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Original Research Article

Design and costing of a stand-alone solar photovoltaic system for a Tanzanian rural household

Thanatchai Kulworawanichpong, Joachim J. Mwambeleko *

School of Electrical Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima, Thailand

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ABSTRACT

Access to energy is essential to reduce poverty. In Tanzania electricity is available to about 24% of the population; 93% of rural households lack access to electricity. Most of these houses are sparsely populated; this makes national grid extension to such areas economically unviable. Solar home systems present a huge promise for these areas but, most of the villagers do not think of solar photovoltaic (PV) system as a cost effective solution to electricity shortage. Aiming at stressing the applicability of solar PV technology in Tanzania, this paper presents a design and costing of a stand-alone solar PV system for a Tanzanian rural household; highlighting some common mistakes done in sizing, installing and maintaining solar home systems. The design is done in two different fashions: (i) The entire system sized as a single system. (ii) The system divided into three subsystems or phases. The paper gives a total cost of the designed systems' components as US$ 422.5 for the entire system sized as a single system, US$ 197.5 for subsystem one (lighting system), US$ 107.5 for subsystem two, and US$ 155.5 for subsystem three.

Introduction

Electricity is an important resource to support economic and social development of any society; it is in fact one of the discoveries that have transformed mankind. Modern society's reliance on electrical power is so great that it is considered a basic need [1]. As there are people who cannot imagine life without electricity, there are others who have never enjoyed the beauty of electricity. In Tanzania electricity is available to about 24% of the population, 93% of rural households lack access to electricity [2,3]. It is very unfortunate that people in rural areas have to use kerosene lamps which provide very poor light. The kerosene is not only detrimental to human health and the environment, but also notable financial burden [4–6]. Some villagers have to travel long distances just to charge their mobile phones. They can use kerosene lamps for lighting, but they do need electricity to recharging their phones [7].

This electricity shortage in rural areas has created another problem in education sector. Most of the primary and secondary school teachers do not prefer living in rural areas with no access to electricity. The students on the other hand, who are taught by very few teachers available, normally help their parents with agricultural activities after school, and they have to study at night using the kerosene lamps (Fig. 1). These have led to very poor performances of the students in rural areas. As mentioned in [8], "students in primary and secondary schools in rural areas of Tanzania are academically isolated".

Most of the rural areas in Tanzania are sparsely populated and this makes national grid extension to these areas economically unviable. Off grid electric systems based on renewable energy sources present a huge promise for these areas [10]. Solar photovoltaics (PV) systems convert solar energy directly into electricity and offer the advantage of long lifetime with minimal maintenance [11,12]. Having matured in space applications, PV technology is now spreading into terrestrial applications ranging from powering remote sites to feeding utility grids around the world [13]. However, unlike most mature technologies, its costs are continuing to decline and solar PV is increasingly commercially attractive to project developers and to small-scale residential or commercial consumers. In 2002, total installed solar PV capacity exceeded 2 GW and 10 years later, in 2012, it surpassed 100 GW. In 2013, new additions of solar PV alone came to 39 GW. Solar PV module prices in 2014 were around 75% lower than their levels at the end of 2009 [11]. Tanzania (being in equatorial region) has high solar irradiation level. The annual daily average solar irradiation on a horizontal surface ranges between 4.38 and 6.57 kWh/m^2, this corresponds to average annual sum horizontal irradiation of 1600–2400 kWh/m^2 depending on a location [14].

This paper therefore aims at stressing the applicability of solar PV technology in Tanzania through a design and costing of a

* Corresponding author.
E-mail address: mwambejoachim@hotmail.com (J.J. Mwambeleko).

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Fig. 1. Students studying using a local kerosene lamp [9].

stand-alone solar PV system for a typical Tanzanian rural household. The house is assumed to be having DC lighting system with energy efficient light emitting diode (LED) lamps; and AC loads such as TV, DVD player, digital satellite receiver, small music system and fan.

A stand-alone solar PV system

As shown in Fig. 2 a stand-alone solar PV system for a typical rural household is expected to comprise the following:

(a) Solar module(s);
(b) charge controller;
(c) storage system (batteries);
(d) inverter (if the system includes ac load); and
(e) DC and/or AC load(s).

Solar module

Solar modules are made of several PV cells connected in series and parallel circuits. The solar array or panel is then a group of several modules electrically connected in a series–parallel combination to generate the required current and voltage [13,15]. The underlying operating principle of a PV cell is the photoelectric effect, by which radiation of photons of greater energy than the bandgap of the semiconductor material excite free electrons. When the PV circuit is closed, the freed electrons flow through an external circuit generating a DC current. Therefore the current generated is directly dependent on the number of incoming photons and thus, the solar irradiation [13].

It is perhaps worth mentioning that in a string of modules, a shaded module reduces the overall voltage of the string instead of adding to it. To overcome this effect, a bypass diode is usually added in parallel to each module. Similarly, in parallel-connected modules or strings, a diode is connected in series to each string to prevent reverse currents flowing into the lower voltage string

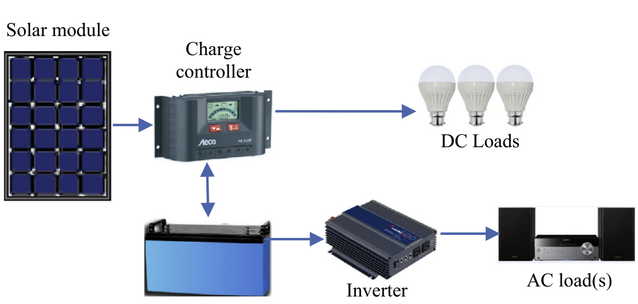

Fig. 2. A stand-alone solar PV system with dc and ac loads.

[16]. Besides reducing shading losses the bypass diodes are also used to prevent the existence of hotspots [17].

Charge controller

The success of any off-grid PV system depends to a large extent on the long-term performance of the batteries. For a system to operate well and have a long lifetime, the batteries must be charged properly and kept at high state of charge. A charge controller regulates power from a PV module to prevent batteries from overcharging and unacceptable voltage levels; it also functions as a low-voltage disconnect to disconnect DC load from the battery, preventing the batteries from over-discharge [18,19].

Given a solar irradiation level and PV cell temperature, maximum power from a PV module is harvested at a certain voltage known as maximum power voltage (V_{mp}), The V_{mp} is highly affected by changes in PV cell temperature. Normally, controllers allow the battery voltage to determine the operating voltage of a PV system. However, the battery voltage may not be the optimum PV operating voltage [19]. A maximum power point tracking (MPPT) charge controller can control PV output voltage such that maximum power is harvested.

Storage battery

Solar resource being intermittent in nature, stand-alone solar PV system is usually coupled with energy storage devices to ensure reliable supply. The most commonly used energy storage device is a battery, mainly lead acid type [12]. Lead-acid batteries are used almost exclusively in photovoltaic stand-alone systems. Although most other types of batteries have advantages such as high storage density or lower self-discharge, the decisive advantage of the lead battery is its lower price [17]. Batteries make up the largest component cost over the lifetime of a stand-alone solar PV system [18].

It might be worth mentioning at this point that, a normal car battery (starter battery) is not suitable as storage in a stand-alone solar plant as it would become defective in a short period due to the cycle operation. The battery is constructed to operate in buffer mode, for most of the time it is fully charged but occasionally must deliver short-term high currents to start the engine [17]. A battery to be used in a stand-alone solar PV system is charged during sun hours, and has to withstand deep discharge during the no-sun hours; such batteries are called deep cycle battery. Different requirements affect the construction of the two different types. In a battery bank, batteries should be of the same type and manufacturer, and about the same age. Old or poorly performing batteries decrease the performance of those to which they are connected [18].

Inverter

An inverter is included in the stand-alone solar PV system to convert the DC into AC electricity. The inverter needs to meet two needs: peak (or surge) power and continuous power. Some appliances, particularly those with electric motors, need a much higher power level at startup than they do when running [1]. Pumps, refrigerators, and blenders are common examples.

Common mistakes done in installing and maintaining solar home systems

In rural areas of Tanzania, it is common to see solar home systems (SHSs) that have been locally installed (not installed by a qualified technician), many of which are inefficient and some unsuccessful. As mentioned in [20], examples of the common