FINANCIAL ASPECTS OF STAND-ALONE SOLAR POWER SYSTEMS IN SUB-SAHARAN AFRICA

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by
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ABSTRACT

Countries in Sub-Saharan Africa have struggled with low electrification rates in rural areas. This research examines various methods of achieving higher rural electrification rates. Among the factors that impede rural electrification via extension of the grid include high connection costs and locations that are a long distance from the grid. Other renewable energy technologies such as small hydropower and small wind home systems also have high initial costs and are limited to implementation under specific geographic conditions. The rise in popularity of solar PV systems has provided a viable option for many rural residents. Although initial costs may be high similar to the other technologies, vendors have put in place mechanisms for payment by installments that makes the technology affordable for a larger proportion of the population. However, repayment terms are still short (mostly within a year); therefore the monthly payments may still be out of reach for some. The modular nature of solar PV systems is also beneficial since users can buy lower capacity components and add on to their system over time. The key findings suggest that extension of the payment period for solar PV systems would make the technology more affordable for a larger segment of the population. In

addition, it proposes future collaboration between solar companies that offer pay-as-you-go financing solutions with informal financial arrangement groups commonly referred to as Rotating Savings and Credit Associations (ROSCAs) or Accumulating Savings and Credit Associations (ASCAs). These partnerships will provide a wider platform to educate rural residents on the benefits of solar lighting and to encourage members to purchase these products for their homes.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Computing and Engineering have examined a thesis titled "Financial Aspects of Stand-alone Solar Power Systems in Sub-Saharan Africa," presented by Angela Ndhuya Oguna Oruoch, candidate for the Master of Science degree, and verify that in their opinion it is worthy of acceptance.

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CONTENTS

ILLUSTRATIONS

TABLES

CHAPTER 1

INTRODUCTION

According to the International Energy Agency (IEA), in 2012, 1.3 billion people worldwide lacked access to electricity, with the bulk of the affected people residing in Sub-Saharan Africa (SSA) and Asia [1]. For the rural population in SSA, on which this thesis focuses, only 16% of the people have access to electricity as illustrated in Table 1 [1]. The primary use of electricity in the rural areas is for lighting and charging small electrical appliances. Due to the lack of electricity, a large segment of the population relies on hazardous forms of flame-based lighting which produce low light levels. This also includes the use of diesel operated generators to charge small televisions, radios and cellphones. Additionally, entrepreneurial traders in local marketplaces will charge a fee to charge cellphones where users have no other alternative. As a result, rural residents incur high costs to provide for their families lighting and cell phone charging needs.

Access to electricity is a major requisite to support socio-economic development and improvement of the living conditions of rural communities [2]. The United Nations General Assembly has unanimously declared the decade 2014-2024 as the Decade of Sustainable Energy for all. The initiative aims to bring together stakeholders in government, the private sector and civil society to work on three objectives: provide universal energy access, to double the rate of global energy efficiency improvement and to double the share of renewable energy in the global energy mix.

Table 1: Rates of electricity access in 2012

Region	Population without electricity (millions)	Electrification rate %	Urban electrification rate %	Rural electrification rate %
Developing countries	1,283	76%	91%	64%
Africa	622	43%	68%	26%
North Africa	1	99%	100%	99%
Sub-Saharan Africa	621	32%	59%	16%
Developing Asia	620	83%	95%	74%
China	3	100%	100%	100%
India	304	75%	94%	67%
Latin America	23	95%	99%	82%
Middle East	18	92%	98%	78%
Transition economies & Organization for Economic Cooperation and Development (OECD) countries	1	100%	100%	100%
WORLD*	1,285	82%	94%	68%

* World total includes OECD and Eastern Europe / Eurasia

The choice of a specific technology for rural electrification is dependent on location, customer and population density, relative distance to the grid, availability of natural resources such as wind, sun or water, economic and financial aspects, and availability of the chosen technology [3]. For grid extension, the community must be close to the grid, and the population density must be considered sufficient. This eliminates from consideration any residents who live far from the grid, and all those who live in sparsely populated areas. Conventional systems use diesel generators, disposable batteries and liquefied petroleum gas (LPG) or biomass technologies to provide electricity. Although these are attractive options due to their familiarity in rural areas, these options are not environmentally sustainable and bring considerable health risks. Renewable energy systems have, in recent years, been considered the optimal approach to electrifying rural areas that cannot be connected to the grid. These include solar photovoltaic (PV) systems, wind energy, small hydropower, bio-energy or ocean energy.

One of the primary barriers to the extension of electrical services to rural areas is affordability. This refers to high connections charged by the electricity utility, or the initial purchase price of modern lighting equipment for renewable energy systems. Other challenges include lack of consumer education, and lack of equipment servicing schemes that render the systems useless within a few years.

This thesis performs a literary review of advancements in solar PV technology in rural Africa in recent years. It focuses on financial challenges facing the deployment of solar PV for rural residents. It highlights the benefits of flexible pay-as-you-go options that have allowed residents to afford the high initial capital costs of the solar PV systems.

The rest of this thesis is structured as follows: Chapter two discusses the current state of technology in meeting lighting needs in rural areas and explores different technologies that are used to achieve rural electrification. Chapter three details the components of solar PV systems and the two available configurations: grid-connected and off-grid systems. Chapter four describes the value in properly sizing the PV system, educating the consumer, providing high quality products and having affordable financing options to create a sustainable solar PV system. Chapter five presents case studies of three solar companies that offer pay-as-you-go payment options that have promoted the growth of solar PV in rural areas. Chapter six presents the conclusion and suggests future partnerships that may further promote the growth of solar PV in rural areas.

CHAPTER 2

TECHNOLOGIES FOR ACHIEVING RURAL ELECTRIFICATION

Grid extension

The traditional approach to delivering electricity to rural households has been extension of the grid. However, when households consider accessing electricity from the national grid, they are faced with two challenges. In the first scenario, the electricity grid may not be physically available in the local area, thereby eliminating the entire community from receiving electricity. The community would then have to consider off-grid options, which are discussed later in this chapter. In the second scenario, the electricity network has already been extended into the community. Each household must then decide whether to obtain the electric service from the grid [4]. In this case, the greatest deciding factor is the price of electricity, which includes the initial connection fee and the monthly charges that are based on each household's consumption.

Although the high electricity charges based on monthly consumption may discourage consumers who think they may not be able to afford it, this is not the main obstacle since these households would still incur high costs from the fuel alternative they choose i.e. kerosene oil, candles and/ or batteries. The greatest barrier for most rural residents has been the high connection charge, which includes connection fees, inspection fees, government taxes and mandatory security deposits. This combination of low-income households and high up-front connection charges slows the pace of providing electricity to a larger proportion of the population [4]. Table 2 lists connection charges for a subset of countries in SSA [1, 3]. See Appendix A for a list of SSA countries.

Table 2: Grid connection charges as a percentage of family income

Country Name	National Electrification Rate (2012)	Connection charges (US$ 2011)	GDP per person (US$ 2012)	GDP per family* (US$ 2012)	Connection charge as % of monthly family income
Benin	7	150	751	1501	119.92
Burkina Faso	14	264	652	1303	243.07
Central African Republic	4	283	479	959	354.14
Cote d'Ivoire	15	127	1366	2732	55.79
Ethiopia	70	75	472	944	95.31
Ghana	7	32	1646	3291	11.67
Kenya	35	400	1166	2331	205.88
Madagascar	19	81	445	890	109.22
Mauritania	3	106	1043	2086	60.99
Rwanda	10	350	630	1260	333.28
Sudan	24	38	1698	3396	13.43
Tanzania	36	297	609	1218	292.68
Uganda	31	125	551	1103	136.02
Zambia	10	200	1772	3544	67.72

* Family income assumes that each household has two income earners.

According to [4], some reasons for these high charges include:

- weak commitment of utilities to provide rural electricity access due to greater emphasis on high consuming urban consumers;
- lack of incentives to adopt solutions to make the connections affordable to poor populations;

- high costs of providing electricity connection due to oversized technical specifications for low loads;
- inefficient procurement practices;
- greater distances between the household and the distribution pole in rural areas; and
- lack of financing to make connection charges affordable.

With this knowledge, some electricity companies in SSA have initiated programs to lower the high connection charges through credit schemes in a bid to make the charges more affordable for rural customers. The Ethiopian Electric Power Corporation (EEPCo) allows rural households to pay 20% of the US$75 (all costs are based on U.S. dollars) connection charge, with the rest being paid in installments of about $1 per month . In Senegal, customers pay an affordable sum of money up-front before being connected. The remainder of the connection cost is then repaid monthly as part of their monthly electricity bill [4].

For households without access to the electricity grid, their only option is to focus on off-grid solutions. The following technologies are discussed in this chapter: solar PV, small hydropower, small wind power, or a hybrid power system that uses renewable energy as the primary electricity source but is backed up with a generator.

Solar photovoltaics

Solar PV is grouped according to power dimensions as follows: portable solar lights, small solar home systems also known as pico PV systems (PPS), solar home systems and solar residential systems [5]. Portable solar lights include a small LED light with a rechargeable battery in a case that is easy to carry for outdoor lighting needs.

Some include a small built-in solar panel, while others are designed to be plugged into a roof-mounted solar panel with an output of less than three watt-peak (Wp), which is sufficient to provide four to six hours of lighting each day. The portable solar light have a retail price ranging from $10 - $60, with the more expensive models offering the ability to charge a mobile phone. Angaza Design and divi Power have developed portable solar lights available to solar off-grid customers as illustrated in Figure 1 [6].

SoLite3 PAYG light (Angaza Design, Inc.) | Oolux PAYG light (Oolux/Antenna Technologies) | diviLite PAYG light (divi Power)

Figure 1: Portable solar lights

Small solar home systems or pico PV systems (PPS) have the ability to light multiple rooms, charge multiple mobile phones and charge small electric appliances such as a radio. They come with an external solar panel (four (4) Wp to 25 Wp) and a central battery pack with DC outlets to power lighting loads, mobile charging and run small electric appliances. These systems have a retail price ranging between $80 - $180 that is roughly the equivalent of one year's expenditure on kerosene and mobile charging fees for a rural customer. M-Kopa Solar and Azuri Technologies sell pico PV systems as illustrated in Figure 2 [6]. Advantages of these systems include easy installation, low investment costs, low maintenance required, and modularity that allows for easy expansion.

'Indigo Duo' (Azuri Technologies)

M-KOPA III (M-KOPA Solar)

Figure 2: Pico photovoltaic solar systems

Larger solar home systems (SHS) are more robust than the PPS. With an output of 30 Wp to 250 Wp, they are composed of solar modules, a charge controller, battery and the loads. Advantages of the SHS include the ability to light up to 12 LED lamps simultaneously and charge DC operated loads such as lamps, radios, fans, televisions and refrigerators [5]. The use of DC operated loads increases the efficiency of the system since there is no conversion to AC power via an inverter. Larger SHS can incorporate AC loads by adding a DC/AC inverter to the configuration. The cost of a DC only system ranges from $200-$400 while versions that include an inverter for AC loads have a price range from $500 to $1,000. This high cost would limit the number of rural residents who would consider investing in the large solar home system. Figure 3 illustrates the configuration of a DC and AC solar home system [5], while Figure 4 illustrates the solar home system offered by Mobisol [6].

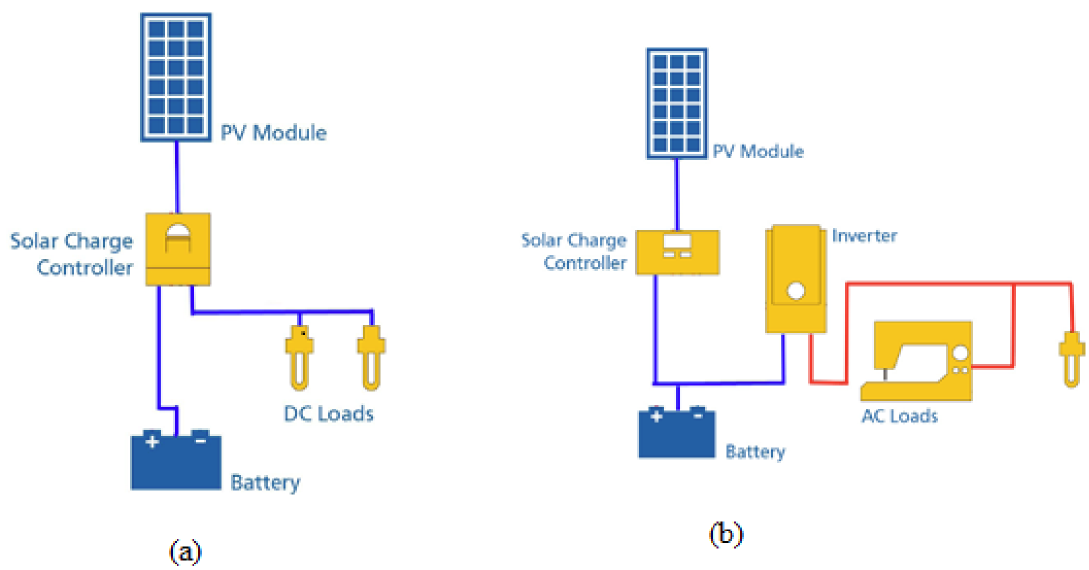


Figure 3: a) DC solar home system b) AC solar home system

Mobisol 80Wp PAYG Solar Home System (Mobisol GmbH)

Figure 4: Large solar home system

Solar residential systems (SRS) have a larger capacity from 500 W to 4000 W, and are used to power large installations such as hospitals, schools and factories. In most cases, they incorporate an inverter to power AC loads as shown in Figure 5 [5].

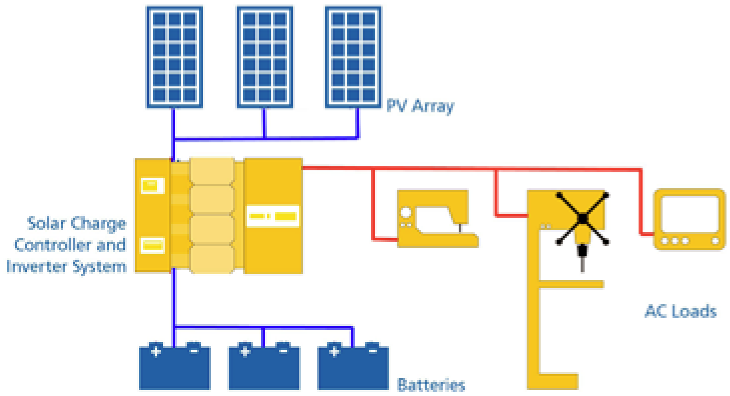


Figure 5: Solar residential system
Source: Rolland, 2011

Due to the low energy consumption for most residential users in the rural areas, most families will opt for either portable solar lights or pico PV systems that can be upgraded over time. Once an accurate load estimate is performed, customers can purchase a solar system that fits their needs.

Small wind home systems

Small wind turbines (SWT) need wind (at least 5 m/ sec), and a proper setting and location that is determined after a wind resource assessment to produce electricity. For small household installations, wind turbines less than two meters in diameter and producing one kW output of power can be used. Commonly used wind turbines have a horizontal axis, which has a higher efficiency than a vertical axis turbine due to better rotor balance. They are always placed on a pole higher than 15 m to reduce interference with ground installations. Most SWT have a permanent magnet generator which produces AC current that is rectified to DC using a simple rectifier in order to allow battery charging. According to the American Wind Energy Association, the cost of a SWT ranges from $4000 - $9000. This high initial cost is prohibitive for most rural residents [7].

Small hydropower

Small hydropower systems provide a mature and reliable technology that has been in use for more than 30 years around the world. They provide a highly efficient system (70% to 90%), have relatively low operation and maintenance costs, and have a lifespan of up to 100 years, which provides and attractive energy pay-back ratio. A hydro plant is considered "small" if it is under 10 MW, "micro" under 100 kW, "pico" under 20 kW and "mini" under 1 kW. Run-of-the-river systems that do not require large storage systems are used for small hydropower systems. They are composed of the following components:

- Water conveyance – a channel, pipeline or pressurized pipeline (penstock) that delivers the water.
- Turbine – transforms the kinetic energy of flowing water into rotational energy.
- Generator – transforms the rotational energy into electricity.
- Regulator – controls the generator.
- Inverter – convert the direct current (DC) into alternating current (AC).
- Wiring – delivers the electricity to the end user [8]

According to the International Renewable Energy Association (IRENA), the installation cost/ kW of a small hydropower plant ranges from $1,300 to $8,000. The operations and maintenance costs are quoted as a percentage of the installed costs and range from one to four percent. Proper siting of the small hydropower system is crucial to the efficiency of the overall system since it determines the available head and flow of water. Rolland [5] estimates that for small hydropower systems, the location and site preparation determines around 75% of the project cost compared to only 25% for the equipment. Residential users wishing to invest therefore have to analyze the cost vs. benefits of this renewable energy method to meet their electricity needs.

Comparison of costs for technologies

Figure 6 compares the costs of the various technologies discussed in this chapter as a means of electrifying rural areas. To facilitate comparison, the connection charges in Kenya are representative of the grid extension option. Median costs were used for the portable solar lights, pico PV system, DC SHS, AC SHS, small wind turbines and the small hydropower systems. These numbers illustrate that the cost of the small wind turbines and small hydropower systems would be prohibitive for rural residents due to the high installation costs. Both solar home systems and grid extension option have high initial costs; however, the grid extension option would eliminate all users who live far from the existing grid. The question then remains as to how to make the initial capital costs for the solar home system affordable for rural residents. This is discussed further in chapters four and five. The portable solar lamps and pico PV system are within reach of many rural residents, especially if flexible financing options are available. Due to the modular nature of pico PV systems, homeowners can buy one package and expand their pico PV system as additional financial resources become available.

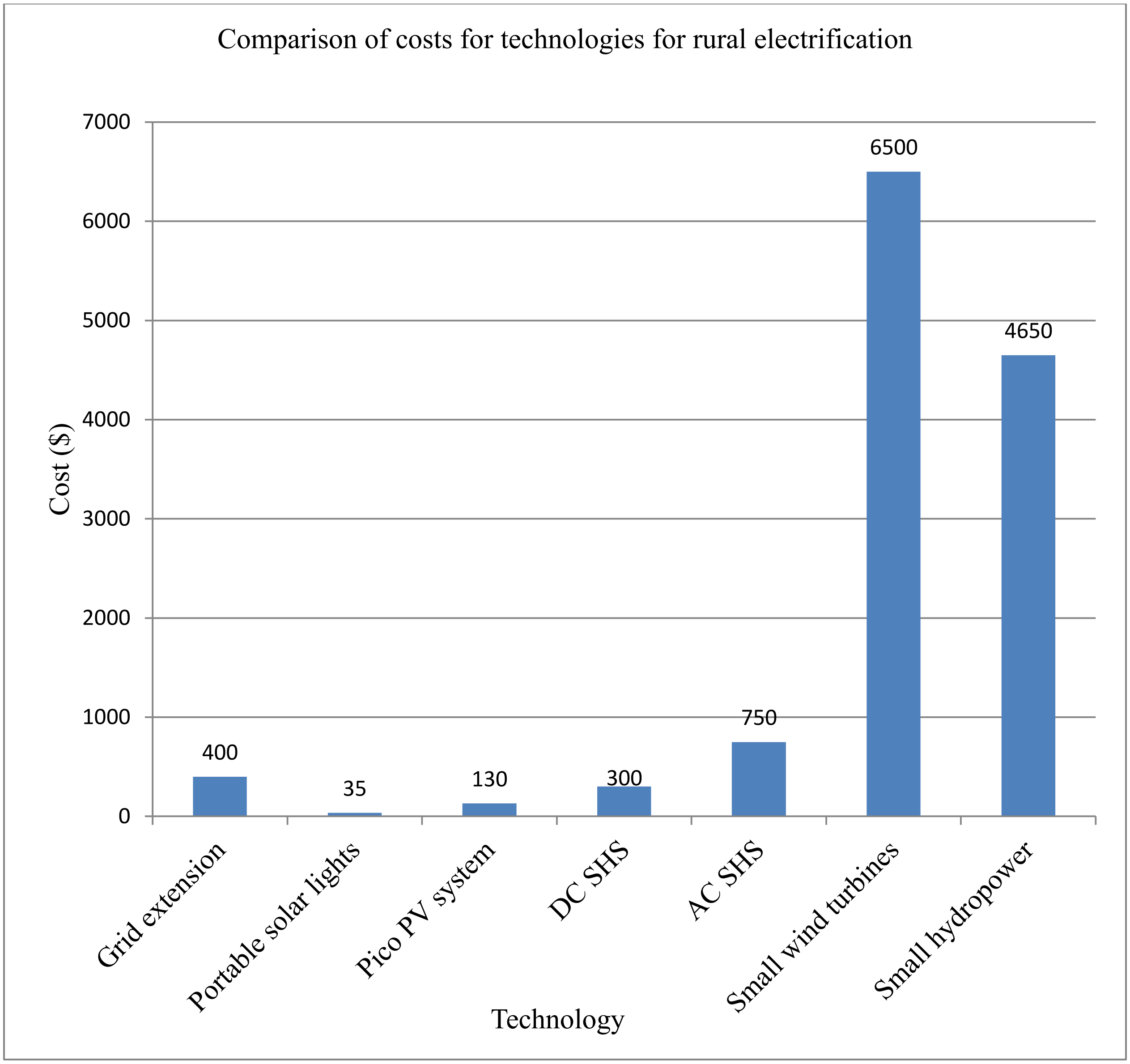


Figure 6: Comparison of costs for technologies for rural electrification

CHAPTER 3

SOLAR PHOTOVOLTAIC TECHNOLOGY

This chapter explains how solar PV technology works by describing the main components: the solar cell, inverters, batteries and charge controllers. The technical operation of each component is described, and the various technologies available that affect the system output and efficiency. In recent years, prices for PV systems have fallen at a fast rate due to technological innovation and lower costs of raw material prices thereby lowering manufacturing costs. Key trends in the cost of solar cells and batteries are included as part of the discussion.

The sun is the primary source of energy for life on planet earth. The sun's energy can be used to generate heat for solar heating systems, or to generate electricity for solar PV systems [9]. This thesis focuses on the latter application. Solar insolation is referred to as the solar radiation received at a given location at a given time, and it is dependent on the location, season, humidity, temperature, air mass and the hour of day. As a result, areas located around the equator (Central and East Africa) receive more solar rays than the areas closer to the poles (Europe or North America).Depending on the sun's location at various times of the year, its rays travel a much longer distance through a thicker layer of atmosphere to reach the earth. This explains why a sunny day in the winter is much colder than a sunny day in the summer. Table 3 [10] compares the solar irradiance between the cities of Kisumu (Kenya) and Kansas City, Missouri (U.S.). Kisumu has a higher solar irradiance all year round, and would provide a high solar output when compared to Kansas City, which experiences seasonal fluctuations in solar irradiation. It is this advantage due to a favorable geographic position that makes solar PV technology an attractive option for countries in SSA.

Table 3: Comparison of solar irradiance (kWh/m^2/day) in Kisumu (Kenya) and Kansas City, MO (US)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kisumu (Kenya)	6.34	6.69	6.55	6.12	5.95	5.78	5.73	6.18	6.45	6.13	5.91	6.20
Kansas City, MO (US)	2.12	2.69	3.87	4.77	5.53	6.09	6.23	5.46	4.61	3.39	2.24	1.87

The Solar Cell

The solar cell is made up of silicon, a semi-conductor material. The silicon atom is electrically neutral: it has 14 protons in the positively charged nucleus, and 14 negatively charged electrons revolving around the nucleus resulting in an electrically neutral atom. The electrons orbit the nucleus in distinct shells around the nucleus: there are two electrons in the first shell, eight electrons in the second shell, and the third shell is incomplete with only four electrons. These four electrons in the outermost shell are referred to as the valence electrons. They are the electrons involved in interactions with other atoms when forming chemical bonds. If two atoms are brought together, the valence electrons are attracted to the positive nucleus of the other atom to form the covalent bond. Each silicon atom forms covalent bonds with four other silicon atoms in a tetrahedral pattern to form the silicon crystal. The intrinsic silicon crystal has an equal number of protons and electrons and is therefore electrically neutral.

Doping is the process by which small numbers of impurity atoms replace some of the silicon atoms in the silicon crystal. N-type silicon is formed by adding phosphorus to the silicon structure. Phosphorus has fifteen electrons: two electrons in the first shell, eight electrons in the second shell and five valence electrons in the outermost shell. When a phosphorus atom combines with a silicon atom, there will be an extra electron that will diffuse through the crystal structure at ordinary temperatures. Due to this extra electron, phosphorus is referred to as an "electron donor." The resulting silicon structure has a net positive charge. P-type silicon is formed by adding boron atoms to the silicon structure. Boron has five electrons: two electrons in the first shell and three valence electrons in the outermost shell. When a boron atom combines with a silicon atom, there will be one less electron in the resulting silicon crystal. This is referred to as an extra "hole" that can diffuse through the crystal at ordinary temperatures, as electrons from neighboring atoms fall into the empty space that is unoccupied. Due to the extra hole, boron is referred to as an "electron acceptor." The resulting silicon structure has a net negative charge. These extrinsic semiconductors that are obtained due to doping form the basis of the solar cell.

A p-n junction is formed when p-type and n-type silicon are in contact with one another. Electrons from the n-type silicon diffuse across the p-n junction to the p-type side. At the same time, holes from the p-type side diffuse across the junction to the n-type side. This results in a net negative charge on the p-type silicon side, and a net positive charge on the n-type silicon side, thus creating a strong electric field across the p-n junction. This electric field separates the holes from the electrons and prevents them from spontaneous recombination, which would cause them to lose their excitation energy.

When the sun shines on the p-n junction, electron-hole pairs will be formed on both the n-type silicon side and the p-type silicon side. Electrons will be attracted to the positively charged n-type side, while the holes will be attracted to the negatively charged p-type side.

A solar cell comprises a p-type silicon layer and an n-type silicon layer sandwiched together. A front and back contact are installed at the top and bottom of the p-n junction to allow the flow of electrons. A minimal number of contacts are used to avoid shadowing the p-n junction. A glass layer is installed at the top to protect the silicon layers and the electrical contacts from damage. The glass layer will have an anti-reflective coating to minimize lost reflected light. Figure 7 [11] shows the configuration of the solar cell. When sunlight strikes a solar cell, electrons are freed from their atoms. The freed electrons are directed toward the front surface of the solar cell, creating a current flow between the negative and positive sides [12].

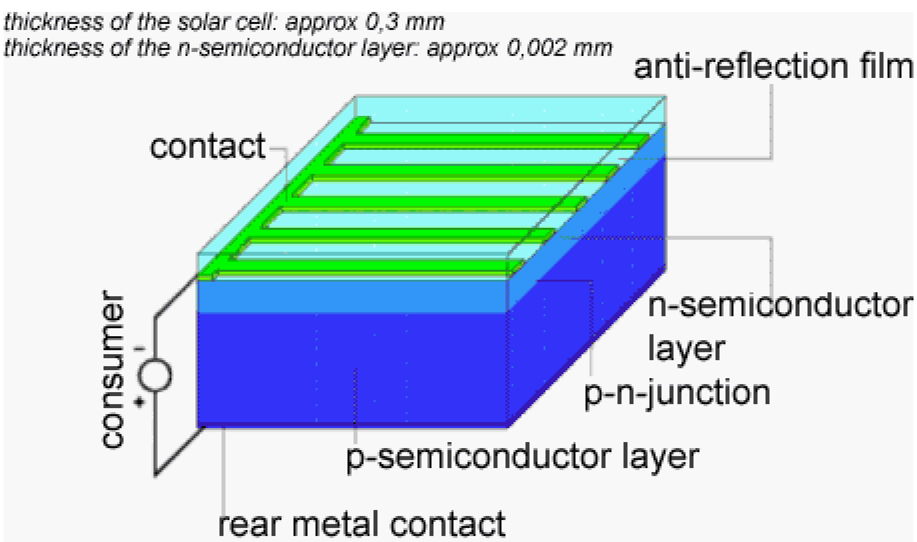


Figure 7: The Solar Cell.
Source:.

Multiple solar cells are connected in series or parallel to create a solar panel (module). Solar panels can be combined in series or parallel to create a solar array. According to Boxwell [9], connecting the panels in series allows the array to operate at a higher voltage, while connecting the panels in parallel allows the array to produce more power. The overall power is increased irrespective to whether the panels are connected in series or parallel. This further increases the solar output of the solar PV system. Figure 8 [13] illustrates the composition of a solar cell, solar panel and solar array.

Figure 8: Formation of a Solar PV Array.

Developments in solar PV cell technology aim to improve the conversion efficiency of the cell and other performance parameters to reduce the cost of commercial solar cells and their modules [14]. The conversion of the PV cell efficiency is defined as follows:

$$Efficiency\ (\eta) = \frac{electrical\ power\ output}{solar\ power\ impinging\ on\ the\ cell}$$

The major types of PV cell are: single-crystalline silicon, poly-crystalline and semi-crystalline silicon, thin film cell and amorphous silicon. Varying methods of production vastly influence the resulting efficiency and manufacturing costs of each cell type. Although single-crystal silicon is the most widely available cell material, its manufacturing process, which involves melting silicon then drawing a seed crystal at a slow constant rate to form the single-crystal ingot, is slow and energy intensive, resulting in high material costs. Additionally, most of the valuable material is also wasted when the silicon ingot is sliced into thin wafer cells. The efficiency of the single-crystal cell type ranges from 14% to 18%. Use of the single-crystal cell is economical when panel space is not limited. Poly-crystalline and semi-crystalline silicone have a faster and lower cost manufacturing process where instead of using seeds, the molten silicon is cast into ingots that form multiple crystals. Although its conversion efficiency is lower in comparison to single-crystal type, its overall cost is much lower, giving a lower cost per watt of power. Thin-film cells are the newest types of PV cells where layers of copper indium diselenide (CuInSe2), cadmium telleride (CdTe) and gallium arsenide (GaAs) are applied sequentially on a glass, plastic, stainless steel, ceramic or other substrate material. Less material is used per square area of the cell, resulting in lower costs per watt of power generated. Research in thin-film cell technology aims at producing high efficiency thin-film devices at low cost. Amorphous silicon is obtained by depositing a 2-μm-thick amorphous silicon vapor film on a glass or stainless steel roll; thereby using only about 1% of the material used in crystalline silicon, Although its efficiency is about half of the crystalline silicon (8-10%), its overall cost per watt is significantly lower than crystalline silicon [14].

In recent years, the price of crystalline silicon PV panels has dropped significantly due to declining component costs and improvements in the manufacturing process [15]. Thin-film technologies have also made substantial cost reductions primarily driven by efficiencies in the manufacturing process, making thin-film technologies cheaper than crystalline silicon on a per watt-peak basis. Figure 9 [15] illustrates the projections for price per watt from 2010, and revised projections for solar cell technologies from 2012.

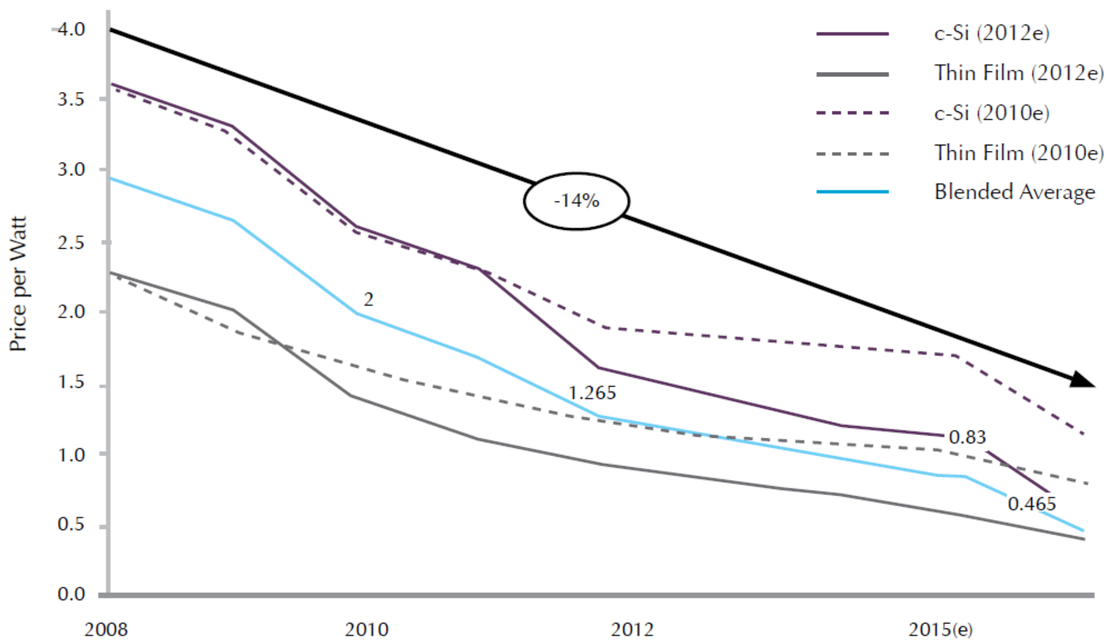


Figure 9: Solar photovoltaic price trends

Inverters

The function of an inverter is to convert DC power generated by the solar panels to AC power that is used by most of the appliances in the home. There are three kinds of inverters based on the output waveform: square wave inverters, modified sine wave inverters and true sine wave inverters. The square wave power inverter has the lowest cost. However, it is inefficient and does not work well with most electrical appliances. The modified sine wave inverter has a higher cost than the square wave inverter, but is still cheaper than the true sine wave inverter. Unlike the square wave inverter, it works well with most electrical appliances; however, it does not work well with appliances that use motor speed controls or timers. It is only suitable for small applications. The true sine wave power inverter produces the purest sine wave of all three inverters. The range of electrical appliances that it can successfully operate is unlimited, and it will automatically turn on and off as loads request service. However, it is the most expensive of the three inverters [16].

The need for inverters can be eliminated if the electrical loads run on DC power. Although many electrical appliances run on alternating power (AC), the needs for most rural customers will be limited to lighting and charging cell phones which run on DC power. The solar PV system for the rural home can therefore be designed without implementing an inverter, resulting in a cheaper system. If the homeowner desires to operate a large TV or additional AC powered devices, it will then be necessary to add an inverter to the system. Advancements in technology have introduced the AC PV module, which is composed of PV modules with in-built micro-inverter technology. As the prices of solar components falls, these systems will continue to increase in popularity.

Batteries

A major disadvantage of electricity is that it is not easily stored on a large scale. This is not a problem for grid systems because conventional power plants are designed to produce power as it is consumed. For renewable energy systems, the solar or wind energy is not always available when energy demand is high, i.e. in the evenings or on calm days. A storage system is therefore essential in the design of stand-alone power systems. The main energy storage categories discussed in this section are: electrochemical batteries, flywheel and compressed air.

There are two types of electrochemical batteries: the primary battery and the secondary or rechargeable battery. The electrochemical reaction that converts chemical energy into electrical energy is non-reversible; therefore the battery is discarded once it is fully discharged. The rechargeable battery has a reversible electrochemical reaction. After the battery discharges (chemical energy converted to electrical energy), it can be recharged by injecting a direct current from an external source that converts the electric energy back to chemical energy. The conversion efficiency ranges from 70% to 80%, since some energy is converted to heat during both reactions. The major rechargeable battery technologies are as follows [14]:

- Lead-acid (Pb-acid) –The Pb-acid battery is composed of lead at the cathode, lead dioxide at the anode and sulfuric acid as the electrolyte. During discharge, water and lead sulfate are formed, and the water dilutes the electrolyte. Recharging reverses the reaction, and lead and lead dioxide are formed again at the cathode and anode respectively. The Pb-acid batteries used in cars are shallow-cycle where a short burst of energy is drawn from the battery to start the engine. The deep-cycle version is used for energy storage applications since it is suitable for repeated full charge and discharge cycles. This is the most common type of battery due to its low cost, although it has the least energy density by weight and volume. The Pb-acid battery is also available in a sealed “gel-cell” version where the electrolyte is a nonspillable gel.

Although it is more expensive, the battery can be mounted sideways or upside down, and is commonly used in military aviation.

- Nickel-cadmium (NiCd) – The anode is made of cadmium, the cathode is made of nickel hydroxide and the electrolyte is potassium hydroxide. It weighs half as much as a Pb-acid battery and is commonly used in consumer application since it is completely sealed. It also has a longer deep-cycle life, and is more temperature tolerant than Pb-acid. Its disadvantage is the memory effect where the battery remembers the depth at which it has delivered most of its capacity in the past. If the battery is discharged beyond this "memory point," the cell voltage drops much below its normal voltage; thus lowering the overall efficiency of the battery. Additionally, cadmium is now being scrutinized under environmental regulations. NiCd batteries are therefore being replaced by Nickel-Metal Hydride and Lithium Ion batteries in consumer electronics.
- Nickel-metal hydride (NiMH) – This is an extension of the NiCd battery with the main difference being the use of a metal hydride anode. Its advantages are that cadmium is no longer a concern and it has a negligible memory effect. Its disadvantages include lower capacity in delivering high peal power, a high self-discharge rate, a high susceptibility to over-charging and high cost.
- Lithium ion (Li ion) – Advantages of the Li ion battery include: higher energy density (three times the energy density of Pb-acid batteries), and a higher cell voltage therefore lowering manufacturing costs since fewer cells will be required in series. Its disadvantage is that it reacts with any liquid electrolyte therefore the lithium

electrodes are stripped away during charging and discharging. The costs of the Li ion battery are high since thick electrodes have to be used to extend the battery life.

Overall battery prices have declined due to advances in technology, with the largest price decrease within the lithium ion segment. It is estimated that the average price of batteries will drop by roughly 20% between 2010 and 2020 as illustrated in Figure 10 [15].

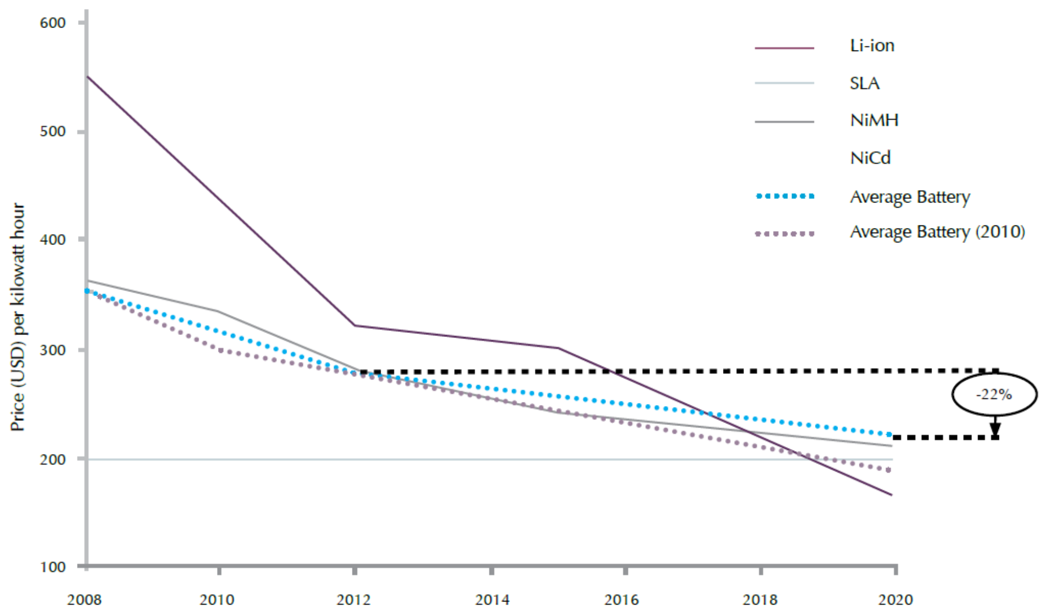


Figure 10: Battery price trends over time

The flywheel stores kinetic energy in a rotating inertia which can be efficiently converted to electrical energy. When electrical energy is input to the flywheel system, it accelerates the mass to speed via an integrated motor-generator [17]. The energy is discharged by drawing down the kinetic energy using the motor-generator. The energy stored in a flywheel is proportional to the moment of inertia and the square of the angular speed as follows:

$$E = \frac{1}{2} J \varpi^2$$

Where: $J = moment\ of\ inertia$

$\varpi = angular\ speed$

The complete flywheel storage system has the following components [14]:

- high speed rotor attached to the shaft via a strong hub;
- bearings with good lubrication system or with magnetic suspension in high-speed rotors;
- electromechanical energy converter which acts as a motor during charging and as a generator during discharging;
- power electronics to drive the motor and to condition the generator power; and
- control electronics for controlling the magnetic bearing and other functions.

Figure 11 [17] illustrates the components of a flywheel storage system.

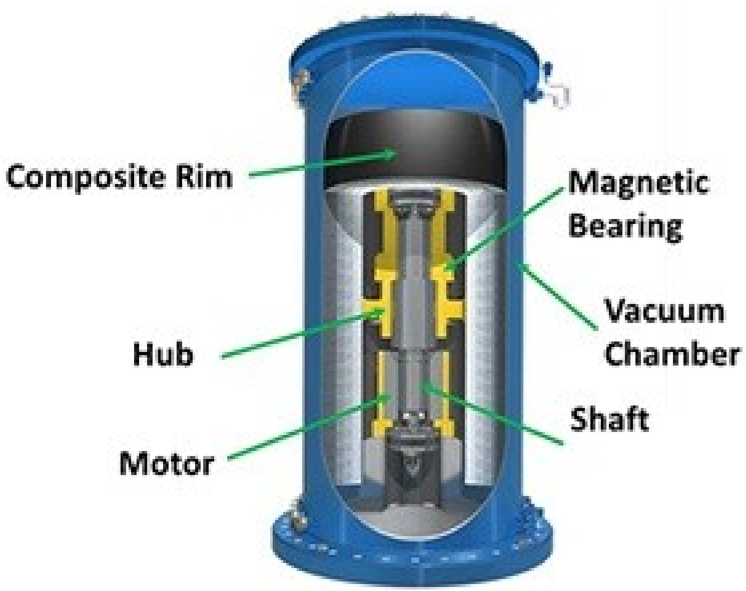


Figure 11: Flywheel energy storage system

The advantages of the flywheel system over battery energy storage are as follows [14]:

- high energy storage capacity per unit of weight and volume;
- high depth of discharge;
- long cycle life;
- high peak power capability without concerns about overheating;
- easy power management because the state of charge is measured by the speed; and
- high round-trip energy efficiency.

Compressed air stores energy in a pressure-volume relation. It stores excess energy of a PV system, and supplies it during lean periods or peak demands. The compressed air energy storage system generates electric power by venting compressed air through an expansion turbine that drives a generator. The compressed air works under a constant pressure or constant volume model. In constant-volume compression, the compressed air is stored in pressure tanks, mine caverns, depleted oil or gas fields or abandoned mines. The primary disadvantage is that the air pressure reduces as compressed air is removed from storage. In constant-pressure compression, the air may be stored in an above-ground variable volume tank or an underground aquifer. The overall efficiency of a compressed air energy storage is about 50% [14].

Charge Controller

A charge controller, also referred to as a charge regulator, is a voltage and/ or current regulator that keeps batteries from overcharging. Overcharging in the lead-acid battery causes loss of water and premature aging. The charge controller allows the maximum rate of charging until the gassing starts, and then the charge current is tapered off to the trickle-charge rate to avoid overcharging [14]. The best method for battery charging is in multiple stages; this is commonly referred to as the three-stage charge cycle. During the bulk phase of the charge cycle, the voltage rises gradually to the bulk level (14.4 V to 14.6 V), and the battery draws maximum current. Once the bulk voltage level is reached, the absorption phase begins. The voltage is maintained at the bulk voltage level while the current gradually tapers off as the batteries charge. The absorption time is limited to a specified time, usually an hour. After the absorption time has passed, the voltage is lowered to the float level during the float stage. The batteries draw a low maintenance current until the next charging cycle begins and the process begins again

[16]. Figure 12 [16] shows the relationship between current and voltage during the three-stage charge cycle.

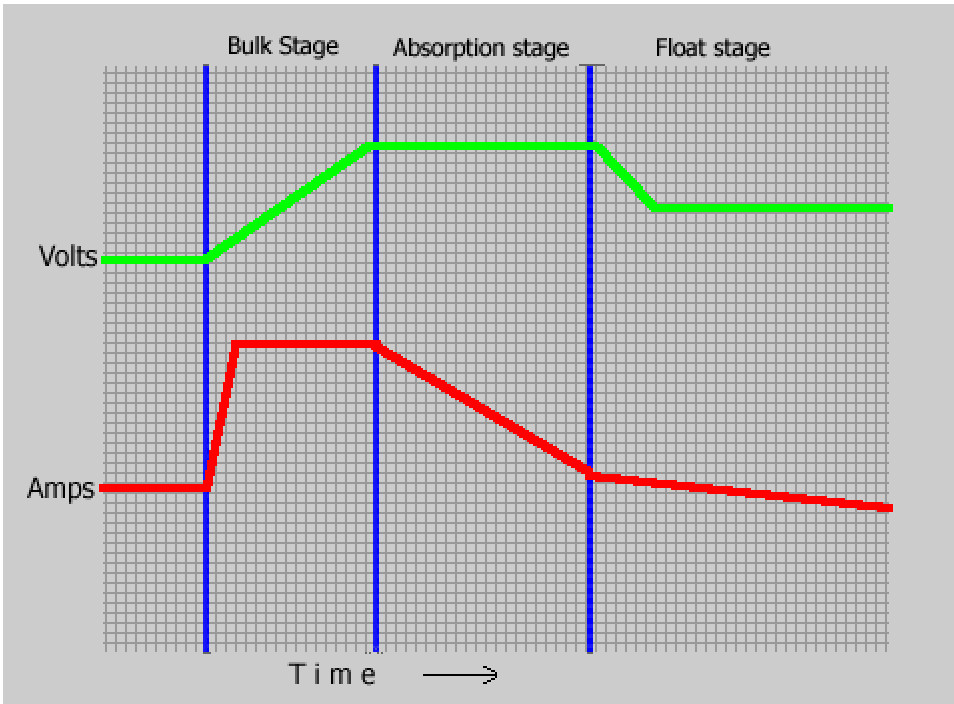


Figure 12: Relationship between current and voltage during three-stage charge cycle

Solar Power Configuration Systems

This section describes how the various components of the solar PV systems and combined in two common configurations: the grid connected solar PV system and the off-grid solar PV system.

Grid-Connected Solar Photovoltaic Systems

Grid-connected systems are the most common type of solar PV system. They are connected to the electrical grid, and allow residents of a building to use solar energy as well as electricity from the grid. As a result, customers using grid-connected systems do not need to produce all of the electricity they want to use in their home, as they can make up the deficit from the grid. The grid connected system works in the following way: first the PV solar modules convert sunlight into DC electricity. The DC electricity flows through a DC disconnect safety device followed by an inverter that converts the DC electricity into AC electricity. Although the addition of an inverter increases the overall cost of the project, the conversion to AC electricity, which can be used by most household electric appliances, eliminates the need for special devices that can run on DC power. The AC electricity flows through an AC disconnect safety device into the breaker panel which disperses the AC electricity to appliances throughout the house. The electricity consumed in the house is measured using a bi-directional utility meter. During the day, energy demand is low; therefore excess electricity that is produced by the PV system will be exported to the electric grid, causing the utility meter to spin backwards. In the evening, when electricity demand is high and the PV system does not produce sufficient electricity to power all the appliances, electricity is imported from the grid and the bi-directional utility meter spins forward. This is referred to as net metering. Figure 13 [18] illustrates the configuration of a grid-connected solar PV system, while Figure 14 [19] shows the variation in PV electricity production vs. electricity demand throughout the day.

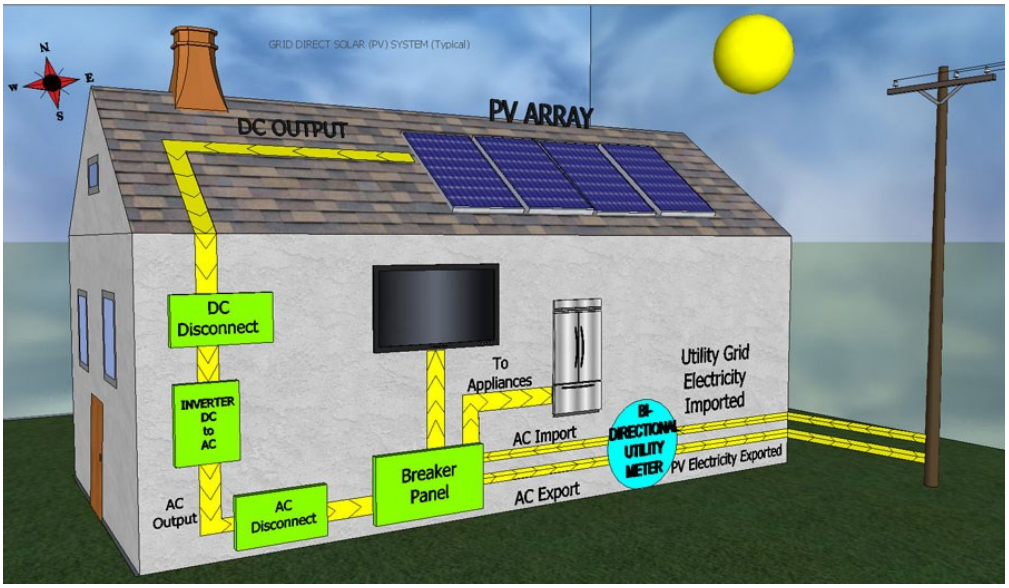


Figure 13: Grid-connected solar PV system

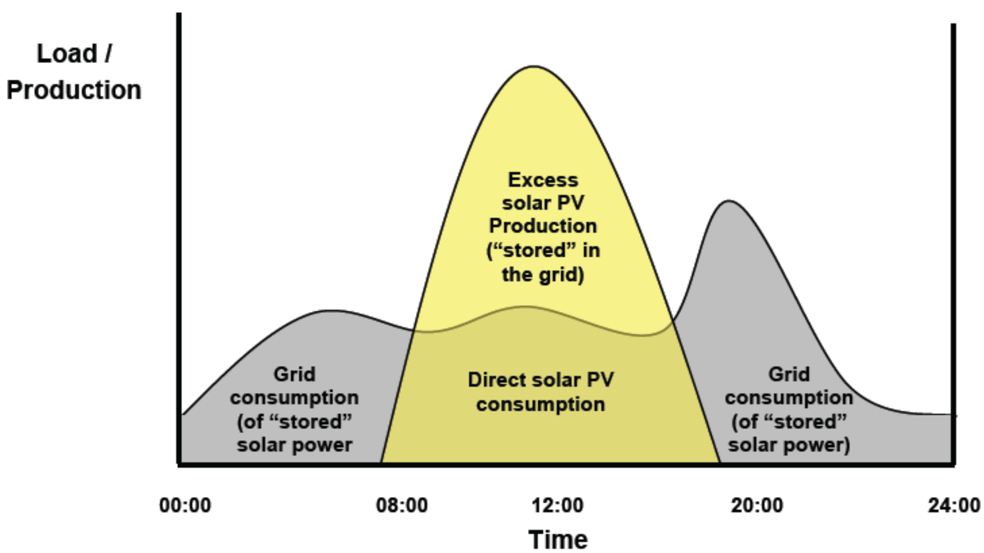


Figure 14: Principles of PV electricity production and daily demand

Advantages of the grid-connected system include lower system costs since the grid acts as a virtual battery eliminating the needs for bulky expensive battery systems. Additionally, homeowners can receive credit for the power they export to the grid depending on the policies of the electric utility. Drawbacks of the grid-connected system include limitation to customers who already have access to grid electricity or are located close to the grid. This would exclude a large proportion of rural customers who live far away from the grid. Net metering is also a new technology and electric utilities are still formulating policies to incorporate distributed generation into their portfolios. According to an economic assessment performed by Hille & Franz [19] for energy consumers in Kenya, net metering is more attractive for customer classes with high energy consumptions (> 1500 kWh/ month). It is therefore not relevant for customers with low energy charges, such as rural residents, who rely on electricity primarily for lighting needs. In South Africa, the state-backed utility, Eskom, currently allows net metering for customers connected to medium voltage or higher. Technical standards and policies are yet to be put in place for customers connected to low voltage (< 1 kV) to participate in net-metering [20]. There is a great need for a resolution of these technical and policy subjects before grid-connected PV systems can be considered a viable solution for rural customers in SSA.

Off-Grid Solar Systems

Off-grid solar PV systems are independent of the electric grid. These systems must therefore be robust enough to meet 100% of the electricity demand in the home. Since most homes have a higher electricity demand in the evening when solar panels produce less electricity, off-grid systems must incorporate storage systems (batteries), back-up energy sources such as a generator or incorporate both options. Alternatively, users can be educated to understand the capacity of their system so they can be conscious of their energy consumption and monitor their energy usage. Consumers can also be proactive and perform some tasks during the day when the rate of electricity production is higher.

The off-grid solar system works as follows: the PV solar modules convert sunlight into DC electricity. The DC electricity flows through a DC disconnect safety device then through a charge controller that regulates the charging rate for the storage battery. If the battery is fully charged, the charge controller bypasses the battery and sends DC electricity directly to the inverter. The inverter receives the DC electrical current from either the charge controller or the storage battery and converts the DC electricity into AC electricity which then feeds the breaker panel to be dispersed to the appliances throughout the home. Figure 15 [21] illustrates the configuration of an off-grid solar PV system

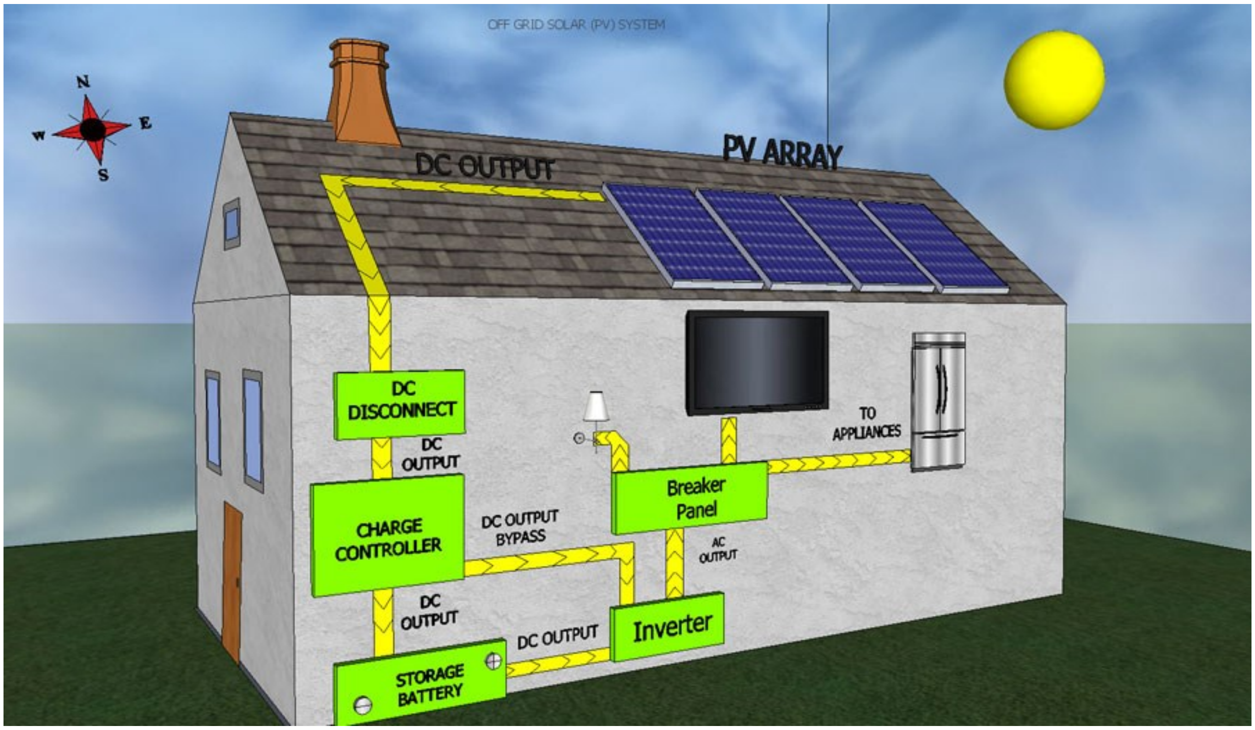


Figure 15: Off-grid solar PV system.

The primary advantage of the off-grid solar system is that its independence from the grid means that it can be installed in any location. This is favorable for most rural customers. However, higher costs are incurred since a battery backup system is required to supplement electricity production when demand exceeds supply.

CHAPTER 4

COMPONENTS OF A SUSTAINABLE SOLAR PV SYSTEM

The success of a solar PV system installation is dependent on a variety of factors which include: properly educating the end user, adequately sizing the system while allowing room for future expansion, ensuring a high quality of products, making provisions for proper operation and maintenance of the solar PV system components and providing flexible payment options that are affordable for rural residents.

Sizing the PV System

A proper understanding of electricity systems, whether grid-based or stand-alone, is dependent on the design of the system. Both the energy supplier and the consumer must understand the consumer's energy consumption, and the capacity of the electricity system to ensure that adequate provisions are made. This is even more important for small solar systems where the periods of peak energy demand (usually in the evening) coincide with nighttime hours when electricity generation is lowest, as was illustrated in Figure 13. The primary demand for the PV system in rural areas will be for lighting, mobile phone charging, and small electrical appliances such as a small television or radio. Table 4 [22] lists the minimum energy demand for lighting, phone and radio for a pico PV system.

Table 4: Minimum energy demand for lighting phone and radio

Load	Type of service	Quantity	Watts	Hr/day	Wh/ day
Study light	50 lumen*	1	0.5	3	1.5
Main light	200 lumen*	1	2	2	4
Night light	10 lumen*	1	0.1	8	0.8
Phone	Charging (50%)	2	2	1	4
Radio	Sound	1	0.5	2	1
TOTAL					9.3
* LED lamp rating = 100 lm/ W					

Lighting needs in a residential home include area lighting for general living spaces and task lighting for reading. Advancements in technology have resulted in high efficiency LED lamps that provide the perfect match for pico PV systems. Benefits of the LED lamps over compact fluorescents include: longer lifetime, more durability, lower energy consumptions and lower maintenance costs. In recent years, there have been large decreases in the cost of LED lights. Investment in research has resulted in more efficient and effective manufacturing processes. Since 2012, the cost of LED lighting equipment has dropped by 30%, and it is estimated to decline by another 34% by 2015 as illustrated in Figure 16 [15].

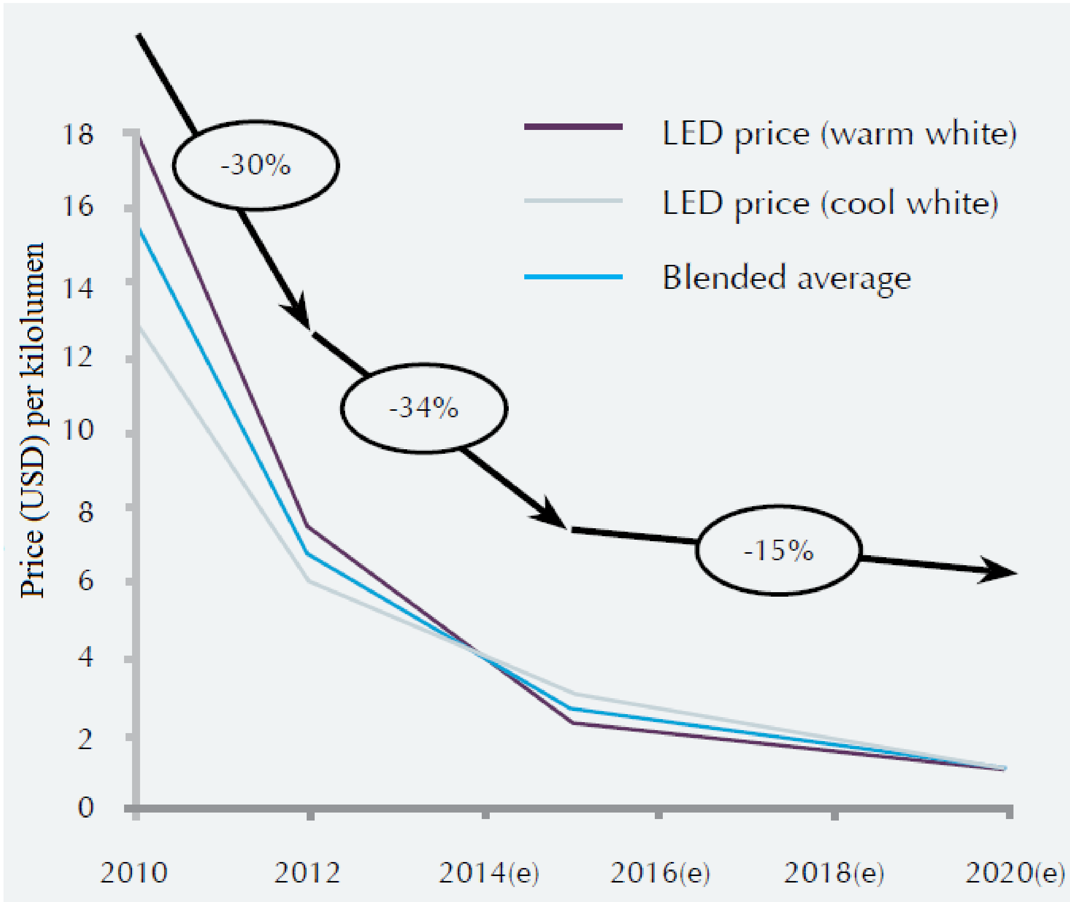


Figure 16: LED price trends over time

Under ideal circumstances, each watt-peak (Wp) of a fixed solar panel can produce up to 5 Wh per day. Taking into consideration that the sun moves and changes the angle at which the solar rays hit the panel, and that there are times when the solar panel will be shaded, a conservative approach approximates an output of 3 Wh/ day from each Wp of the panel. System losses when charging and discharging the battery result in an overall system efficiency of 80%; therefore the overall output is assumed to be 2.5 Wh/day/ Wp of the PV panel. The size of a panel producing approximately 10 Wh/ day will therefore be:

$$PV\ panel\ size\ (Wp) = \frac{10\ \text{Wh/day}}{2.5\ \text{Wh/ day/Wp}} = 4\ \text{Wp}$$

In order to extend the battery lifetime, the depth of discharge is limited to a maximum of 50% discharge. Rough estimates for the lifetime of a battery measured in the number of charge-discharge cycles are as follows [22]:

- Lead acid batteries at 60% depth of discharge (DoD) – 500-cycle lifetime
- Lead acid batteries at 25% depth of discharge – 1200-cycle lifetime

The minimum capacity ratio will therefore be 2.5 Wh/0.6 = 4.17 Wh/Wp for 60% DoD, and 2.5 Wh/ 0.25 = 10 Wh/ Wp for 25% DoD. The use of lithium-ion batteries, despite their higher cost, allows for much higher DoD values at approximately 75%. The minimum capacity factor is therefore much lower at 2.5 Wh/ 0.75 = 3.33 Wh/Wp. When customers understand their energy demand, and the supply from their solar home system, they are able to make informed decisions about how they use their system. These could be simple decisions such as ensuring lights are turned off when not in use, to charging mobile phones during the day when the energy supply is highest. Customer education about their solar device will allow them to obtain greater utility from it and the system will last for a longer period.

Consumers also need to be aware of the operation and maintenance requirements of the solar lighting systems. The solar panels are designed for outdoor use and will not be damaged by wet conditions. However, the rest of the components: charge controller, battery and lamps are designed for indoor use only. Minimal maintenance is required for the solar panel and would include cleaning the panel every few months to remove accumulation of dust particles that would limit the energy output of the system. Per the calculations described above, consumers should also remember to limit the depth of discharge on the battery to less than 50% in order to extend its life.

Consumer Education

For some rural residents, solar PV technology is a technology that is completely new to them. Solar home system vendors therefore have to invest time in outreach activities to their target area depending on their education level, financial status and most importantly their energy needs. When vendors are in tune with the home's energy demand, they can prescribe a solar PV system to meet the specific home needs. This has to match the family's financial situation, so that they are not overwhelmed and put off by the cost of solar PV device. Depending on the available marketing budget, consumer awareness can be achieved through several avenues: roadshows, door-to-door campaigns and even outreach through schools. On May 14th 2012, Phillips Company launched "The Phillips Cairo to Cape Town Roadshow" that is set to visit eleven countries and seventeen cities in Africa. Companies invest in door-to-door sales events where they teach the consumers how to use the solar products. The social, health and economic benefits of replacing traditional light sources such as kerosene or candles with solar (listed in Table 5 [23]) are highlighted at these visits so that rural residents are aware of the benefits of solar technology.

Table 5: Impacts of solar lighting systems

Social impacts	▪ Longer hours and better illumination for studying. ▪ Social cohesion and community development. ▪ Safety and equitable development for women.
Health impacts	▪ Improve safety by reducing hazards associated with flammable fuels and candles. ▪ Reduce indoor air pollution with a significant effect on consumers' health.
Environmental impacts	▪ Prevent 90 million tons of CO_2 emissions annually. ▪ Reduce annual global kerosene consumption by 25 billion liters. ▪ Prevent 270,000 tons of black carbon annually, with a warming effect equivalent to about 240 million tons of CO_2. ▪ Protect natural habitats against deforestation.
Economic impacts	▪ Free up $27 billion spent annually on fuel to be invested in more sustainable businesses. ▪ Reduce household spending on kerosene or candles, and increase savings up to 15% of a household's income. ▪ Generate new income, stimulate economic activities, and offer new opportunities for small businesses by lengthening the day. ▪ Multiply trade activities and job creation to increase state income and facilitate overall socioeconomic development.

Educational institutions have also been used to increase consumer awareness and education. SunnyMoney sells their solar modules through school teachers who demonstrate the advantages of solar lamps and solar home systems to students' parents. The teachers are respected in the community, and they already have a relationship with many community members. They are able to use their positions of influence to encourage the community to adopt the new technology. The Barefoot College advances this approach by training individuals in the community (mainly women) to become "Barefoot Solar Engineers" who not only use the solar home systems, but also know how to fabricate, install and maintain solar powered household lighting systems. The common thread among these approaches is the need to identify trusted community members who can act as champions and encourage their family, friends and neighbors to replace their lighting system with solar powered lights [24].

Quality of Products

One of the market risks in the deployment of solar lighting products is the entrance of counterfeit, low quality products that are unreliable and result in a poor brand image. Any customers who use products that do not meet their expectations i.e. low light output or poor battery performance will share their negative review with family and friends; thereby slowing down the adoption of solar lighting systems. To curb this, internationally recognized quality standards have been adopted and approved by manufacturers and distributors. In Kenya, the Kenya Bureau of Standards has also adopted its own standards, based on the international standards, to which both locally made and imported solar lighting systems must abide. This does not eliminate all the low quality products in the market, but it provides some protection to the consumer and also the producer against defective products. Many manufacturers also offer product guarantees for limited periods for their lighting products. The solar lighting systems manufactured by M-Kopa and Azuri Technologies both come with a two-year warranty that is a good sales technique to reach new customers. Table 6 [5] lists the international standards for various components of the solar lighting system.

Table 6: International standards for stand-alone PV systems and components

Components	International Standards and Explanation
Panels	IEC 61215 Ed. 2.0: Crystalline silicon terrestrial photovoltaic modules - Design qualification and type approval.
	IEC 61646 Ed. 1.0: Thin-film terrestrial photovoltaic modules - Design qualification and type approval.
Charge Controllers	IEC 62509 Ed.1: Performance and functioning of photovoltaic battery charge controllers
	IEC 62109: Safety of power converters for use in photovoltaic power systems. Part 1: General requirements, Part 3: Controllers.
	IEC 62093 Ed. 1.0: BOS components - Environmental reliability testing - Design qualification and type approval.
	IEC CISPR 11:1990, Limits and methods of measurement of electromagnetic disturbance characteristics of industrial, scientific and medical (ISM) radio-frequency equipment.
	IEC 61000-4:1995, Electromagnetic compatibility (EMC). Part 4: Testing and measurement techniques, Sections 2-5.
	PV GAP, PVRS6A "Charge controllers for photovoltaic stand-alone systems with a nominal voltage below 50V" accepted for use in the IECEE PV scheme.
Inverters	IEC 61683 Ed. 2.0: Photovoltaic systems - Power conditioners - Procedure for measuring efficiency
	IEC 62109 Safety of power converters for use in photovoltaic power systems. Part 1: General requirements. Part 2: Particular requirements for inverters.
	IEC 62093 Ed. 1.0: BOS components - Environmental reliability testing - Design qualification and type approval.
	IEC CISPR 11:1990, Limits and methods of measurement of electromagnetic disturbance characteristics of industrial, scientific and medical (ISM) radio-frequency equipment.
	IEC 61000-4:1995, Electromagnetic compatibility (EMC). Part 4: Testing and measurement techniques, Sections 2-5.
	PV GAP, PVRS 8A "Inverters for photovoltaic stand-alone systems."
Energy-efficient lights	IEC 60969 Ed 2: Self ballasted lamps for general lighting purposes - Performance Requirements.
	IEC 61347-1: 2007, Lamp control gear. Part 1: General and safety requirements.
	IEC 61347-2: Lamp control gear. Part 3: Particular requirements for AC-supplied electronic ballasts for fluorescent lamps, Part 4: Particular requirements for DC-supplied electronic ballasts for general lighting.

Components	International Standards and Explanation
	PV GAP, PVRS7A "Lighting systems with fluorescent lamps for photovoltaic stand-alone systems with a nominal voltage below 24 V."
BOS components and minor equipment	IEC 60669-1: Switches for household and similar fixed-electrical installations. Part 1: General requirements.
	IEC 60227-1-4: Polyvinyl chloride insulated cables of rated voltage up to and including 450 V/750 V-Parts 1-4: General requirements.

Financing Options for Solar Lighting Systems

Affordability of solar lighting systems has been identified as one of the barriers to universal access to electricity, especially in rural areas. Although rural residents may be willing to pay for the solar lighting systems, their ability to pay is limited to a large extent by their monthly income. This section approximates the average monthly income for a rural household. It also shows that the costs of solar lighting systems (both portable solar lanterns and pico PV systems) will be within reach of rural residents if alternative payment options such as pay-as-you-go schemes are incorporated to make the devices more affordable. Income data from Kenya is used to represent average income levels for the rural population in SSA that is largely dependent on agriculture as the primary income source. Kenya is geographically located in East Africa, and it straddles the equator and receives high solar irradiation year-round making it a favorable location for solar PV technology. According to the 2009 national census, the population of adults above the age of 18 was 19.5 million, with 35% and 65% of the population living in urban and rural areas respectively. The most recent financial access survey commissioned by the Financial Access Program [25] classified the sources of income for Kenyan households, and the average monthly income by livelihood as shown in Table 7. Most rural residents, especially those who live in remote areas, rely on agriculture as the primary source of their family income. In limited cases, residents may be supported by family members who live in urban areas to supplement earning from sale of their farm produce. The monthly income from agriculture ($33.63) will therefore be used as the average income for a rural resident.

Table 7: Livelihood classification, distribution and average monthly income in Kenya

Classification	Source of Income	% of population	Average monthly income (USD)*
Agriculture	▪ Selling produce from their own farm (cash or subsistence crops). ▪ Selling livestock. ▪ Fishing. ▪ Employment on others' farms.	44.2	33.63
Employed	▪ Employment to do domestic chores. ▪ Employment by the government. ▪ Employed in the private sector.	12	88.42
Own business	Running own business (manufacturing, trading/ retail or services)	15.6	68.71
Dependent	▪ Pension ▪ Family/ friends ▪ Aid agency	18.6	29.86
Other	▪ Letting of land/ houses/ rooms. ▪ Investments.	9.6	83.24
Average exchange rate: 1 USD = Ksh. 90			

The two solar PV options listed as possible options for solar lighting systems in chapter two were portable solar lanterns and pico PV systems (PPS). Rural customers could invest in portable solar lights with future plans to upgrade to PPS. With a power output of less than 25 Wp, and a selling price range of $80- $180, PPS would be sufficient for lighting and cell phone charging options per energy estimates listed in Table 4. However, the total cost would still exceed a household's ability to pay if a cash payment was requested, since the portable solar lamp might typically exceed the family's monthly income while the cost of PPS would be equal to several months' pay. Large solar home systems, on the other hand, would be oversized for a small rural home's energy needs with a power output of up to 250 Wp, and the system costs which range from $200 - $1,000 would not be affordable for the residents. Although residents may be attracted to solar PV systems and be willing to pay for the advanced technology, their ability to pay is limited to their available monthly income, unless outside funding in the form of government assistance or grants are made available.

CHAPTER 5

CASE STUDIES FOR PAY-AS-YOU-GO SOLAR LIGHTING SYSTEMS

This chapter examines pay-as-you-go payment options implemented by companies such as M-Kopa, Azuri Technologies and SunnyMoney to alleviate the high initial cost of portable solar lamps and PPS for rural residents. An additional complexity in financing solar PV systems is the lack of access to formal banking services for many rural residents. According to the FinAccess National Survey [25] performed in Kenya, only 21% of rural residents have a bank account compared to 54% who have access to mobile money transactions through their cell phones. The mobile penetration rate in SSA at the end of 2013 stood at around 70%, and this is expected to increase as the mobile revolution increases [26]. It is this rise in access to mobile phone technology that has facilitated the development of pay-as-you-go (PAYG) payment schemes, thus allowing more rural residents to embrace solar PV technology. This chapter examines the cost of the solar lighting systems, payment options, mode of payments and highlights successful marketing and consumer education methods that have resulted in high sales numbers of the lighting products. The chapter concludes by summarizing the future of PAYG schemes in the advancement of solar lighting systems in rural areas.

M-KOPA Solar

M-KOPA Solar provides customers with a small solar home system manufactured by d.light. In 2013, the company released their third-generation PAYG solar home solution branded “M-KOPA III,” with the following components: an eight watt solar panel, two LED solar lights, one solar rechargeable LED flashlight, a solar rechargeable radio, mobile phone charger and battery, as illustrated in Figure 17 [27]. The solar panel provides 60% more charging capacity than the previous model, and the battery is also larger. Additionally, the M-KOPA III can be upgraded to included two additional solar lights that are sold separately. Payments for the system include an initial deposit of $33.32, followed by 365 daily payments of $0.44 for the remainder of the $162.22 cost. This is down from previous daily payments of $0.56 since the Kenyan government removed value added tax (VAT) requirements on solar products. After the customer buys the device, they use the instruction manual to install the system. They then call a customer care representative who unlocks the device after explaining the contract terms and conditions. The device comes with five days of pre-paid electricity, following which the daily payments shall be made. Flexible payments, in terms of frequency and amount, are made using M-PESA (Kenya's mobile banking system by the Safaricom mobile provider); however, the entire $162.22 must be paid within a year. Once payments are completed, the device is permanently unlocked and the customer owns the system. To encourage users to try the product with limited risk, the $33.32 deposit is refundable anytime during the payment period, and the system also comes with a two-year warranty. In addition to using the mobile platform to make payments, it also allows for real time monitoring and control of the system so that the technical support team can respond to glitches in the system promptly. The same remote monitoring system will lock the device if the daily payments are not made [27]. In April 2013, 10,000 customers had signed up with M-KOPA and subscription had more than doubled by August 2013 to 25,000 customers [28]. By September 2014, M-KOPA had expanded to serve customers in

Uganda and had served its 100,000th customer. Customers in Uganda make payments through Airtel Money or MTN Mobile money. M-KOPA products are now also available in Tanzania and most recently in Ghana, furthering the success of the PAYG platform in expanding access to solar PV systems.

Figure 17: M-KOPA III solar lighting system

Azuri Technologies

Azuri Technologies was launched in August 2012 as a spinoff from the UK-based company Eight19 in order to promote the Indigo PAYG model. They market the Indigo Duo small solar home system, which consists of a 2.5 Wp PV module, a long-life 3.3 Ah lithium iron phosphate battery, an Indigo controller, two 60-lumen LED lights and a USB socket for phone charging. Appendix B [29, 30] shows that the system components are built to meet global lighting standards described in Chapter 4. Customers obtain the Indigo Duo system by paying a $10 deposit to have the system installed in their homes, and weekly installments of $1.50 by purchasing top-up cards. The top-up cards are either physical cards bought for cash, or codes obtained using a mobile money system. Users who purchase physical cards send the top-up number along with the serial number of the Indigo unit by SMS to an Azuri in-country gateway that relays the information to the Azuri central server to obtain an activation code. The unit is then unlocked by entering the code on the keypad, which activates the system for either a one-week or four-week period, depending on the top-up amount. After approximately 80 weekly payments, users have two options: they can pay a $10 fee to have their system permanently unlocked or they can choose to upgrade their system to a larger, more powerful unit by making additional payments. Azuri sells its products to locally based distribution partners who install the systems, sell top-up cards and provide after sales services. Ownership of the system remains with Azuri until the final payment is paid to have the device permanently unlocked. If a user stops buying top-ups for an extended period, the unit will be taken away to recover costs [31]. The Indigo Duo system is currently available in Kenya, Uganda, Tanzania, Ethiopia, Rwanda, South Sudan and Zimbabwe.

SunnyMoney

SunnyMoney is a social enterprise created in 2006 by the UK-based charity SolarAid, whose goal is to eradicate the kerosene lamp from Africa by 2020. SunnyMoney does not manufacture lights, but instead focusses on the challenge of distribution and marketing. Appendix C [32] shows the range of solar lighting products offered in Kenya, their specifications and costs in 2014. All solar lights are durable, reliable, come with a two-year warranty and meet or exceed World Bank Lighting Global

Standards. The flexibility in the range of products allows customers to begin with a small system, e.g. the d.light S2, but they can plan to upgrade to a light that can charge their mobile phone such as the S300 or Sun King Pro 2. SunnyMoney tacked the challenge of building distribution channels and marketing by working with teachers to raise trust and build awareness of solar lighting options. SunnyMoney holds local meeting with headteachers to promote the benefits of solar lights, and headteachers collect orders from students. Direct sales are also used where independent agents are recruited to sell the full range of solar products within their community. However, uptake of the new technology through this system averaged only about 15% of the residents who had been exposed to the technology. In 2013, SunnyMoney launched a pilot program in Senegal to test a new model called the Light Library. Fifty-eight schools were given a library of solar lights to be used by students and the community for a small daily fee. This allowed community members to test the solar lights at home without committing to the full upfront cost. Nearly 5,000 lights were borrowed regularly from the Light Libraries, exposing a large portion of the community to the new technology. In 2014, SunnyMoney returned to the 58 schools and to 58 schools that had not been exposed to the Lighting Libraries to offer solar lights for purchase. Demand for solar lights in the two areas was at 35% and 15% of the school population respectively, showing that the increased exposure for the families that had tested the system had encouraged them to consider purchasing a solar light. All products are currently offered on a cash sale basis where the full cost of the device is paid up front. The SunnyMoney Brains unit was set up in 2012 to develop solutions to increase the number of people who benefit from solar energy. They are currently trialing a PAYG system for solar lights that will enable customers to pay off the cost of the lighting systems in installments. This will make the higher capacity systems offered by SunnyMoney more affordable for lower-income, risk-averse families. By April 2014, SunnyMoney had sold more than 1 million lights, with 60% of those sold in the 2013-2014 financial year. The sales growth demonstrates the potential of solar lighting systems and the interest that families have to invest in them. SunnyMoney is currently available in Kenya, Malawi, Senegal, Tanzania, Uganda and Zambia [32, 33, 34].

Future of Pay-As-You-Go Financing

The flexibility offered by PAYG financing schemes in allowing users to pay an initial deposit followed by periodic installments over time matches the needs of rural consumers whose economic situation is often unpredictable. These business models that leverage mobile payments to extend end-user financing and deliver prepaid energy services provide several opportunities to improve the provision of essential services to underserved consumers. Most PAYG options offer pricing models with lenient penalties in case of late payments. For example, a customer whose prepaid balance expires might be allowed multiple days or weeks of non-use before the device is repossessed to make up for missed payments. On the other hand, the solar company can develop metrics and incentives to monitor customer portfolios to estimate their financial assets and liabilities. For many rural residents, paying off a PAYG solar product might be the first formal credit history in life. In future, this data can be used to meet prerequisites for these customers to obtain other financial services that require formal credit history. Additionally, a customer could store excess cash in their prepaid solar account as a form of savings, and this could be used in the future to replace damaged solar components or those that have exceeded their useful life, or to upgrade to larger solar lighting systems. For the solar companies that partner with mobile communication companies that have mobile money platforms, PAYG solar devices help the mobile money services gain traction in rural areas. Finally, the data collected and analyzed by solar companies allows a clearer understanding of customer requirements and energy usage, favorable pricing schemes and how to improve future products for the off-grid market. This data could be used by governments and regulators to better direct energy subsidies for target populations [6].

CHAPTER 6

CONCLUSION AND FUTURE WORK

Rural electrification in developing countries in SSA faces socio-economic barriers resulting in the inability of rural households to connect to electricity services. This thesis has highlighted the fact that connection to the traditional grid is not only hampered by high connection costs, but also many households are located too far away from the grid to consider grid extension as a feasible solution. Other renewable energy systems, such as small wind home systems and small hydropower also have high installation costs that hinder access to many rural residents. Additionally, small hydropower has site specific requirements that limit its availability to a small population of rural residents. Advancements in solar PV technology have developed portable solar lamps and pico-PV systems that are ideal for the energy consumption of a rural household. With an energy output ranging between one Wp to 25 Wp, these systems provide sufficient power to light LED lamps, charge cellphones and power small electric devices such as radios. This thesis further examined the physical components of the solar PV system such as: the solar cell, inverters, batteries and charge controllers. It highlighted the decrease in costs of the solar cell and batteries in recent years that have contributed to the development of solar PV technology. The two main configuration systems: grid connected and off-grid solar systems are discussed. For rural residents, off-grid solar systems are most applicable as the grid is not currently available in many areas.

The following components are vital for a successful and sustainable uptake of solar PV technology in rural areas: appropriate sizing of the system, a well-thought out consumer education and marketing approach, ensuring good quality of solar system components and understanding the financial capability of residents. Depending on the location of the panel and the available solar insolation, the solar panel and battery are sized to generate sufficient power during the day, and store enough charge to power the lighting system and charge cellphones in the evening. The solar systems have a modular design that allows customers to increase the power available by adding solar panels and storage systems in the future to increase their capacity. Consumer education has taken many forms such as roadshows, collaboration with education partners and door-to-door visits that inform residents of the benefits of solar lighting over using traditional lighting systems such as kerosene and candles. Customers are informed of the economic savings and health benefits of switching to the cleaner technology to encourage them to make the switch. They are also educated on the specifications of their systems and the charge and discharge cycles to understand their system capabilities and limitations. Through this awareness, users are informed on maintenance requirements such as periodic cleaning, and proper use that will ensure a long lifetime for their device. International standards have been implemented to ensure high quality solar panels, batteries and lights enter the market. Several participants in the solar market not only ensure that their products meet or exceed lighting standards, but they also offer limited time warranties to back their products.

Affordability of solar lighting systems has been identified as one of the barriers to universal access to electricity especially in rural areas. With many households having a daily income of less than $1.25, investing in a portable solar lamp or pico PV system whose cost ranges from $10 to $180 is a considerable challenge. Pay-as-you-go solutions are a popular form of business transactions as they are used by most cell phone companies. The development in mobile technology has allowed companies to offer flexible payment options where users make an initial deposit and pay off the rest of the cost in installments. The partial payments have flexible payment terms (duration and amount) that are made using mobile money transfers across a variety of mobile platforms, or customers can purchase scratch cards to top-up their system. Once the full payment is made, the solar lighting system is permanently unlocked and fully owned by the customers. In some instances, the customers can choose to upgrade their system to a higher output one by opting to make additional payments.

This thesis concludes by examining case studies of three solar lighting options that currently incorporate or are investigating PAYG payment options. These are M-KOPA, Azuri Technologies and SunnyMoney. In addition to the flexible payment options, all three products meet or exceed lighting standards, and are backed by product warranties thus ensuring high quality systems. Consumer education has been achieved by a variety of means: M-KOPA launched roadshows around Kenya, while SunnyMoney has partnered with schools to reach out to parents and the community to switch to solar lighting system. All the products have recorded high sales growth in a few years, showing the interest in solar products and commitment to better lighting solutions if the device is properly marketed to rural residents. This flexibility of PAYG financing schemes has facilitated the advancement of solar PV technology in rural areas.

Future Work

Future work could include collaboration of solar companies that offer PAYG payment schemes with microfinance institutions to enable rural customers to gain access to additional funding opportunities. Past payment history for the solar lighting system products could act as "collateral" for small loans to improve the quality of life for rural residents. A large segment of rural residents rely on informal financial arrangements to save money and/ or finance short term projects. In these settings, groups of individuals meet for a defined period to save and borrow money together. In a Rotating Saving and Credit Association (ROSCA), each member contributes the same amount at each meeting, and one member takes the whole amount at pre-determined intervals. This differs slightly for Accumulating Savings and Credit Associations (ASCAs), where members accumulate the pooled money to make a larger investment, or to make short term loans to group members. Both ROSCAs and ASCAs allow members the opportunity to save money for both short and long-term investments. Formal financial institutions are now specifically targeting these groups to offer financial services aimed to attract their business. This provides a prime opportunity for solar companies to work with both ROSCAs and ASCAs to encourage the adoption of solar lighting technology. The group setting allows companies to target their consumer education and marketing plan to the demographic that they want to reach. Discounts can be offered to the group if multiple lighting systems are ordered in bulk thereby saving the members money. Since most of the members live in the same geographical area, maintenance costs will be lowered since technicians know that they can serve a larger number of customers in the same area in case of equipment failure. Since the solar lighting devices have an estimated lifetime of about five to seven years depending on the product, members could also be encouraged to include in their monthly payment a small amount of money that could accumulate over time to replace their solar lighting component when the device failed. This would further increase the exposure of the rural population to affordable solar lighting options.

APPENDICES

Appendix A: Electricity access rates in Africa in 2012

Region	Population without electricity millions	National electrification rate %	Urban electrification rate %	Rural electrification rate %
Africa	622	43%	68%	26%
Sub-Saharan Africa	621	32%	59%	16%
Angola	15	30%	46%	6%
Benin	7	28%	55%	6%
Botswana	1	66%	75%	51%
Burkina Faso	14	16%	54%	2%
Burundi	9	10%	34%	7%
Cameroon	10	54%	88%	17%
Cabo Verde	0	94%	100%	84%
Central African Republic	4	3%	5%	1%
Chad	12	4%	16%	0%
Comoros	0	45%	72%	35%
Congo	3	35%	52%	5%
Côte d'Ivoire	15	26%	42%	8%
Democratic Republic of Congo	60	9%	24%	1%
Djibouti	0	50%	61%	14%
Equatorial Guinea	0	66%	93%	48%
Eritrea	4	32%	86%	17%
Ethiopia	70	23%	85%	10%
Gabon	1	60%	64%	34%
Gambia	1	35%	60%	2%
Ghana	7	72%	90%	52%
Guinea	10	12%	28%	3%
Guinea-Bissau	1	20%	37%	6%
Kenya	35	20%	60%	7%
Lesotho	2	28%	55%	17%
Liberia	4	2%	3%	0%
Madagascar	19	15%	37%	4%
Malawi	15	9%	33%	5%

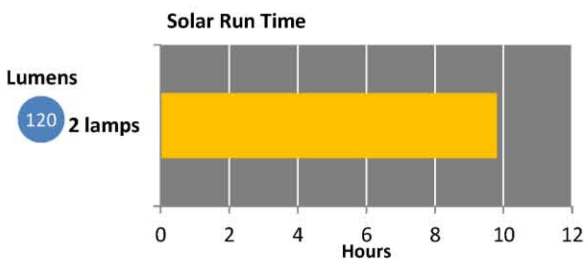
Region	Population without electricity millions	National electrification rate %	Urban electrification rate %	Rural electrification rate %
Mali	11	27%	55%	12%
Mauritania	3	21%	47%	2%
Mauritius	0	100%	100%	100%
Mozambique	15	39%	66%	27%
Namibia	2	30%	50%	17%
Niger	15	14%	62%	4%
Nigeria	93	45%	55%	35%
Réunion	0	99%	100%	87%
Rwanda	10	17%	67%	5%
Sao Tome and Principe	0	59%	70%	40%
Senegal	6	55%	90%	28%
Seychelles	0	97%	97%	97%
Sierra Leone	6	5%	11%	1%
Somalia	9	15%	33%	4%
South Africa	8	85%	88%	82%
South Sudan	11	1%	4%	0%
Sudan	24	35%	63%	21%
Swaziland	1	27%	40%	24%
Tanzania	36	24%	71%	7%
Togo	5	27%	35%	21%
Uganda	31	15%	55%	7%
Zambia	10	26%	45%	14%
Zimbabwe	8	40%	80%	14%
North Africa	1	99%	100%	99%
Algeria	0	99%	100%	96%
Egypt	0	100%	100%	99%
Libya	0	100%	100%	99%
Morocco	0	99%	100%	97%
Tunisia	0	100%	100%	100%

Appendix B: Indigo Duo solar home system specifications

Indigo Duo Solar Home System

Azuri Technologies, Ltd. *Verify Online:* www.lightingglobal.org/products/az-indigo

Results based on test procedures detailed in IEC 62257-9-5, ed. 2.0 *Valid Until:* October, 2014



Meets Lighting Global Minimum Quality Standards

Mobile Charging

2 **Light Points**

Warranty Information

A 1-year warranty from the original date of purchase.

Performance Details

	Brightness Setting***
Performance Measure	**2 lamps**
Full battery run time* (hours)	13
Run time per day of solar charging* (hours)	9.8
Total light output (lumens)	120
Total area with illumination > 25 lux** (m^2)	0.56
Total lighting service (lumen-hours / solar-day)	1200

* Run time estimates do not account for mobile phone charging or other auxiliary loads; the run time is defined as the time until the output is 70% of the initial, stabilized output.

** Total area with illumination > 25 lux is determined by the maximum area with adequate illumination at a 0.75 m distance and at the distance from which the product would normally provide task lighting service.

*** Additional brightness settings (not tested):

Lighting Details

Lamp type	LED
Description of light points	Identical light points; 12 LEDs per light point
Colour characteristics	CRI 75 CCT "Cool" (5000-7000 K)
Distribution type	Wide
Lumen maintenance	101% of the original output remains after 2,000 hours run time

Special Features	
Mobile charging	Adapters included to charge mobile phone from battery
Payment system	Pay-as-you-go using scratch cards and SMS service

Durability	
Overall durability and workmanship	Pass
Durability tests passed	Drop test, switch and connector cycling, physical ingress protection test, and no water ingress protection

Solar Details	
PV module type	Polycrystalline silicon
PV maximum power point	2.6 watts

Battery Details	
Battery replaceability	Easily replaceable with common tools
Battery chemistry	Lithium iron phosphate
Appropriate battery protection circuit	Pass
Replacement batteries can be installed by the local distributor	

Marks and Certifications	
Factory certification	ISO 9001

Product Details	
Manufacturer name	Azuri Technologies, Ltd.
Product name	Indigo Duo Solar Home System
Product model / ID number	Indigo Duo Solar Home System
Contact information	info@azuri-technologies.com
Website	www.azuri-technologies.com

SSS Information	
Specs sheet expiration date	October, 2014
Minimum Quality Standards Framework Version	2012
Revision	2014.01

Appendix C: SunnyMoney solar lighting options

Affordable study lights

Lights and Mobile Chargers

SunKing Mobile

- Day and night phone charging
- USB port and five adapters
- Up to 36 hours of light in a full charge
- 1.5 Watt separate solar panel
- Two year warranty; up to five year battery life

USD 29.40

S300

- Four brightness settings for light from 4 Hours to 100 Hours
- Charges mobile phones, five common adapters included
- 1.3 Watt solar panel includes 4 meter cable
- Battery charge level indicator
- Two year replacement warranty; up to five year battery life

USD 35.30

SunKing Pro 2

- Day and night phone charging
- Two USB ports and five adapters for phone charging
- Up to 36 hours of light in a full charge
- 3.3 Watt separate solar panel
- Two year warranty; up to five year battery life

USD 42.40

Multi-Room/ Small business

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VITA

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While working as an Electrical Engineer at Black & Veatch Corporation in Kansas City, Missouri, Ms. Oruoch began work on a master's program in electrical engineering at the University of Missouri- Kansas City. Upon completion of her degree requirements, she plans to continue her career in electrical engineering with an emphasis in power systems.