free” in the sense that you do not add water, but they are also limited by the fact that you cannot add water which generally limits their useful life. This battery design incorporates sufficient reserve electrolyte to operate over its typical service life without water additions. These batteries are often employed in small stand-alone PV systems such as in rural homes and lighting systems, but must be carefully charged to achieve maximum performance and life. While they are low cost, they are really designed for shallow cycling, and will generally have a short life in most PV applications.

Lead-Antimony/Lead-Calcium Hybrid

These are typically flooded batteries, with capacity ratings of over 200 ampere-hours. A common design for this battery type uses *lead-calcium* tubular *positive* electrodes and pasted *lead-antimony negative* plates. This design combines the advantages of both lead-calcium and lead-antimony design, including good deep cycle performance, low water loss and long life. *Stratification* and *sulfation* can also be a problem with these batteries, and must be treated accordingly. These batteries are sometimes used in PV systems with larger capacity and deep cycle requirements.

2.2.3 Nickel-Cadmium Batteries

Nickel-cadmium (NiCd) batteries are *secondary* or *rechargeable* batteries, and have several advantages over lead-acid batteries that make them attractive for use in stand-alone PV systems. These advantages include *long life*, *low maintenance*, survivability from excessive discharges, excellent low temperature *capacity retention*, and *non-critical voltage regulation* requirements. The main disadvantages of nickel-cadmium batteries are their *high cost* and limited availability compared to lead-acid designs. A typical nickel-cadmium cell consists of positive electrodes made from *nickel-hydroxide* (NiO(OH)) and negative electrodes made from *cadmium* (Cd) and immersed in an alkaline *potassium hydroxide* (KOH) electrolyte solution. When a nickel-cadmium cell is discharged, the nickel hydroxide changes form (Ni(OH)2) and the cadmium becomes cadmium hydroxide (Cd(OH)2). The concentration of the electrolyte does not change during the reaction so the freezing point stays very low.

2.2.4 Specifying Batteries

The following are considered when specifying a properly sized and installed battery storage system for a stand-alone photovoltaic system:

Depth of Discharge - This term is the percentage of the rated battery capacity that has been withdrawn from the battery. The capability of a battery to withstand discharge depends on its construction. The most common batteries have electrically active lead alloy plates immersed in a mild acid electrolyte. Plate types are Planté (pure lead), pasted, or tubular. The plates can be made with different thicknesses and different alloys, such as lead calcium, or lead antimony, for different applications. Generally, the more massive the plates the better the battery will withstand discharge and recharge (cycling). Two terms, *shallow-cycle* and *deep-cycle*, are commonly used to describe batteries. Shallow Cycle batteries are lighter, less expensive, and will have a shorter lifetime particularly if recommended discharge levels are exceeded regularly. Many sealed (advertised as no maintenance) batteries are shallow-cycle types. Generally, the shallow-cycle batteries should not be discharged more than 25 percent.

Deep-cycle batteries are more often used for stand-alone PV systems. These units have thicker plates and most will withstand discharges up to 80 percent of their rated capacity. Most of these are flooded batteries which mean the plates are covered with the electrolyte. The electrolyte level must be monitored and distilled water added periodically to keep the plates fully covered.

Another type of battery using nickel cadmium (NiCd) plates can be used. NiCd batteries are more expensive but can withstand harsh weather conditions. NiCd batteries can be completely discharged without damage and the electrolyte will not freeze.

The maximum depth of discharge value used for sizing should be the worst case discharge t hat the battery will experience. The battery charge controller should be set to prevent discharge below this level. Because nickel cadmium batteries can be discharged nearly 100 percent without damage, some designers do not use a controller if NiCd batteries are used.

Temperature Correction – Batteries are sensitive to temperature extremes and a cold battery will not provide as much power as a warm one. Most manufacturers provide temperature correction curves. For instance, a battery at 25°C has 100 percent capacity if discharged at a current rate of C/20. (The discharge rate is given as a ratio of the rated capacity, C, of the battery.) However, a battery operating at 0°C would have only 75 percent of the rated capacity if discharged at a C/20 rate. If the discharge rate is higher, say C/5, only 50 percent of the rated capacity will be available when the temperature is minus 20°C. Although more than the rated capacity can be obtained when the battery temperature is high, hot temperatures should be avoided because they will shorten battery life. Battery should be kept near room temperature.

Rated Battery Capacity – This term indicates the maximum amount of energy that a battery can produce during a single discharge under specified conditions of temperature and discharge rate. You will not be able to obtain rated capacity repeatedly when the batteries are used in PV systems. However, rated capacity sets a baseline on which to compare-battery performance. When comparing the rated capacity of different batteries, be sure the same discharge rate is being used.

State-of-Charge (SOC) -This is the amount of capacity remaining in a battery at any point in time. It is equal to 1 minus the depth of discharge given as a percentage.

Battery Life (cycles) - The lifetime of any battery is difficult to predict because it depends on a number of factors such as charge and discharge rates, depth of discharges, number of cycles, and operating temperatures. It would be unusual for a lead acid type battery to last longer than 15 years in a PV system but many last for 5-10 years. Nickel cadmium batteries will generally last longer when operated under similar conditions and may operate satisfactorily for more than 15 years under optimum conditions.

Battery Safety - Batteries which are used in photovoltaic systems are potentially dangerous if improperly handled, installed, or maintained. Dangerous chemicals, heavy, weight and high voltages and currents are potential hazards and can result in electric shock, burns explosion or corrosive damage to your person or property.

Days of Autonomy - Autonomy refers to the number of days a battery system will provide a given load without being recharged by the photovoltaic array. Correctly selecting a number of days will depend on the system, its location, its total load and the nature of the system's load.
Weather conditions determine the number of no sun days which may be the most significant variable in determining autonomy.

2.3 Charge Controllers

Charge controllers are included in most photovoltaic systems to protect the batteries from overcharge or excessive discharge. Overcharging can boil the electrolyte from the battery and cause failure. Allowing the battery to be discharged too much will cause premature battery failure and possible damage to the load. The controller is a critical component in the PV system.
A controller's function is to control the system depending on the battery state-of-charge (SOC). When the battery nears full SOC the controller redirects or switches off all or part of the array current. When the battery is discharged below a preset level, some or the entire load is disconnected if the controller includes the low voltage disconnect (LVD) capability. Most controllers use a measurement of battery voltage to estimate the state-of-charge. Measuring battery temperature improves the SOC estimate and many controllers have a temperature probe for this purpose.

The controller voltage must be compatible with the nominal system voltage and it must be capable of handling the maximum current produced by the PV array.

2.3.1 Types of controllers

There are two basic types of controllers used for small PV systems.

- Shunt controller - redirects or shunts the charging current away from the battery. These controllers require a large heat sink to dissipate the excess current. Most shunt controllers are designed for smaller systems producing 30 amperes or less.
- Series controller - interrupts the charging current by open-circuiting the PV array. This switching controller is thus limited by the current handling capability of the components used to switch the dc current.
- Single stage controllers - disconnect the array when the battery voltage reaches the high voltage level.
- Multistage controllers - allow different charging currents as the battery nears full state-of charge. This technique also provides a more efficient method of charging the battery. As the battery nears full SOC, its internal resistance increases and using lower charging current wastes less energy.

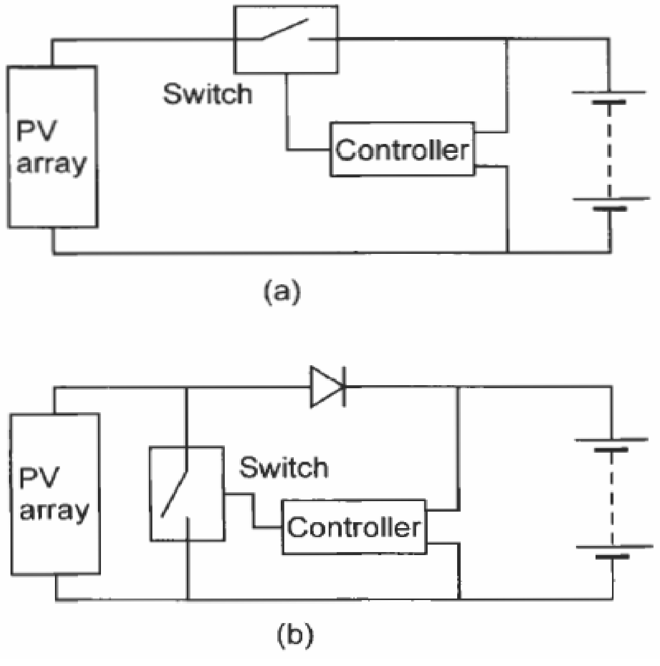


Figure 2.4 (a) Series Controller (b) Shunt Controller

2.3.2 Blocking Reverse Current

Photovoltaic panels work by pumping current through the battery in one direction. At night, the panels may pass a bit of current in the reverse direction, causing a slight discharge from the battery. Battery here represents either a single battery or bank of batteries. The potential loss is minor, but it is easy to prevent. Some types of wind and hydro generators also draw reverse current when they stop (most do not except under fault conditions).

In most controllers, charge current passes through a semiconductor (a transistor) which acts like a valve to control the current. It prevents reverse current without any extra effort or cost. In some controllers, an electromagnetic coil opens and closes a mechanical switch. This is called a relay. The relay switches off at night, to block reverse current.

If a PV array is being used only to trickle-charge a battery (a very small array relative to the size of the battery), then a charge controller may not be needed.

2.3.3 Preventing Overcharge

When a battery reaches full charge, it can no longer store incoming energy. If energy continues to be applied at the full rate, the battery voltage gets too high. Water separates into hydrogen and oxygen and bubbles out rapidly. There is excessive loss of water, and a chance that the gasses can ignite and cause a small explosion. The battery will also degrade rapidly and may possibly overheat. Excessive voltage can also stress loads or cause the inverter to shut off.

Preventing overcharge is simply a matter of reducing the flow of energy to the battery when the battery reaches a specific voltage. When the voltage drops due to lower sun intensity or an increase in electrical usage, the controller again allows the maximum possible charge. This is called "voltage regulating." It is the most essential function of all charge controllers. The controller "looks at" the voltage, and regulates the battery charging in response.

Some controllers regulate the flow of energy to the battery by switching the current fully on or fully off. This is called "on/off control." Others reduce the current gradually. This is called "pulse width modulation" (PWM). Both methods work well when set properly for your type of battery.

A PWM controller holds the voltage more constant. If it has two-stage regulation, it will first hold the voltage to a safe maximum for the battery to reach full charge. Then, it will drop the voltage lower, to sustain a "finish" or "trickle" charge. Two-stage regulating is important for a system that may experience many days or weeks of excess energy (or little use of energy). It maintains a full charge but minimizes water loss and stress.

The voltages at which the controller changes the charge rate are called set points. When determining the ideal set points, there is some compromise between charging quickly before the sun goes down, and mildly overcharging the battery. The determination of set points depends on the anticipated patterns of usage, the type of battery, and to some extent, the experience and philosophy of the system designer or operator. Some controllers have adjustable set points, while others do not.

2.3.4 Control Set Points vs. Temperature

The ideal set points for charge control vary with a battery's temperature. Some controllers have a feature called "temperature compensation." When the controller senses a low battery temperature, it will raise the set points. Otherwise when the battery is cold, it will reduce the charge too soon. If the batteries are exposed to temperature swings greater than about 30° F (17° C), compensation is essential.

Some controllers have a temperature sensor built in. Such a controller must be mounted in a place where the temperature is close to that of the batteries. Better controllers have a remote temperature probe, on a small cable. The probe should be attached directly to a battery in order to report its temperature to the controller.

An alternative to automatic temperature compensation is to manually adjust the set points (if possible) according to the seasons.

2.3.5 Control Set Points vs. Battery Type

The ideal set points for charge controlling depend on the design of the battery. The vast majority of RE systems use deep-cycle lead-acid batteries of either the flooded type or the sealed type. Flooded batteries are filled with liquid. These are the standard, economical deep cycle batteries.

Sealed batteries use saturated pads between the plates. They are also called "valve-regulated" or "absorbed glass mat," or simply "maintenance-free." They need to be regulated to a slightly lower voltage than flooded batteries or they will dry out and be ruined. Some controllers have a means to select the type of battery. Never use a controller that is not intended for your type of battery.

Typical set points for 12 V lead-acid batteries at 77° F (25° C)
Example of set points;
High limit (flooded battery): 14.4 V
High limit (sealed battery): 14.0 V
Resume full charge: 13.0 V

Low voltage disconnect: 10.8 V
Reconnect: 12.5 V

Temperature compensation for 12V battery:
-.03 V per ° C deviation from standard 25° C

2.3.6 Low Voltage Disconnect (LVD)

The deep-cycle batteries used in renewable energy systems are designed to be discharged by about 80 percent. If they are discharged 100 percent, they are immediately damaged. Every time this happens, both the capacity and the life of the battery will be reduced by a small amount. If the battery sits in this over discharged state for days or weeks at a time, it can be ruined quickly. The only way to prevent over discharge when all else fails, is to disconnect loads (appliances, lights, etc.), and then to reconnect them only when the voltage has recovered due to some substantial charging. When over discharge is approaching, a 12 volt battery drops below 11 volts (a 24 V battery drops below 22 V). A low voltage disconnect circuit will disconnect loads at that set point. It will reconnect the loads only when the battery voltage has substantially recovered due to the accumulation of some charge. A typical LVD reset point is 13 volts (26 V on a 24 V system).

2.3.7 Overload Protection

A circuit is overloaded when the current flowing in it is higher than it can safely handle. This can cause overheating and can even be a fire hazard. Overload can be caused by a fault (short circuit) in the wiring, or by a faulty appliance (like a frozen water pump). Some charge controllers have overload protection built in, usually with a push-button reset.

Built-in overload protection can be useful, but most systems require additional protection in the form of fuses or circuit breakers. If you have a circuit with a wire size for which the safe carrying capacity (ampacity) is less than the overload limit of the controller, then you must protect that circuit with a fuse or breaker of a suitably lower amp rating.

2.4 Inverters

Inverters which are also known as Power conditioning units are necessary in any stand-alone PV system with ac loads. The choice of inverter will be a factor in setting the dc operating voltage of your system. When specifying an inverter, it is necessary to consider requirements of both the dc input and the ac output. All requirements that the ac load will place on the inverter should be considered, not only how much power but what variation in voltage, frequency, and waveform can be tolerated. On the input side, the dc voltage, surge capacity, and acceptable voltage variation must be specified. Selecting the best inverter for an application requires a study of many parameters. The choice of inverter will affect the performance and reliability of a PV system.

2.4.1Characteristics

Stand-alone inverters typically operate at 12, 24, 48 or 120 volts dc input and create 120 or 240 volts ac at 50 Hertz. The selection of the inverter input voltage is an important decision because it often dictates the system dc voltage; the shape of the output waveform is an important parameter. Inverters are often categorized according to the type of waveform produced;

1. Square wave,
2. Modified sine wave
3. Sine wave.

The output waveform depends on the conversion method and the filtering used on the output waveform to eliminate spikes and unwanted frequencies that result when the switching occurs.

Square wave inverters are relatively inexpensive, have efficiencies above 90 percent, high harmonic frequency content, and little output voltage regulation. They are suitable for resistive loads and incandescent lamps. Modified sine wave inverters offer improved voltage regulation by varying the duration of the pulse width in their output. Efficiencies can reach 90 percent. This type of inverter can be used to operate a wider variety of loads including lights, electronic equipment, and most motors. However, these inverters will not operate a motor as efficiently as a sine wave inverter because the energy in the additional harmonics is dissipated in the motor windings. Sine wave inverters produce an ac waveform as good as that from most electric utilities.

They can operate any ac appliance or motor within their power rating. In general, any inverter should be oversized 25 percent or more to increase reliability and lifetime. This also allows for modest growth in load demand. The efficiency of all inverters is lowest for small load demand and reach their nominal efficiency (around 85 percent) when the load demand is greater than about 50 percent of rated load. The manufacturers' specification sheets will list some of the following parameters.

- **Power Conversion Efficiency** - This value gives the ratio of output power to input power of the inverter. Efficiency of stand-alone inverters will vary significantly with the load. Values found in manufacturers' specifications are the maximum that can be expected.
- **Rated Power** - Rated power of the inverter. However, some units cannot produce rated power continuously. See duty rating. Choose an inverter that will provide at least 125 percent of simultaneous peak load requirements to allow for some growth in load demand.
- **Duty Rating** - This rating gives the amount of time the inverter can supply its rated power. Some inverters can operate at their rated power for only a short time without overheating. Exceeding this time may cause hardware failure.

- **Input Voltage** - This is determined by the total power required by the ac loads and the voltage of any dc loads. Generally, the larger the load, the higher the inverter input voltage. This keeps the current at levels where switches and other components are readily available.
- **Surge Capacity** - Most inverters can exceed their rated power for limited periods of time (seconds). Surge requirements of specific loads should be determined or measured. Some transformers and ac motors require starting currents several times their operating level for several seconds.
- **Standby Current** - This is the amount of current (power) used by the inverter when no load is active (power loss). This is an important parameter if the inverter will be left on for long periods of time to supply small loads. The inverter efficiency is lowest when load demand is low.
- **Voltage Regulation** - This indicates the variability in the output voltage. Better units will produce a nearly constant root-mean-square (RMS) output voltage for a wide range of loads.
- **Voltage Protection** - The inverter can be damaged if dc input voltage levels are exceeded. Remember, battery voltage can far exceed nominal if the battery is overcharged. A 12-volt battery may reach 16 volts or more and this could damage some inverters. Many inverters have sensing circuits that will disconnect the unit from the battery if specified voltage limits are exceeded.
- **Frequency** - Most loads in Kenya require 50 Hz. High-quality equipment requires precise frequency regulation variations can cause poor performance of clocks and electronic timers.
- **Modularity** - In some systems it is advantageous to use multiple inverters. These can be connected in parallel to service different loads. Manual load switching is sometimes provided to allow one inverter to meet critical loads in case of failure. This added redundancy increases system reliability.
- **Power Factor** - The cosine of the angle between the current and voltage waveforms produced by the inverter is the power factor. For resistive loads, the power factor will be 1.0 but for inductive loads, the most common load in residential systems, the power

factor will drop, sometimes as low as 0.5. Power factor is determined by the load, not the inverter.

2.4.2 Installation

An inverter should be installed in a controlled environment because high temperatures and excessive dust will reduce lifetime and may cause failure. The inverter should not be installed in the same enclosure with the batteries because the corrosive gassing of the batteries can damage the electronics and the switching in the inverter might cause an explosion. However, the inverter should be installed near the batteries to keep resistive losses in the wires to a minimum. After conversion to ac power, the wire size can be reduced because the ac voltage is usually higher than the dc voltage. This means the ac current is lower than the dc current for a equivalent power load.

Both the input and output circuits of the inverter should be protected with fuses or circuit breakers. These safety devices should be accessible and clearly labelled. Using a surge protection device on the inverter input to protect against nearby lightning strikes is recommended for most areas. A component such as a movistor shunts surge current to ground. If a nearby lightning strike occurs, this may destroy the movistor, but its destruction might prevent expensive inverter repair bills.

CHAPTER 3: DESIGN

3.1 Photovoltaic system sizing

Sizing a photovoltaic system for a stand-alone photovoltaic power system involves a five step process which will allow the photovoltaic system designer or user to accurately size a system based on users projected needs, goals and budget. These steps are:

1. Estimating The Electric Load
2. Sizing and Specifying An Inverter
3. Sizing and Specifying Batteries
4. Sizing and Specifying An Array
5. Specifying A Controller

3.2 Photovoltaic system sizing worksheet instructions

3.2.1 Estimating the Electric Load

The first task for any photovoltaic system design is to determine the system load. This load estimate is one of the key factors in the design and cost of the stand-alone PV system. Worksheet 1, which is shown in the insert, is used to calculate average daily loads and the result will be the sum of the estimated loads for both ac and dc appliances. If the loads vary significantly on a seasonal basis or are of a critical nature the peak load values are used.

The following steps are followed for Electric Load Estimation;

- Identify each load and the number of hours of use per day. Enter the load current in amperes and the operating voltage for each load and calculate the power demand. The power demand is the product of the current and the voltage. List the ac loads at the top of the worksheet and dc loads, at the bottom. A power conditioning unit (PCU) is required for ac loads. A PCU, commonly called an inverter, adds complexity to a system and causes a 10-15 percent loss of power because of the efficiency of converting dc power to ac power. If only a small percentage of the loads require ac power, it may be better to replace those devices with ones that use dc power.

- Group the loads by type and operating voltage and sum the Power demand for each group. The recommended voltage of the standalone PV system will be determined by considering this information.

- After selecting the system voltage, calculate the total daily ampere hours required at this voltage.

The load determination is straightforward the power requirements of any electrical device that will be included in the system are calculated and multiplied by the amount of time that specific appliances will operate each day. The power required by an appliance can be measured or obtained from manufacturer’s data sheets. However, the amount of time the appliance will be used per day, week, or month must be estimated. For residential systems (and many others) the hours of use can be controlled by the system owner.

The design should consider energy conserving substitutes for items that are used often. Large and/or variable loads are determined and if they can be eliminated or changed to operate from another power source. Fluorescent lamps should be used in place of incandescent lamps. They provide the same light levels with much lower power demand. Dc appliances considered to avoid the loss in the dc/ac power conversion process. DC lights and appliances usually cost more, but are more efficient and last longer. The number of ac appliances available is greater but efficiencies are usually lower because these appliances are designed for use on an “infinite” utility power supply.

Summary of Worksheet 1

The Electric load estimation is computed by adding the wattage of each and every component in the system. DC and AC loads are totalled separately. This will give the ‘Total Connected Watts’. The ‘Average Daily Load’ is then computed by multiplying the Total connected watts by the hours of use per day and the hours of use per week and the result is divided by 7 (total number of days in a week).

WORKSHEET 1: ELECTRIC LOAD ESTIMATION

Table 3.1 Electric Load Estimation

ELECTRIC LOAD ESTIMATION																	
LOADS	VOLTS	×	AMPS	×	QTY	=	WATTS		×	USE HRS/DAY	×	USE DAYS/WK	÷	7 DAYS/WK	=	AVG. WATT HR/ DAY	
							AC	DC								AC	DC
		×		×		=			×		×		×		=		
		×		×		=			×		×		×		=		
		×		×		=			×		×		×		=		
		×		×		=			×		×		×		=		
		×		×		=			×		×		×		=		
		×		×		=			×		×		×		=		
		×		×		=			×		×		×		=		
		×		×		=			×		×		×		=		
		×		×		=			×		×		×		=		
AC TOTAL CONNECTED WATTS									×	**AC AVERAGE DAILY LOAD**					=		
DC TOTAL CONNECTED WATTS									×	**DC AVERAGE DAILY LOAD**					=		

3.2.2 Specifying an Inverter

The Alternating current total connected watts or those that will be used simultaneously as computed above is divided by the direct current system voltage. This will provide the Maximum direct Current Amps continuous which the system will require. The inverter specification should be made on the basis of the AC watts since essentially it should supply this load. The inverter should meet the system's wattage specification.

WORK SHEET 2: INVERTER SPECIFICATION

Table 3.2 Inverter specification

INVERTER SPECIFICATION						
AC TOTAL CONNECTED WATTS	÷	DC SYSTEM VOLTAGE	=	MAXIMUM DC AMPS CONTINUOS	ESTIMATED SURGE WATTS	LISTED DESIRED FEATURES
	÷		=			
INVERTER SPECIFICATION		MAKE				MODEL

3.2.3 Sizing and specifying a battery

Worksheet 3, which is shown in the inset, can be used to determine the size of the battery storage required for a stand-alone PV system. Before making these choices, the concept of system availability and battery parameters should be taken into consideration. Some of the considerations made when sizing the battery are;

- First, the amount of back-up energy to be stored is calculated for the given application. This is usually expressed as a number of no sun days, in other words, for how many cloudy days must the system operate using energy stored in batteries. This depends on the application, the type of battery, and the system availability desired.

- When specifying, the difference between rated battery capacity and usable capacity should be enumerated. Many Battery manufacturers publish a rated battery capacity (the amount of energy that their battery will provide if discharged once under favourable conditions of temperature and discharge rate). This is usually much higher than the amount of energy that can be taken out of the battery repeatedly in a PV application. For some shallow-cycle, sealed batteries the usable capacity is only 20 percent of the rated capacity, i.e., taking more than 20 ampere-hours from a 100 ampere-hour battery will cause the battery to quickly fail. Other types of batteries designed for deep cycling will have usable capacities up to 80 percent of rated capacity. For most PV applications the bigger and heavier the battery the better. The best recommendation for the number of days of storage is to put in as much battery capacity as can be afforded. Obviously, for areas with extended periods of cloudiness need more storage capacity to keep the load going during these periods of inclement weather. Also, if it is critical that loads have power at all times, it is advisable to have a large battery capacity. A smaller battery size can be specified if one can live with some power outage. The PV system design takes into consideration all these aspects plus more when choosing the battery type and size. Some factors can outweigh the technical sizing decision. For instance, if batteries can be obtained locally thus making savings in shipping costs. This savings can be used to buy more batteries.

- Also, there are many types of batteries with a large variance in quality and cost. Figure 3.1 gives a starting point for making battery size selection using the design month peak sun hours. Just find the peak sun hours for the design month and read up to the days of storage for system availabilities of 95 or 99 percent. It is important to buy quality batteries that can be discharged and recharged many times before failure. Automobile batteries should not be used if there is any alternative. Automobile batteries are designed to produce a high current for a short time. The battery is then quickly recharged. PV batteries may be discharged slowly over many hours and may not be recharged fully for several days or weeks.

- Finally, it is important to understand the close interrelation between the battery and the charge controller. When a battery is bought a compatible charge controller should also be purchased. A charge controller is an electronic device that attempts to maintain the battery state-of-charge (SOC) between preset limits. The battery voltage is measured and used as the primary estimator of SOC. (Some charge controllers measure battery temperature in addition to voltage to improve the estimate of SOC.) If the charge controller does not operate properly the battery may be over charged or allowed to discharge too much. Either way the lifetime of the battery will be shortened more money will be spent money to replace the batteries.

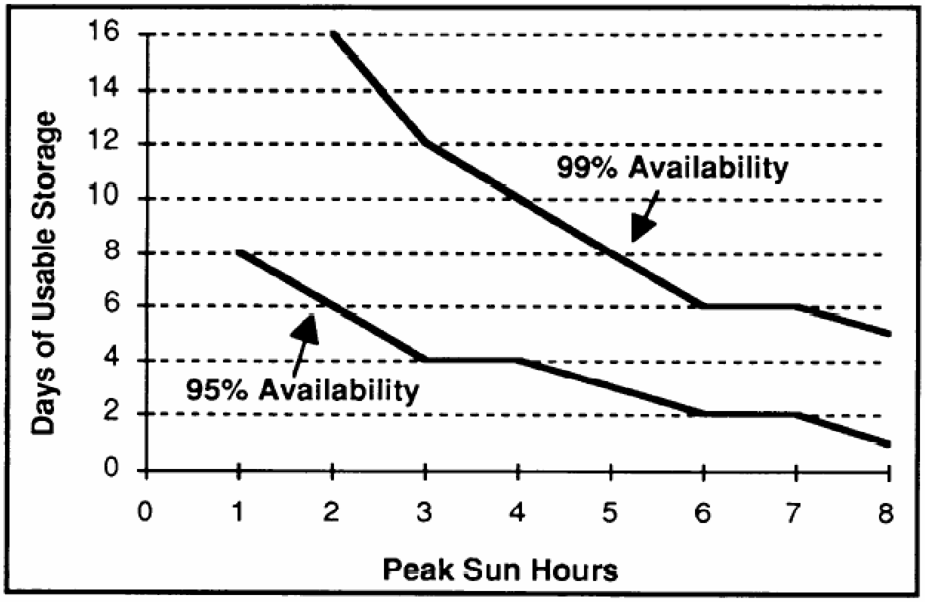


Figure 3.1 Graph of Days of Usable Storage against Peak Sun Hours

Summary of Worksheet 3

To the specify the battery we first establish the inverter losses which will occur by inputting the Alternating current Average daily load and dividing it by the inverter efficiency which is usually less than 90 percent(0.9). This watt hour total is then added to the Direct Current Average Daily Load and the result divided by the Direct Current System Voltage to arrive at the Average Amp Hour per Day Load.

This Average Amp hour per Day Load should be multiplied by the desired Days of Autonomy to determine the required battery capacity. The total is divided by the Discharge limit or the Battery's Maximum Depth of Discharge (a number less than 1.0) to determine the required Battery capacity.

WORKSHEET 3: BATTERY SIZING

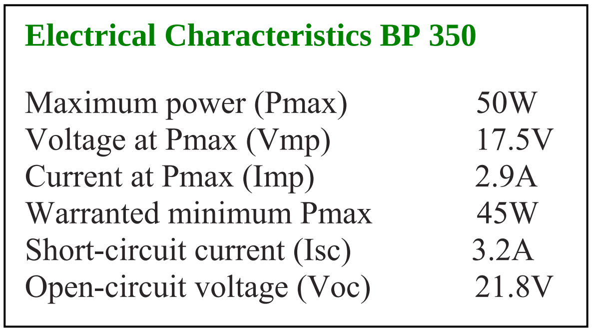
Table 3.3 Battery sizing

BATTERY SIZING								
AC AVERAGE DAILY LOAD	÷	INVERTER EFFICIENCY	+	DC AVERAGE DAILY LOAD	÷	DC SYSTEM VOLTAGE	=	AVE AMP HOUR PER DAY LOAD
	÷				÷		=	
AVE AMP HOUR PER DAY LOAD	÷	DAYS OF AUTONOMY	÷	DISCHARGE LIMIT	÷	BATTERY AMP HR. CAPACITY	=	BATTERIES IN PARALLEL
	÷		÷		÷		=	
DC SYSTEM VOLTAGE	÷	BATTERY VOLTAGE	=	BATTERIES IN SERIES	×	BATTERIES IN PARALLEL	=	TOTAL BATTERIES
	÷		=		×		=	

3.2.4 Sizing and Specifying an Array

The design method for the array uses current (amperes) instead of power (watts) to describe the load requirement because it is easier to make a meaningful comparison of PV module performance, i.e., specifying PV modules that will produce 30 amperes at 12 volts and a specified operating temperature rather than try to compare 50 watt modules that may have different operating points. The module specifications are obtained for available modules so that a comparison of performance, physical size, and cost can be made. Generally, there are several modules that will meet a given set of requirements.

The worksheet requests the entry of rated module current. This is the current produced at standard test conditions (STC) of 1,000w/m² irradiance and 25°C temperature. The module specifications given by one module manufacturer are shown in Fig 3.2.The current values given are at short circuit, Isc, and at the peak power point, Imp. The value used in the worksheet for rated module current should be Isc. The voltage at the peak power point is stated as 17.5volts. However, the operating voltage of a PV array is determined by the battery voltage. This varies over a narrow range depending on the battery state of charge and ambient temperature but is usually 1 to 4 volts lower than the voltage at which peak power figures are quoted by module manufacturers.



Electrical Characteristics BP 350

Maximum power (Pmax)	50W
Voltage at Pmax (Vmp)	17.5V
Current at Pmax (Imp)	2.9A
Warranted minimum Pmax	45W
Short-circuit current (Isc)	3.2A
Open-circuit voltage (Voc)	21.8V

Figure 3.2 50W Module Specification

Fortunately, the current changes little from the peak power voltage (17.5 volts) to normal system operating voltages (12 volts). For crystalline silicon modules, the operating voltage will decrease about one-half of one percent for each degree centigrade rise in temperature. The module described in Figure 3.2 has a peak power voltage of 17.5volts at 25°C. If this module operates at 50°C in a specific application, the peak power voltage would drop to about 15.5 volts. This is still adequate for use in a nominal 12-volt battery system, but the design makes sure the current supplied by the module is adequate under the hottest expected conditions. Also, if a blocking diode is used between the module and the battery, this will cause a voltage drop of about 0.7 volts. The module must be able to sustain this drop plus any voltage drops caused by the wires and still supply enough voltage to fully charge the battery.

The number of parallel-connected modules required to produce the design current is rarely a whole number, the design must make a decision whether to round up or round down. The system availability requirements should be considered when making this decision. Since the design presented here is intended to just meet the load during the design month of an average year, the conservative approach is to round up to the nearest whole module. The number of series-connected modules is calculated by dividing the system voltage by the nominal module voltage (12 volt modules are commonly used for stand-alone PV systems).

Summary of Worksheet 4

To begin this section the battery inefficiency is calculated. This value can be taken from manufacturer's data sheets. The Average Amp Hour per Day Load is then divided by an estimated "Battery Energy Efficiency" which is usually about 0.8. This figure includes the balance of system inefficiencies and is the amp-hour production required of the array. The result is divided by the number of "Peak Sun Hours per Day" available and this will give the "Array Peak Amps". Peak sun hours may be adjusted to account for other variables such as added reflectance or shading. The Array Peak Amps is then divided by "Peak Amps per Module". The Peak amps per Module is a tested value at one peak sun and should be found in a module manufacturer's module specifications. This calculation will result in the number of modules in parallel which the system will require.

WORKSHEET 4: SYSTEM ARRAY SIZING

Table 3.4 Array sizing

ARRAY SIZING								
AVERAGE AMP HOUR PER DAY LOAD	÷	BATTERY ENERGY EFFICIENCY	÷	PEAK SUN HOURS/ DAY	=	ARRAY PEAK AMPS		
	÷		÷		=			
ARRAY PEAK AMPS	÷	PEAK AMPS PER MODULE	=	MODULES IN PARALLEL		MODULE SHORT CIRCUIT CURRENT		
	÷		=					
DC SYSTEM VOLTAGE	÷	NOMINAL MODULE VOLTAGE	=	MODULES IN PARALLEL	×	MODULES IN SERIES	=	TOTAL MODULES
	÷		=		×		=	

3.2.5 Specifying a Controller

The controller must not only be able to handle typical or rated voltages and currents, but must also be sized to handle expected peak or surge conditions from the PV array or required by the electrical loads that may be connected to the controller. It is extremely important that the controller be adequately sized for the intended application. If an undersized controller is used and fails during operation, the costs of service and replacement will be higher than what would have been spent on a controller that was initially oversized for the application.

Typically it is expected that a PV module or array produces no more than its rated maximum power current at 1000 W/m2 irradiance and 25^{o}C module temperature.

The size of a controller is determined by multiplying the peak rated current from the module by the modules or strings in parallel. To be conservative, the short-circuit current (Isc) is generally used.

Summary of Worksheet 5

To specify the controller the 'Module Short Circuit Current' is multiplied by 'Modules in parallel.' The result is the Maximum array amps the controller would encounter under short circuit condition. Charge controllers should be sized according to the voltages and currents expected during operation of the PV system.

WORKSHEET 5: CONTROLLER SPECIFICATION

Table 3.5 Controller Specification

CONTROLLER SPECIFICATION						
MODULE SHORT CIRCUIT CURRENT	×	MODULES IN PARALLEL	=	MAXIMUM ARRAY AMPS	CONTROLLER ARRAY AMPS	LISTED DESIRED FEATURES
	×		=			
DC TOTAL CONNECTED WATTS	÷	DC SYSTEM VOLTAGE	=	MAXIMUM DC LOAD AMPS	CONTROLLER LOAD AMPS	
	÷		=			

3.2.6 Summary of Steps for sizing

Estimating the Electric Load

1) Compute the Total connected watts for both AC and DC.
2) Compute the Average Daily Load for Both AC and DC.

Specifying an Inverter

3) Compute the Total AC connected watts.
4) Specify an Inverter to supply the AC Total connected watts.

Battery Sizing

5) Establish the Inverter Losses.
6) Divide the AC Average Daily Load by the Inverter efficiency.
7) Add the result in (6) to the DC Average Daily Load.
8) Divide the result in (7) by the system voltage to get 'Average Amp Hour Day Load'.
9) Divide the result in (8) by the Days of Autonomy.
10) Divide the result In (9) to get the' Total Amp Hour Capacity' of the System.
11) Specify a battery and divide the Total Connected watts by the battery's rated its Amp Hour to get the Batteries needed to be connected in Parallel.
12) Divide the DC system voltage by the battery voltage to get the batteries wired in series.
13) Multiply (11) and (12) to get the Total number of batteries needed.

Array Sizing

14) Establish the battery energy efficiency.
15) Divide the Amp hour day Load by the battery efficiency.
16) Divide the result in (15) by the 'Peak Sun Hours' to get 'Total Array Peak Amps'.
17) Specify a module and divide the Array peak amps by the Peak amps produced by each module to get the Modules needed in parallel.
18) Divide the Dc system voltage by the nominal module voltage to get the Modules in Series.

19) Multiply the result in (17) by that in (18) to get the Total number of modules needed.

Specifying a Controller

20) Multiply the module short circuit current by the total number of module to get the minimum Amp rating for the Charge Controller.

CHAPTER 4: RESULTS

4.1 Sample System Problem

The following exercise will design a stand-alone PV system. The system parameters are listed followed by the Sizing worksheets prepared in Microsoft Word Excel (Appendix C). The design is based on standard loads for an urban house hold. The sizing has carried out for major areas in Kenya; this is to show the variance in system requirements for different areas.

4.2 Stand-Alone PV System parameters

The first section considers the location in Nairobi with a solar radiation of 4.5 – 5.0 (See Appendix A figure A.2). The lower of these two values is taking to ensure a safety factor in the case of low solar radiation. Manufacturer data sheets are provided in Appendix B, for some system parameters. The electric Load information is provided in Worksheet 1.

System parameters;

DC system voltage: 12V

Peak sun hours = Solar radiation = 4.5

Days of Autonomy: 6

Battery depth of discharge: 50%

Battery Choice: Gaston 200AH battery (GT12-200 C-2)

PV Module choice: 130W BP Solar Module

- Power = 130Watts
- 12Volt nominal
- Peak Amps = 7.5
- Short Circuit Amps = 8.2

Controller Choice: Outback MX60 Charge Controller

- 12Volt nominal
- Maximum Pass through Amperage = 60A

Inverter Choice: Xantrex 4024 Inverter

Efficiency = 94%

Continuous Power output = 4000W

12 Volt nominal

Surge capacity 35 Amps AC

4.3 Sizing Worksheet Calculations

1. ELECTRIC LOAD ESTIMATION

ELECTRIC LOAD ESTIMATION															
LOADS	WATTS	×	QTY	=	WATTS		×	USE HRS/DAY	×	USE DAYS/WK	÷	7 DAYS/WK	=	WATT HRS AVG. DAY	
					AC	DC								AC	DC
29' TV	300	×	1	=	300		×	8	×	7	×	2400	=	2400	
H/THEATRE	100	×	1	=	100		×	6	×	5	×	428.57	=	428.57	
KETTLE	1500	×	1	=	1500		×	1	×	7	×	1500	=	1500	
FRIDGE	150	×	1	=	150		×	8	×	7	×	1200	=	1200	
IRON	1000	×	1	=	1000		×	0.3	×	4	×	171.43	=	171.43	
WAHING MACHINE	300	×	1	=	300		×	1	×	4	×	171.43	=	171.43	
RADIO	110	×	1	=	110		×	5	×	5	×	392.86	=	392.86	
COMPUTER	80	×	1	=	80		×	7	×	6	×	480	=	480	
ESAVER LIGHTS	20	×	10	=		200	×	7	×	7	×	1400	=		1400
AC TOTAL CONNECTED WATTS					3540		×	**AC AVERAGE DAILY LOAD**					=	6744.29	
DC TOTAL CONNECTED WATTS						200	×	**DC AVERAGE DAILY LOAD**					=		1400

2. INVERTER SPECIFICATION

INVERTER SPECIFICATION				
AC TOTAL CONNECTED WATTS	÷	DC SYSTEM VOLTAGE	=	MAXIMUM DC AMPS CONTINUOS
3540	÷	12	=	295
INVERTER SPECIFICATION		USE A XANTREX 4000W INVERTER		

3. BATTERY SPECIFICATION

BATTERY SIZING										
AC AVERAGE DAILY LOAD	÷	INVERTER EFFICIENCY	+	DC AVERAGE DAILY LOAD	÷	DC SYSTEM VOLTAGE	=	AVE AMP HOUR PER DAY LOAD		
6744.28571	÷	0.94		1400	÷	12	=	714.56		
AVE AMP HOUR PER DAY LOAD	×	DAYS OF AUTONOMY	÷	DISCHARGE LIMIT	÷	BATTERY AMP HR. CAPACITY	=	BATTERIES IN PARALLEL		
714.56	×	6	÷	0.5	÷	200	=	42.87		
DC SYSTEM VOLTAGE	÷	BATTERY VOLTAGE	=	BATTERIES IN SERIES	×	BATTERIES IN PARALLEL	=	TOTAL BATTERIES		
12	÷	12	=	1		43		43		

43× 200Ah Batteries are to be connected in parallel.

4. SIZING AND SPECIFYING AN ARRAY

ARRAY SIZING						
AVERAGE AMP HOUR PER DAY LOAD	÷	BATTERY ENERGY EFFICIENCY	÷	PEAK SUN HOURS DAY	=	ARRAY PEAK AMPS
714.56	÷	0.8	÷	4.5	=	216.075
ARRAY PEAK AMPS	÷	PEAK AMPS PER MODULE	=	MODULES IN PARALLEL		MODULE SHORT CIRCUIT CURRENT
216.075	÷	7.5	=	26.47		8.2

26 × 130Watts Modules are to be connected in parallel.

5. CONTROLLER SPECIFICATION

CONTROLLER SPECIFICATION						
MODULE SHORT CIRCUIT CURRENT	×	MODULES IN PARALLEL	=	MAXIMUM ARRAY AMPS	CONTROLLER ARRAY AMPS	LISTED DESIRED FEATURES
8.2	×	26.47	=	217.02	240	
DC TOTAL CONNECTED WATTS	÷	DC SYSTEM VOLTAGE	=	MAXIMUM DC LOAD AMPS	CONTROLLER LOAD AMPS	
200	÷	12	=	16.6666667	16.67	

4 × 60Amps Charge Controllers are used to be able to handle the Maximum array amps of 217.02 Amps.

Summary of Sample Sizing for Nairobi

From the calculations in the Worksheets the solar PV system requirements are;

- 26 × 130W Solar PV modules are to be connected in parallel
- 43 × 200Ah Batteries are to be connected in parallel
- 1 × 4000 watts Inverter
- 4 × 60Amps Charge Controllers

4.2 Sizing for Other Areas

1) Nyanza and Coast Province

Both have an average solar radiation of between 5.0 - 5.5. Taking the lower of the two which is 5.0, the sizing calculations are done;

- 24 × 130W Solar PV modules are to be connected in parallel.
- 36 × 200Ah Batteries are to be connected in parallel.
- 1 × 4000 watts Inverter.
- 4 × 60Amps Charge Controllers.

2) Western and North Eastern Province

Average Solar radiation between 5.0 -5.5

- 22 × 130W Solar PV modules are to be connected in parallel.
- 39 × 200Ah Batteries are to be connected in parallel.
- 1 × 4000 watts Inverter.
- 4 × 60Amps Charge Controllers.

3) Rift Valley and Eastern Province

Average Solar radiation between 6.0 - 6.5

- 20 × 130W Solar PV modules are to be connected in parallel.
- 39 × 200Ah Batteries are to be connected in parallel.
- 1 × 4000 watts Inverter.
- 4 × 60Amps Charge Controllers.

CHAPTER 5: CONCLUSION

5.1 Problems encountered

Getting various maps from the Geological department for available solar insolation in Kenya was a headache due to a lot of bureaucracy. I was forced to resort to the Ministry of energy and check archived reports for these maps. (Provided in Appendix A)

Access to internet services was costly as such services provided by the university are minimal and do not cater for the student population.

5.2 Recommendations

It is a highly recommended that stand alone photovoltaic system designers adopt this design as it incorporates all the aspects of system sizing and also any unforeseen losses in power due to equipment. The design is also simple to use and quite straight forward. Some practical recommendations for designing, installing, and operating stand-alone PV systems are;

1) **Keep the design simple** - Complexity lowers reliability and increases maintenance cost.
2) **Understand system availability** - Achieving 99 + percent availability with any energy system is expensive.
3) **Be thorough but realistic, when estimating the load** - A 25 percent safety factor can cost a great deal of money.
4) **Cross-check weather sources** - Errors in solar resource estimates can cause disappointing system performance. The system may be undersized or oversized and this means that it will not meet requirements.
5) **Know the installation site before designing the system** - A site visit is recommended for good planning of component placement, wire runs, shading, and terrain peculiarities.
6) **Install the system carefully** - Make each connection as if it had to last 30 years-it does. Use the right tools and technique. The system reliability is no higher than its weakest connection.
7) **Safety first and last** – Do not take shortcuts that might endanger life or property. Comply with local and national building and electrical codes.

8) **Plan periodic maintenance** - PV systems have an enviable record for unattended operation, but no system works forever without some care. Routine maintenance is important to increase the life span of this system.

5.3 Conclusion

The variances in solar radiation can cause huge difference in the system size. This is because the solar radiation gives the available sun hours. If sun hours are low then a bigger system is required. From the results section it can be observed that the location of the system plays a great part in sizing. The areas that have low solar radiation like Nairobi require more PV modules and batteries. It is vital that accurate information on solar radiation is obtained to avoid over sizing or under sizing of the system.

It can also be noted that the size of the inverter and charge controller do not change with location. This is because their sizing only depends on the loads connected. It is important that accurate load and component data is taken from manufacturer's data sheets to ensure accuracy in the calculations.

The objectives of the project were achieved as well as the comprehensive understanding of PV systems. The system sizing technique presented is consistent and is recommended for stand-alone PV system design.

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APPENDIX

APPENDIX A

A1. Current situation of solar energy utilization in Kenya

Kenya is well known for a large-scale market-driven penetration of very small photovoltaic (PV) systems in rural areas. It is estimated that about 200,000 rural households already use PV systems, and that the figure is growing by about 20,000 users per annum. The PV systems have a typical capacity of 12-50 W consisting of low-cost amorphous modules and car batteries. In most cases, the components are bought one after the other, so that they are not well matched or sized to each other and often are not very reliable or long lasting. Nevertheless, due to comparatively low costs, the use of PV in rural households is much more widespread in Kenya than in other African countries though some of them have special PV household electrification programs.

The application of PV systems for infrastructure and business uses focuses particularly on telecommunication, protection of pipelines, water pumping, and small commercial or noncommercial establishments. Also in most of these cases, the installation is initiated by the companies, owners or organisations as an individual investment decision. Under the Rural Electrification Programme the Ministry of Energy (MoE) has launched a programme for educational and health institutions in arid and semi-arid areas. MoE commenced the programme of installing solar electricity to secondary boarding schools in North Eastern Province in Financial Year (FY) 2005/06.

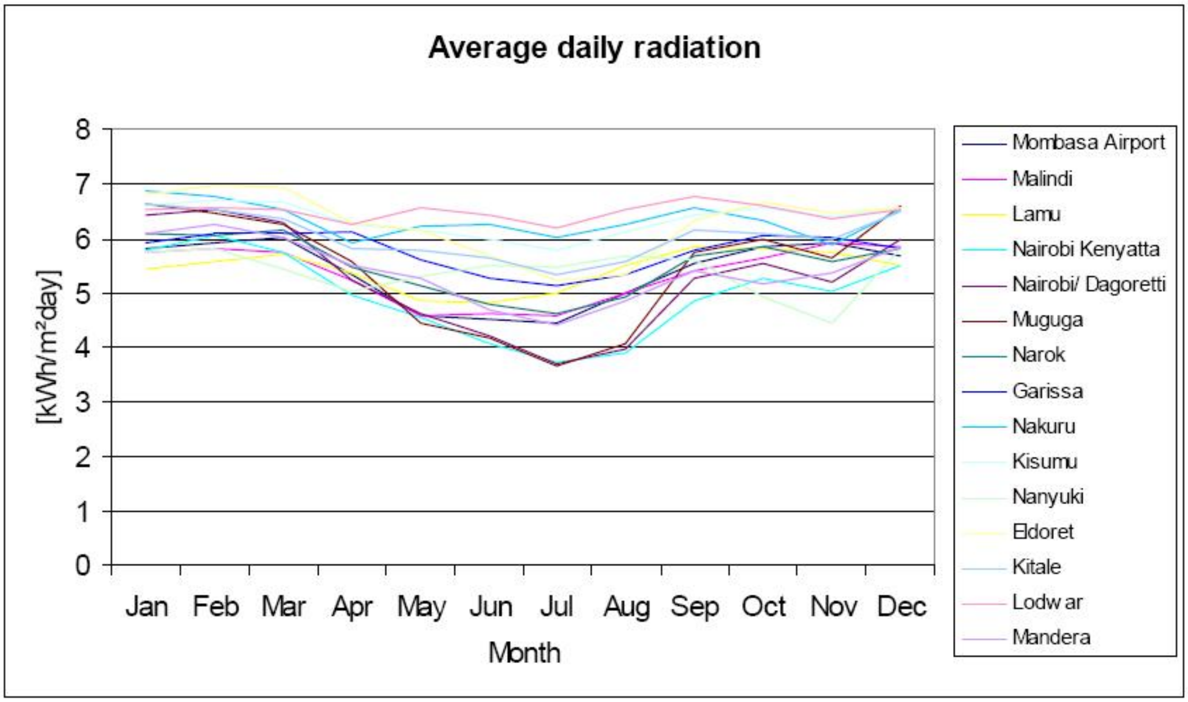
A.2 Available data sources on the solar energy potential

A.2.1 World Radiation Data Centre (WRDC)

The Meteorological Department of Kenya operates some 35 meteorological stations all over the country. However, the access to the measured data is limited. The WRDC collects radiation data as provided from the national meteorological departments from more than 1100 stations worldwide since 1964. For 15 meteorological stations in Kenya, daily radiation data are available covering a 30-year period of 1964-1993. However, for all existing stations, data are collected manually, which might include several mistakes and data gaps. In addition, sometimes the sensors are covered by dirt or are shaded after some time by new buildings and growing trees in the surroundings, so that reliability of the data cannot be ensured.

The following graph shows the annual course of the measured average daily solar radiation. For several locations in warm and semi-arid to arid areas of Kenya, the average daily radiation is above 6 kWh/m²*d throughout the year, thus resulting in a continuously good and relatively stable potential. On the contrary, mainly the mountainous areas in central Kenya, which are affected by colder and cloudy weather during the main rainy and the following cool season, face a significant drop in the available radiation between May and September and an ensuing reduction in their solar energy potential.

Figure A.1: Average Daily Radiation Measured at 15 Meteorological Stations in Kenya by Month of Year in the Period 1964-1993



A.2.2 Solar Wind Energy Resources Assessment (SWERA) Data Base

The SWERA program aims at providing online data and maps on solar and wind potential all over the world. This information has been gathered and is provided by various institutions and sources for the different countries. There is no general standard or verification mechanism. The different maps are calculated by using different meteorological models as preferred by the individual institutions. The ensuing deviations between the different models might, however, be in the range of some percent only. This does not appear dramatic, because such a range would also be expected as general uncertainty of the calculated data.

The following map shows the global horizontal solar radiation calculated by NREL (National Renewable Energy Laboratory for the U.S. Department of Energy), using the Climatological Solar Radiation (CSR) Model (also developed by NREL). This model uses information on cloud cover, atmospheric water vapour and trace gases, and the amount of aerosols in the atmosphere, in order to calculate the monthly average daily total insolation on a horizontal surface. The cloud cover data used as input to the CSR model are a 7-year histogram (1985-1991) of monthly average cloud fraction provided for grid cells of 40 km x 40 km in size, which is also the spatial resolution of the CSR model.

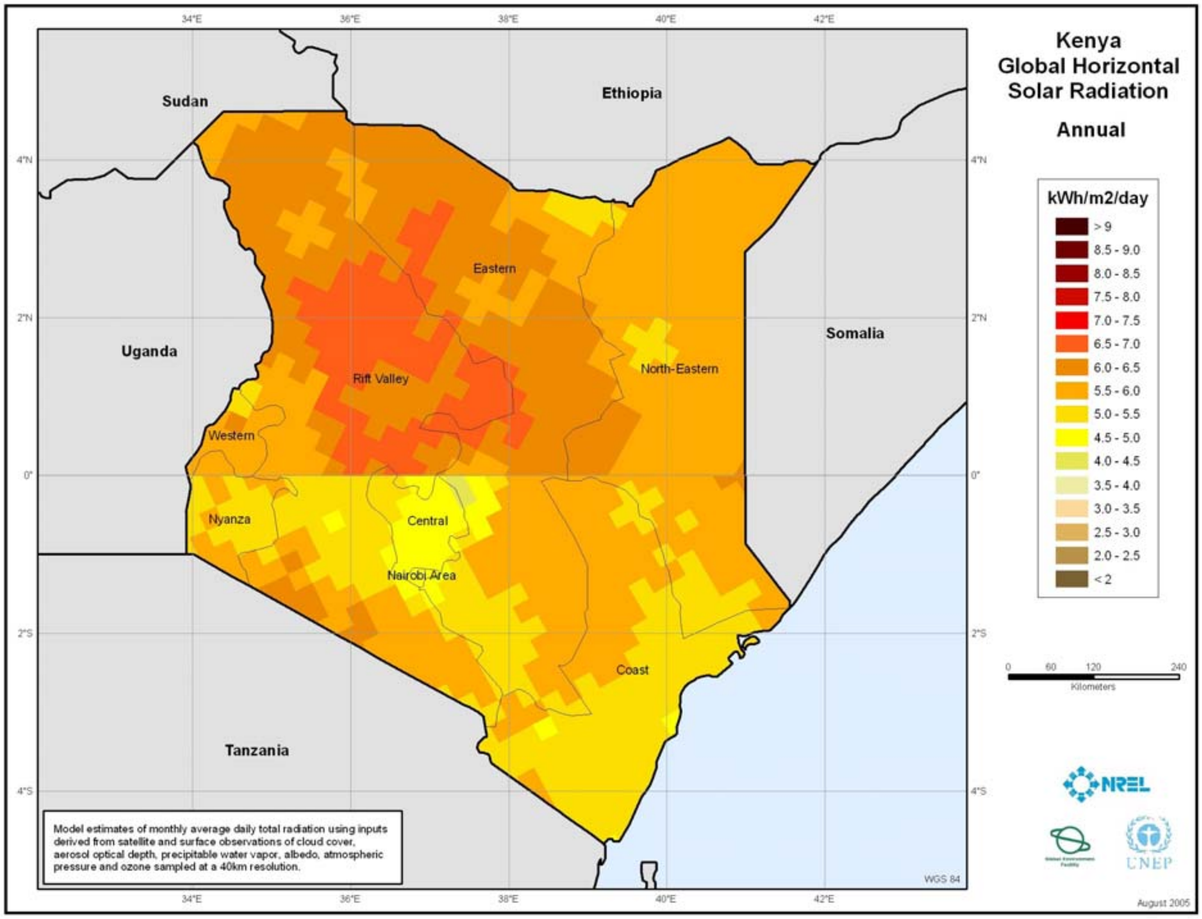
It is not clear in how far existing ground measurement stations were considered reliable and were used to validate the model. NREL itself estimates the uncertainty of the modelled results at roughly 10%. Terrain effects and other microclimate influences (i.e. water surfaces), the local cloud cover can vary significantly even within a single grid cell of 40 km x 40 km. Furthermore, the uncertainty of the modelled estimates increases with distance from reliable measurement sources and with the complexity of the terrain.

Another special in the considered case is the problem arising from the fact that the model calculations are separated into patches (i.e. northern and southern hemisphere), which may cause unsteadiness at the interfaces. Despite the mentioned shortcomings, the general information appears reasonable and corresponds to a large extent to the results of the Meteorological Department at certain sites.

Since solar energy plays an important role for off-grid and stand-alone applications, the proper system design (module size as well as storage capacity) is of major importance. Therefore, the annual mean radiation is not the appropriate parameter for sizing of an isolated system, but rather the lowest radiation month or season, respectively, should be the basis for system design, in order to ensure supply security.

The following map is regarded as sufficiently reliable basis for designing PV systems.

Figure A.2: Calculated Average Figures of Daily Global Horizontal Solar Radiation in Kenya 1985-1991

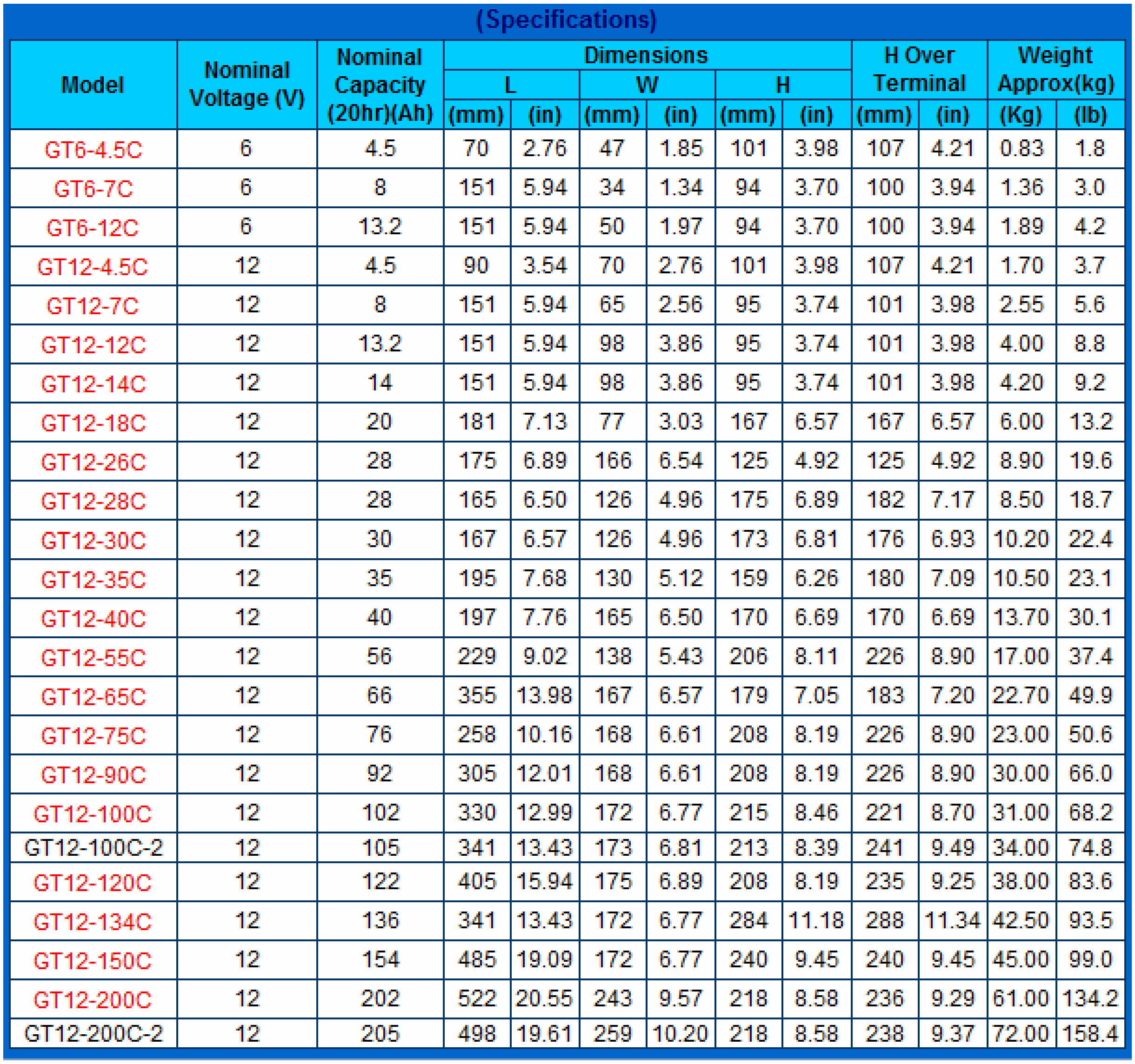


Model estimates of monthly average daily total radiation using inputs derived from satellite and surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone sampled at a 40km resolution.

APPENDIX B

B.1 Manufactures Data Sheets

Table B.1 Gaston Batteries Specification



(Specifications)

Model	Nominal Voltage (V)	Nominal Capacity (20hr)(Ah)	Dimensions						H Over Terminal		Weight Approx(kg)	
			L		W		H					
			(mm)	(in)	(mm)	(in)	(mm)	(in)	(mm)	(in)	(Kg)	(lb)
GT6-4.5C	6	4.5	70	2.76	47	1.85	101	3.98	107	4.21	0.83	1.8
GT6-7C	6	8	151	5.94	34	1.34	94	3.70	100	3.94	1.36	3.0
GT6-12C	6	13.2	151	5.94	50	1.97	94	3.70	100	3.94	1.89	4.2
GT12-4.5C	12	4.5	90	3.54	70	2.76	101	3.98	107	4.21	1.70	3.7
GT12-7C	12	8	151	5.94	65	2.56	95	3.74	101	3.98	2.55	5.6
GT12-12C	12	13.2	151	5.94	98	3.86	95	3.74	101	3.98	4.00	8.8
GT12-14C	12	14	151	5.94	98	3.86	95	3.74	101	3.98	4.20	9.2
GT12-18C	12	20	181	7.13	77	3.03	167	6.57	167	6.57	6.00	13.2
GT12-26C	12	28	175	6.89	166	6.54	125	4.92	125	4.92	8.90	19.6
GT12-28C	12	28	165	6.50	126	4.96	175	6.89	182	7.17	8.50	18.7
GT12-30C	12	30	167	6.57	126	4.96	173	6.81	176	6.93	10.20	22.4
GT12-35C	12	35	195	7.68	130	5.12	159	6.26	180	7.09	10.50	23.1
GT12-40C	12	40	197	7.76	165	6.50	170	6.69	170	6.69	13.70	30.1
GT12-55C	12	56	229	9.02	138	5.43	206	8.11	226	8.90	17.00	37.4
GT12-65C	12	66	355	13.98	167	6.57	179	7.05	183	7.20	22.70	49.9
GT12-75C	12	76	258	10.16	168	6.61	208	8.19	226	8.90	23.00	50.6
GT12-90C	12	92	305	12.01	168	6.61	208	8.19	226	8.90	30.00	66.0
GT12-100C	12	102	330	12.99	172	6.77	215	8.46	221	8.70	31.00	68.2
GT12-100C-2	12	105	341	13.43	173	6.81	213	8.39	241	9.49	34.00	74.8
GT12-120C	12	122	405	15.94	175	6.89	208	8.19	235	9.25	38.00	83.6
GT12-134C	12	136	341	13.43	172	6.77	284	11.18	288	11.34	42.50	93.5
GT12-150C	12	154	485	19.09	172	6.77	240	9.45	240	9.45	45.00	99.0
GT12-200C	12	202	522	20.55	243	9.57	218	8.58	236	9.29	61.00	134.2
GT12-200C-2	12	205	498	19.61	259	10.20	218	8.58	238	9.37	72.00	158.4

Battery Depth of discharge- 50%, Battery efficiency 80%

Table B.2 Recommended Days of Autonomy

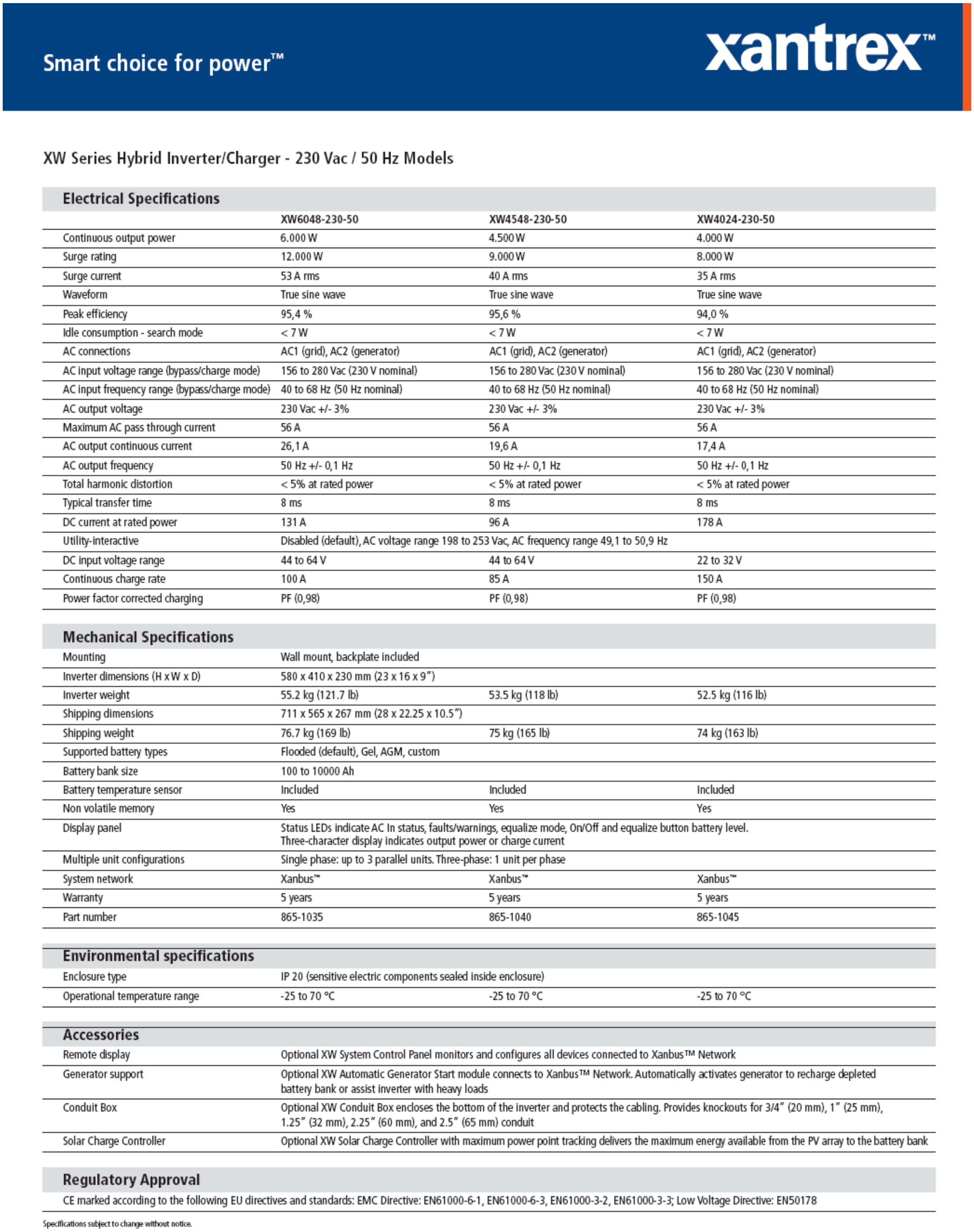
kW/m$_2$/day	Days of Storage
4.5+	5
3.5 to 4.5	6
2.7 to 3.5	7
2.0 to 2.7	8
<2.0	Up to 14

Table B.3 Solar Module sizes available in Kenya from BP Solar.

bp solar

Type	Dimensions (mm)	Rated power (Pmax) (w)	Current at Pmax (Imp) (A)	Voltage at Pmax (Vmp)(V)	Short circuit current (Isc)(A)	Open circuit voltage (Voc)(V)	Maximum system voltage (V)
REW350	839x537x50	50	2.9	17.5	3.2	21.8	600
REW365	931x536x35	65	3.6	18	3.8	22.2	600
REW375	1209x537x50	75	4.3	17.3	4.7	21.8	1000
REW380	1209x537x50	80	4.5	17.6	4.8	22.1	1000
REW3125	1510x674x50	125	7.2	17.4	8.1	22	1000
REW3130	1510x674x50	130	7.5	17.3	8.2	22	1000

Table B.4 Xantrex 4024 Inverter Datasheet



Smart choice for power™

xantrex™

XW Series Hybrid Inverter/Charger - 230 Vac / 50 Hz Models

Electrical Specifications

	XW6048-230-50	XW4548-230-50	XW4024-230-50
Continuous output power	6.000 W	4.500 W	4.000 W
Surge rating	12.000 W	9.000 W	8.000 W
Surge current	53 A rms	40 A rms	35 A rms
Waveform	True sine wave	True sine wave	True sine wave
Peak efficiency	95,4 %	95,6 %	94,0 %
Idle consumption - search mode	< 7 W	< 7 W	< 7 W
AC connections	AC1 (grid), AC2 (generator)	AC1 (grid), AC2 (generator)	AC1 (grid), AC2 (generator)
AC input voltage range (bypass/charge mode)	156 to 280 Vac (230 V nominal)	156 to 280 Vac (230 V nominal)	156 to 280 Vac (230 V nominal)
AC input frequency range (bypass/charge mode)	40 to 68 Hz (50 Hz nominal)	40 to 68 Hz (50 Hz nominal)	40 to 68 Hz (50 Hz nominal)
AC output voltage	230 Vac +/- 3%	230 Vac +/- 3%	230 Vac +/- 3%
Maximum AC pass through current	56 A	56 A	56 A
AC output continuous current	26,1 A	19,6 A	17,4 A
AC output frequency	50 Hz +/- 0,1 Hz	50 Hz +/- 0,1 Hz	50 Hz +/- 0,1 Hz
Total harmonic distortion	< 5% at rated power	< 5% at rated power	< 5% at rated power
Typical transfer time	8 ms	8 ms	8 ms
DC current at rated power	131 A	96 A	178 A
Utility-interactive	Disabled (default), AC voltage range 198 to 253 Vac, AC frequency range 49,1 to 50,9 Hz		
DC input voltage range	44 to 64 V	44 to 64 V	22 to 32 V
Continuous charge rate	100 A	85 A	150 A
Power factor corrected charging	PF (0,98)	PF (0,98)	PF (0,98)

Mechanical Specifications

Mounting	Wall mount, backplate included		
Inverter dimensions (H x W x D)	580 x 410 x 230 mm (23 x 16 x 9")		
Inverter weight	55.2 kg (121.7 lb)	53.5 kg (118 lb)	52.5 kg (116 lb)
Shipping dimensions	711 x 565 x 267 mm (28 x 22.25 x 10.5")		
Shipping weight	76.7 kg (169 lb)	75 kg (165 lb)	74 kg (163 lb)
Supported battery types	Flooded (default), Gel, AGM, custom		
Battery bank size	100 to 10000 Ah		
Battery temperature sensor	Included	Included	Included
Non volatile memory	Yes	Yes	Yes
Display panel	Status LEDs indicate AC In status, faults/warnings, equalize mode, On/Off and equalize button battery level. Three-character display indicates output power or charge current		
Multiple unit configurations	Single phase: up to 3 parallel units. Three-phase: 1 unit per phase		
System network	Xanbus™	Xanbus™	Xanbus™
Warranty	5 years	5 years	5 years
Part number	865-1035	865-1040	865-1045

Environmental specifications

Enclosure type	IP 20 (sensitive electric components sealed inside enclosure)		
Operational temperature range	-25 to 70 °C	-25 to 70 °C	-25 to 70 °C

Accessories

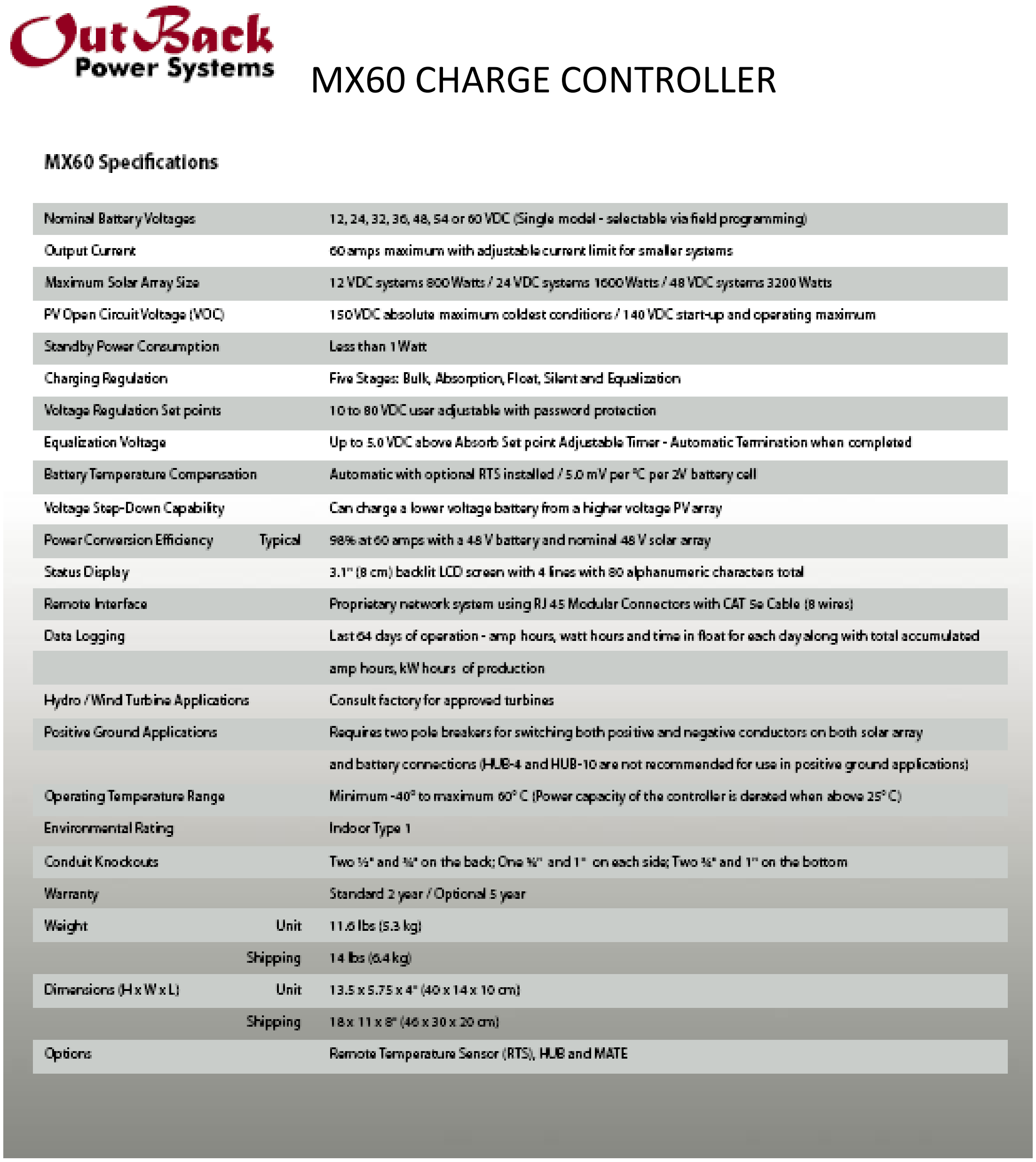
Remote display	Optional XW System Control Panel monitors and configures all devices connected to Xanbus™ Network
Generator support	Optional XW Automatic Generator Start module connects to Xanbus™ Network. Automatically activates generator to recharge depleted battery bank or assist inverter with heavy loads
Conduit Box	Optional XW Conduit Box encloses the bottom of the inverter and protects the cabling. Provides knockouts for 3/4" (20 mm), 1" (25 mm), 1.25" (32 mm), 2.25" (60 mm), and 2.5" (65 mm) conduit
Solar Charge Controller	Optional XW Solar Charge Controller with maximum power point tracking delivers the maximum energy available from the PV array to the battery bank

Regulatory Approval

CE marked according to the following EU directives and standards: EMC Directive: EN61000-6-1, EN61000-6-3, EN61000-3-2, EN61000-3-3; Low Voltage Directive: EN50178

Specifications subject to change without notice.

Table B.5 Outback MX60 Charge Controller Datasheet



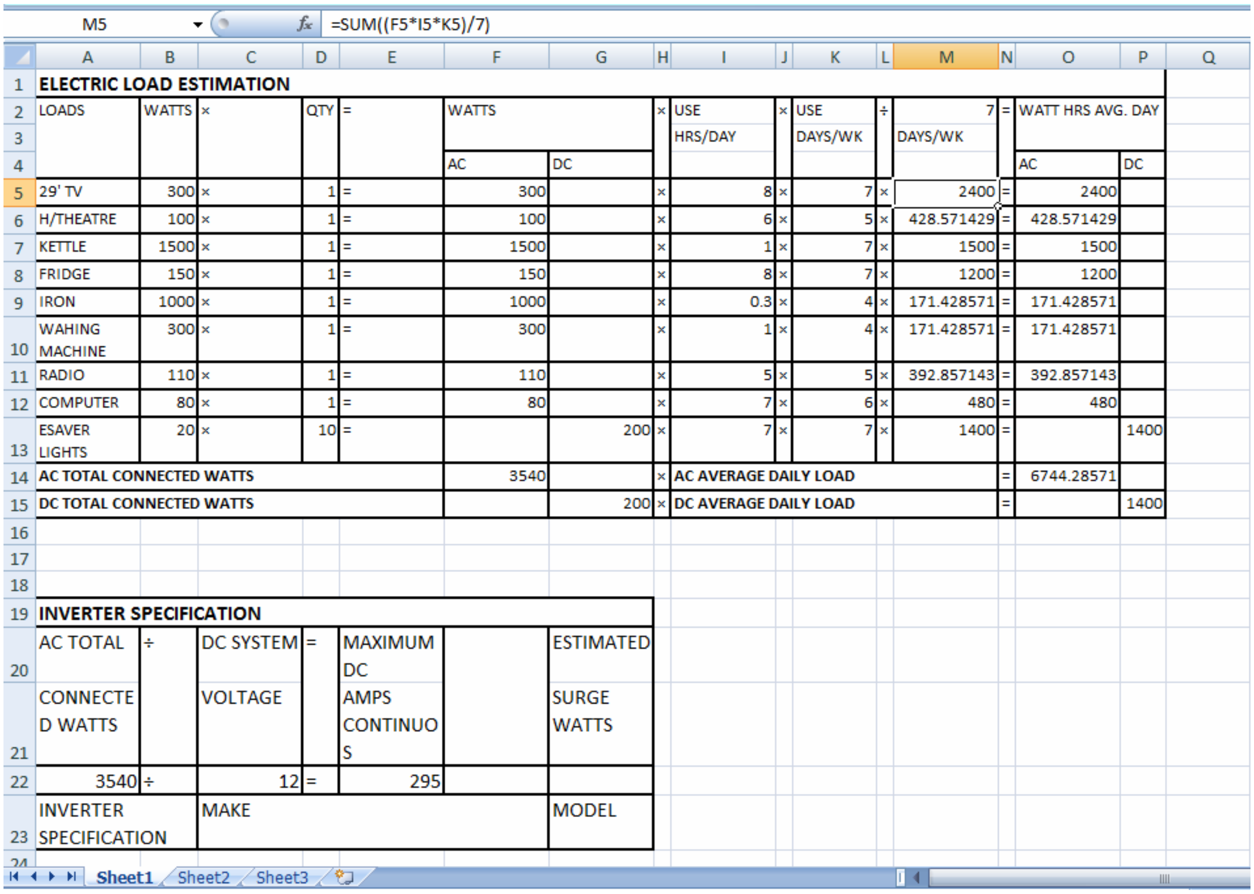
OutBack Power Systems

MX60 CHARGE CONTROLLER

MX60 Specifications

Nominal Battery Voltages		12, 24, 32, 36, 48, 54 or 60 VDC (Single model - selectable via field programming)
Output Current		60 amps maximum with adjustable current limit for smaller systems
Maximum Solar Array Size		12 VDC systems 800 Watts / 24 VDC systems 1600 Watts / 48 VDC systems 3200 Watts
PV Open Circuit Voltage (VOC)		150VDC absolute maximum coldest conditions / 140 VDC start-up and operating maximum
Standby Power Consumption		Less than 1 Watt
Charging Regulation		Five Stages: Bulk, Absorption, Float, Silent and Equalization
Voltage Regulation Set points		10 to 80 VDC user adjustable with password protection
Equalization Voltage		Up to 5.0 VDC above Absorb Set point Adjustable Timer - Automatic Termination when completed
Battery Temperature Compensation		Automatic with optional RTS installed / 5.0 mV per °C per 2V battery cell
Voltage Step-Down Capability		Can charge a lower voltage battery from a higher voltage PV array
Power Conversion Efficiency	Typical	98% at 60 amps with a 48 V battery and nominal 48 V solar array
Status Display		3.1" (8 cm) backlit LCD screen with 4 lines with 80 alphanumeric characters total
Remote Interface		Proprietary network system using RJ 45 Modular Connectors with CAT 5e Cable (8 wires)
Data Logging		Last 64 days of operation - amp hours, watt hours and time in float for each day along with total accumulated
		amp hours, kW hours of production
Hydro / Wind Turbine Applications		Consult factory for approved turbines
Positive Ground Applications		Requires two pole breakers for switching both positive and negative conductors on both solar array
		and battery connections (HUB-4 and HUB-10 are not recommended for use in positive ground applications)
Operating Temperature Range		Minimum -40° to maximum 60° C (Power capacity of the controller is derated when above 25° C)
Environmental Rating		Indoor Type 1
Conduit Knockouts		Two ½" and ¾" on the back; One ¾" and 1" on each side; Two ¾" and 1" on the bottom
Warranty		Standard 2 year / Optional 5 year
Weight	Unit	11.6 lbs (5.3 kg)
	Shipping	14 lbs (6.4 kg)
Dimensions (H x W x L)	Unit	13.5 x 5.75 x 4" (40 x 14 x 10 cm)
	Shipping	18 x 11 x 8" (46 x 30 x 20 cm)
Options		Remote Temperature Sensor (RTS), HUB and MATE

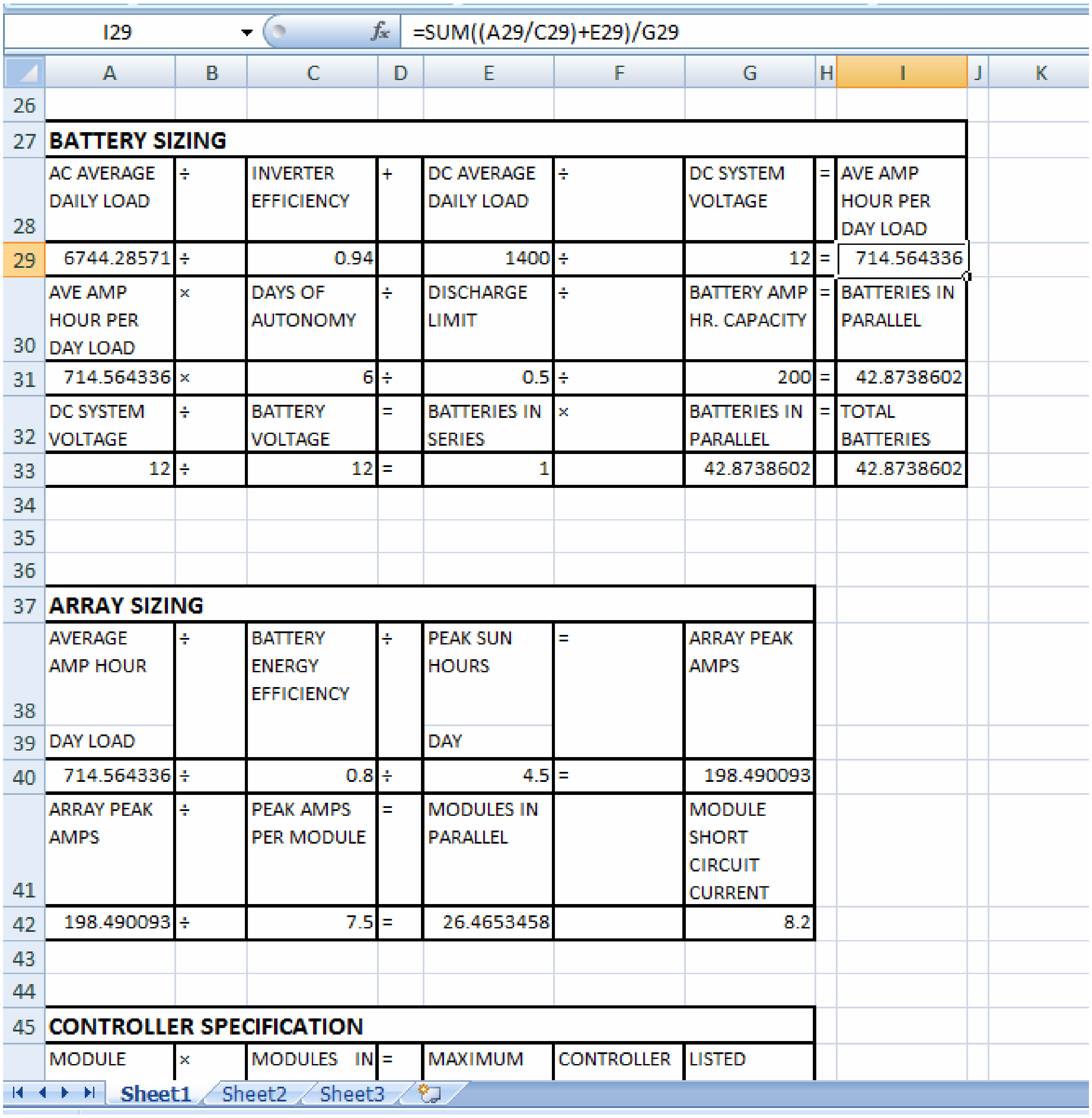
APPENDIX C



M5 =SUM((F5*I5*K5)/7)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	**ELECTRIC LOAD ESTIMATION**															
2	LOADS	WATTS	×	QTY	=	WATTS		×	USE	×	USE	÷	7	=	WATT HRS AVG. DAY	
3									HRS/DAY		DAYS/WK		DAYS/WK			
4						AC	DC								AC	DC
5	29' TV	300	×	1	=	300		×	8	×	7	×	2400	=	2400	
6	H/THEATRE	100	×	1	=	100		×	6	×	5	×	428.571429	=	428.571429	
7	KETTLE	1500	×	1	=	1500		×	1	×	7	×	1500	=	1500	
8	FRIDGE	150	×	1	=	150		×	8	×	7	×	1200	=	1200	
9	IRON	1000	×	1	=	1000		×	0.3	×	4	×	171.428571	=	171.428571	
10	WAHING MACHINE	300	×	1	=	300		×	1	×	4	×	171.428571	=	171.428571	
11	RADIO	110	×	1	=	110		×	5	×	5	×	392.857143	=	392.857143	
12	COMPUTER	80	×	1	=	80		×	7	×	6	×	480	=	480	
13	ESAVER LIGHTS	20	×	10	=		200	×	7	×	7	×	1400	=		1400
14	**AC TOTAL CONNECTED WATTS**					3540		×	**AC AVERAGE DAILY LOAD**					=	6744.28571	
15	**DC TOTAL CONNECTED WATTS**						200	×	**DC AVERAGE DAILY LOAD**					=		1400
16																
17																
18																
19	**INVERTER SPECIFICATION**															
20	AC TOTAL	÷	DC SYSTEM	=	MAXIMUM DC		ESTIMATED									
21	CONNECTED WATTS		VOLTAGE		AMPS CONTINUOUS		SURGE WATTS									
22	3540	÷	12	=	295											
23	INVERTER SPECIFICATION		MAKE				MODEL									

Figure C.1 MS Excel Worksheet calculations for Table 3.1 and 3.2



=SUM((A29/C29)+E29)/G29

	A	B	C	D	E	F	G	H	I	J	K
26											
27	**BATTERY SIZING**										
28	AC AVERAGE DAILY LOAD	÷	INVERTER EFFICIENCY	+	DC AVERAGE DAILY LOAD	÷	DC SYSTEM VOLTAGE	=	AVE AMP HOUR PER DAY LOAD		
29	6744.28571	÷	0.94		1400	÷	12	=	714.564336		
30	AVE AMP HOUR PER DAY LOAD	×	DAYS OF AUTONOMY	÷	DISCHARGE LIMIT	÷	BATTERY AMP HR. CAPACITY	=	BATTERIES IN PARALLEL		
31	714.564336	×	6	÷	0.5	÷	200	=	42.8738602		
32	DC SYSTEM VOLTAGE	÷	BATTERY VOLTAGE	=	BATTERIES IN SERIES	×	BATTERIES IN PARALLEL	=	TOTAL BATTERIES		
33	12	÷	12	=	1		42.8738602		42.8738602		
34											
35											
36											
37	**ARRAY SIZING**										
38	AVERAGE AMP HOUR	÷	BATTERY ENERGY EFFICIENCY	÷	PEAK SUN HOURS	=	ARRAY PEAK AMPS				
39	DAY LOAD				DAY						
40	714.564336	÷	0.8	÷	4.5	=	198.490093				
41	ARRAY PEAK AMPS	÷	PEAK AMPS PER MODULE	=	MODULES IN PARALLEL		MODULE SHORT CIRCUIT CURRENT				
42	198.490093	÷	7.5	=	26.4653458		8.2				
43											
44											
45	**CONTROLLER SPECIFICATION**										
	MODULE	×	MODULES IN	=	MAXIMUM	CONTROLLER	LISTED				

Figure C.2 MS Excel Worksheet calculations for Tables 3.3 and 3.4

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