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Comparison of off-grid power supply systems using lead-acid and lithium-ion batteries

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ABSTRACT

Solar home systems (SHS) and solar photovoltaic village power supply systems can play an important role in the supply of electrical energy to off-grid areas. This paper presents a comparison of solar home systems and village power supply systems using two different types of battery technologies, namely lithium nickel cobalt aluminum oxide (NCA) and lead-acid (Pb) batteries. The developed models were implemented in Matlab/Simulink where solar radiation, temperature and electrical load data from Dodoma, the capital of Tanzania were used as model inputs.

Two topologies were analyzed for SHS: A system which is directly coupled to the battery and another system which uses a Maximum Power Point Tracker (MPPT) charge controller. The main idea of analyzing these two topologies was to find an affordable solution for off-grid population, but at the same time the selected topology should have the ability of extracting maximum output from the PV panel.

Since most of the off-grid settlements in Tanzania today use SHS with lead-acid batteries as storage, analysis was carried out for SHS with lead-acid batteries and SHS with lithium-ion batteries by simulating and optimizing the systems for 20 years. The levelized cost of electricity (LCOE) for both storage systems was compared and it was found that the SHS with lithium-ion (NCA) battery generally had a lower LCOE compared to the SHS with lead-acid battery. This is mainly due to both the longer life time of NCA batteries and the reduction of the price of NCA batteries as a result of significantly increasing global production scales.

For the case of solar photovoltaic village power supply systems, an energy management system was implemented to optimize power flows in a hybrid storage system containing both lead-acid and lithium-ion batteries. Optimization of this "hybrid" system led to a selection of both types of batteries with small capacity of lead-acid battery (0.24 kW h) compared to NCA battery (1.44 kW h) backed up with diesel generator. Further analysis was done regarding the benefits of village power supply systems over individual SHS, and it was found that the LCOE for solar PV village power supply systems was lower than the LCOE for single SHS.

1. Introduction

Electricity is one of the driving factors for the economic development of any country. A high level of access to electricity is commonly accompanied with a better Human Development Index. Among other important key figures, quality of life, economic output growth and GDP are positively correlated to electricity access Bhattacharyya (2013)

The African continent is one of the least electrified regions in the world, especially sub-Saharan Africa[a]. Its electrification rate in rural areas amounts to 17% whereas North Africa is 99% electrified Ondraczek (2013), Opiyo (2016) and Trotter (2016). If electrical power is available at all it is mostly provided by expensive diesel generators. Ahlborg and Hammar (2014) and Dagnachew et al. (2017) reported that usually the price of electricity in those areas with diesel generator is higher compared to what a consumer with a grid connection pays.

In the sub-Saharan region, there is an enormous potential of using alternative sources for power generation. Most of these areas have global solar irradiations ranging from 1500 kW h/kWp to 2000 kW h/

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Nomenclature

AC	alternating current
cr	coupling relationship
DC	direct current
DG	diesel generator
dir.coup	direct coupling
DOD	depth of discharge
EMS	energy management system
Eol	end of life of the battery
GA	genetic algorithm
GDP	gross domestic product
kW h/kWp.a	kilowatt hours per kilowatt peak per year
LCOE	levelized cost of electricity (€/kW h)
LFP	lithium iron phosphate
LTO	lithium titanate
max	maximum
min	minimum
MPP	maximum power point
MPPT	maximum power point tracker
NCA	lithium nickel cobalt aluminum oxide
P AC/DC	power of AC/DC converter
P DC/DC	power of DC/DC converter
P dir.coup	power of a direct coupled system
p.a	per annum
Pb	lead-acid
PBat	battery power
PDG	diesel generator power
P_{load}	load power
PV	photovoltaic
SHS	solar home system
SOC	state of charge
SOC_{avg}	average SOC
U_{batt}	battery voltage
Umpp	voltage at maximum power point
VPSS	village power supply system

kWp per year, which when fully utilized could increase the electrification rate especially in off-grid areas.

Tanzania, one of the countries in the sub-Saharan region, has a total population of 51.82 million people of which 70% have no access to electricity. The rural electrification rate amounts to only 4% of which solar electricity plays an insignificant role in these areas (Moner-Girona et al., 2016). In 2015, solar electricity accounted for less than 2% of the energy used for lighting and just 0.2% of the energy used for cooking (IEA, 2015). Despite the fact that Tanzania has a high potential for solar energy, the resource is not fully utilized especially in off-grid rural areas.

One of the approaches for utilizing this potential in rural areas is to install either an off-grid village power supply system or a solar home system. The fluctuation of the resource can then be compensated by the use of energy storage systems such as batteries. In order to make this source of energy a tempting option for consumers (i.e. by providing energy at lower cost than fossil energy conversion), an optimal system design needs to be found.

There are a number of studies which presented different models for designing either off-grid village power supply systems or solar home systems, for example Merei et al. (2013), Kaabeche and Ibtiouen (2014), Majumder et al. (2016), Campana et al. (2016), Fara and Craciunescu (2017), Zubi et al. (2016) and Okoye and Solyalı (2017).

While the development of precise solar PV models plays an important role in optimal system design, the selection of an appropriate storage technology needs to be taken into consideration as well. For the current study, solar PV models with two types of battery storage technologies (NCA and lead-acid batteries) were investigated. Most of the PV systems installed today use lead-acid batteries as storage. This is due to the fact that the lead-acid battery is a mature technology and its initial investment cost is lower than the cost for the other technologies Hoppmann et al. (2014), Pavlov (2017), Jaiswal (2017) and Kwiecien et al. (2017).

Many studies, as presented for example by Achaibou et al. (2012), Rand and Moseley (2015), Lujano-Rojas et al. (2016), Oliveira e Silva and Hendrick (2016) and Bogno et al. (2017)), specifically investigated different models and optimization tools for PV systems with a lead-acid battery as a storage technology.

An interesting study by Anuphappharadorn et al. (2014) on economic analysis of standalone PV systems with lead-acid and lithium-ion batteries, also found that a system with lead-acid battery was economically cheaper than a system with lithium-ion battery due to its higher initial investment cost.

They furthermore reported that, although economic parameters showed that a PV standalone system with lead-acid battery was more suitable than a PV stand alone system with lithium-ion battery, lithium-ion batteries had nevertheless many advantages when compared to the lead-acid battery technology in terms of high energy density, low maintenance and higher number of lifecycles.

Due to the above mentioned advantages of lithium-ion batteries over lead-acid batteries, Jaiswal (2017) recently evaluated seven different types of lithium-ion batteries as potential replacement of lead-acid batteries in solar home systems. Three battery technologies were found to be optimal: NCA, LFP and LTO. These batteries were found viable in a way that they had longer lifetimes which reduced replacement costs. Above this, the price of lithium-ion is presently decreasing with a rate of 8–16% p.a, hence reducing tremendously the initial investment cost which used to be a barrier.

More studies, for example by Diouf and Pode (2015), Zubi et al. (2016) and Parra and Patel (2016), revealed that solar PV systems with lithium-ion batteries were the cheaper solution compared to PV systems with lead-acid batteries.

Although most of the reviewed authors in the current study either developed a model for solar home systems or village power supply systems, or did a comparison between different storage technologies, none of them made a comparison between solar home systems and village power supply systems using different types of batteries.

Even less work has been done to analyze the pros and cons of SHS in off-grid areas in Tanzania with either MPPT charge controller or with a direct coupled system. It is well known that a MPPT extracts maximum power from the PV panels at different solar radiation levels, as shown by Rajani and Pandya (2016), Jouda et al. (2017) and Ezinwanne et al. (2017). Its usage in a PV system reduces losses which could occur due to differences in voltage level between the PV panels and the battery as it occurs in direct coupled systems.

For the majority of off-grid population, the main issue to be considered is the initial investment cost. Low average incomes can hinder the investment of additional devices such as MPPT charge controllers. A direct coupled system could be used here if an economical analysis and comparison was done between these two systems by taking the additional losses into consideration which occur in direct coupled systems.

In this paper, a comparison of solar home systems and village power supply systems with different battery storage technologies for off-grid solutions in Tanzania is presented. For the case of solar home system, a direct coupled system with battery as a storage has been analyzed and compared with a system which uses a MPPT charge controller.

Since most of the people in rural Tanzanian areas today use solar home systems with lead-acid batteries, the analysis was done to see whether a SHS with lead-acid battery is economically cheaper compared to a system with lithium-ion battery.