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Techno-Economic Analysis of the Viability of Solar Home Systems Using Lithium-ion Batteries in Sub-Saharan Africa

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Abstract

One of the biggest challenges facing us today is finding a sustainable solution to provide clean and affordable energy to the millions of Africans who live without it. Over 600 million people in Sub-Saharan Africa did not have access to electricity in 2015 and while more than 60% of them live in rural areas, the rate of residential rural electrification there is as low as 17% [1]. Solar Home Systems can potentially increase the penetration of electricity access in rural Sub-Saharan Africa. In this paper, the viability of using Solar Home Systems which employ lithium-ion batteries is investigated, particularly considering the degradation of batteries. It is found that, exposed to the hot climates of Sub-Saharan Africa, capacity fade after 5 years of cycling is approximately 20% equating to a battery system replacement cost of approximately USD 50. Although this, in-and-of-itself, is not preventive, the upfront costs of Solar Home Systems, in the region of USD 7k-21k, can act as a deterrent.

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1. Introduction

Worldwide, 79% of the less developed countries' and 74% of Sub Saharan African countries' population live without access to electricity, compared to 28% of all developing countries combined [2]. An International Energy Agency (IEA) study showing a duality between energy consumption and economic growth also shows a lack thereof is correlated with a daily living expense of less than $2 [3]. Given that energy access plays a vital role in agriculture, manufacturing, education, trade, health, and communication, inadequate access to energy can impede countries from achieving their development goals [4]. Therefore, an increased energy consumption is a necessary result for the growth and development of Sub-Saharan African economies [4].

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The desired economic growth for Sub-Saharan Africa in addition to a steadily increasing population, necessitates increased energy demands which subsequently compels higher carbon emissions. Given that a large part of the emissions arises from consumption of fossil fuels, the obvious route to limiting carbonisation is reducing energy consumption. The the possible negative impacts on economic growth arising from cutting back energy demand however, forces governments to seek more environmentally clean alternative energy resources. To this end, many Sub-Saharan African countries have been promoting the use of renewable energy resources, such as hydro-generation, geothermal, solar, and wind energy [4]. There is an abundance of renewable energy resources in Africa, with 1100 MW of hydropower capacity, 9000 MW of geothermal potential (hot water and steam based), abundant biomass, and significant solar and wind potential [5]. The use of these renewable technologies has the advantage of increasing access to energy services while mitigating the effects of environmental damage.

Building centralized power plants and expanding the electricity grid to reach rural communities has proven to be ineffective and recent studies show a deteriorating situation where population growth is outpacing electrification [6]. Mini-grids and off-grid systems (powered by solar photovoltaic energy systems) are seen as strong contenders to help solve this problem [7]. In Africa, these small scale off-grid systems have an installed cost ranging between 1.9 - 5.9 $\$/W$ (for systems >2 kW). For solar home systems in Africa (typically <1 kW) the installed cost ranges between 4 – 16 $\$/W$, but this can be much lower (2.5 – 7 $\$/W$) for systems $1kW < Power \leq 2kW$[8].

A challenge with certain types of renewable energy systems, such as wind and solar PV, is the intermittent nature of their supply caused by their heavy dependence on local weather conditions. This makes is difficult to achieve the necessary flexibility required to match short term supply and demand. This requirement is particularly pronounced in electrical energy systems in which demand and supply need to match at each time point. To balance the supply and demand, energy storage is required; this can either be at a grid or residential level. In most modern PV systems, lithium-ion batteries (LiB) are employed to store energy. These batteries are however, subject to degradation depending on the specific conditions of storage (namely temperature and state of charge), the conditions of cycling (namely depth of discharge and current rate) and the frequency of cycling. Previous techno-economic studies of the economic viability of PV storage [9], [10] chose not to consider battery degradation in their analysis. In addition, the reason for this exclusion are not always fully defined within the related publications and therefore a full analysis of their motivations is not possible. This is despite a report by the International Renewable Energy Agency (IRENA) showing that battery costs accounted for 14-69% of total installed costs of PV energy systems in Africa [8].

In this work therefore, we address the economic viability of solar home systems (SHS) in Sub-Sharan Africa from an energy storage degradation perspective. For this, we employ a comprehensive battery degradation model based on long-term ageing data collected from more than fifty long-term degradation experiments on commercially available lithium ion batteries. This comprehensive model accounts for all established modes of degradation including calendar age, capacity throughput, temperature (T), state of charge (SoC), depth of discharge (DoD) and current (I). The model was validated using a highly transient real-world usage cycle with environmental conditions corresponding to Dallol, Ethiopia. Employing this model, the viability of storing energy using lithium ion batteries is studied using typical domestic electricity loads for households in rural off-grid farming villages in Zimbabwe and Uganda. Electricity usage data was taken from previous studies. Estimates for PV energy production was made using the Solar Radiation Algorithm developed by Reda and Andreas [11] and the National Renewable Energy Laboratory's (NREL's) PVWatts® calculator [12]. Using the validated battery degradation model and model estimated annual power profiles, a comparison of economic feasibility is made.

2. Electricity demand and PV generation in Zimbabwe and Uganda

The SHS market in Africa has seen rapid growth in recent years, but installations are small (smaller than 100 Watt on average) and typically require battery storage with charge controllers which can carry a significant portion of the project cost [8]. These small solar home systems have an average battery cost of around USD 2 $per\ Amp-hour$ when considering storage capacity of 20 – 220 $Amp-hours$ [8]. The addition of a charge controller can be around USD 6.8 $per\ Watt$, but this is also dependent on the size of the installation [8].

Electrification projects in rural Sub-Saharan Africa are typically very expensive which is why it is important to have a good understanding of the design parameters when planning for such projects [8]. One such focus point is the electricity demand profile [13]. Getting an accurate estimation of demand profiles can be very challenging for several reasons, foremost, due to the difficulty in predicting how new users will use electricity that many of them have never had access to before [13]. This matter is further complicated when the adaption and evolution of electricity usage by new customers is considered. Previous research has shown that as new consumers adapt to the availability of electricity, they begin adding additional loads, often overloading the system [6], [13], [14].