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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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Keywords: Type your keywords here, separated by semicolons ;

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].

Two components make up the total energy throughput profile: the load profile which is the daily electricity consumption and the generation profile which is the daily PV generation; these are characterised by the amount of energy generated/consumed and time of use. Figure 1 shows load profiles for rural African villages which are remarkably similar in shape to many other village studies [13]. The electricity demand profiles shown in Figure 1 are based on data collected by Tinarwo [15] and Sprei [16] for Bulawayo in Zimbabwe and Najjeera village in Uganda, respectively. Both Tinarwo [15] and Sprei [16] collected data at timescales of less than half-an-hour; however, because the data points were not linearly spaced, half-hourly demand profiles were estimated by fitting 4th order polynomials between each data point and then extracting the value corresponding to 30 minute intervals. Similar consumption patterns can be found for many rural African villages that are agriculture oriented with little activity in the home during the day. While this is certainly not the case for all these villages (some communities might acquire electrically powered equipment used during the day, like water pumps) it is a very common occurrence.

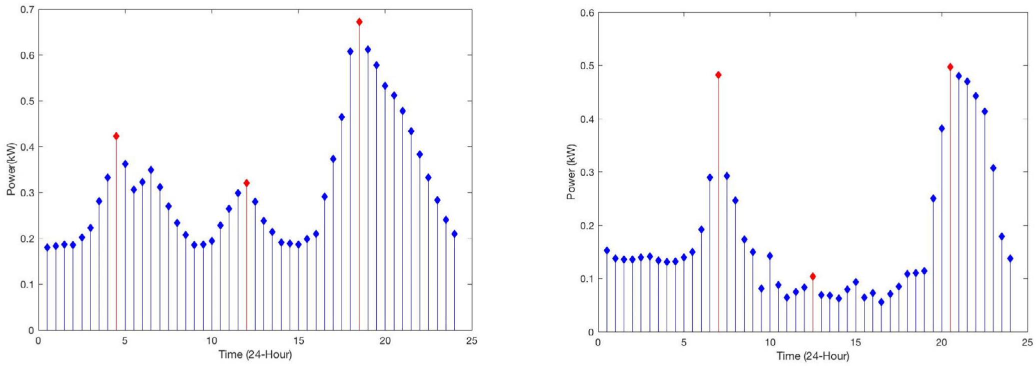

Figure 1: Showing half-hourly electricity demand for a household in a rural farming village in Bulawayo, Zimbabwe (left hand panel) and Najjeera village in Uganda (right hand panel).

PV generation is governed by the Global Horizontal Irradiation (GHI). The Global Horizontal Radiation, also referred to as total solar radiation, is the sum of Direct Normal Irradiance (DNI) and the Diffuse Horizontal Irradiance (DHI), and ground-reflected radiation; however, because ground reflected radiation is usually insignificant compared to direct and diffuse, for all practical purposes global radiation is taken to be the sum of direct and diffuse radiation only:

$$GHI = DNI \times \cos(\theta) + DHI \quad (1)$$

where θ is the solar zenith angle. PV generation is governed by the GHI which means that there are several factors such as tracking, shading and the efficiency and performance characteristics (among other things) that influence the electrical output. For more details of estimating power from the solar radiation, readers are directed to Ref. [17], where further information is provided. In this work, the efficiency of PV cells is assumed to be 14%, which is typical for commercially mass produced cells [18]. The inclination angle of the PV panels is assumed to be that which maximises energy generation. Furthermore, a 3 kW system is assumed. DNI and DHI data for Bulawayo in Zimbabwe and Najjeera village in Uganda is gathered from Meteonorm [19]. The National Renewable Energy Laboratory's (NREL's) Solar Positioning Algorithm for Solar Radiation [11] and PVWatts® calculator [12] was then used to estimate the electrical energy generated.

The solar load profile is agglomerated with the consumption profile presented in Figure 1 to estimate a total daily load profile for the entire year, shown in Figure 2.

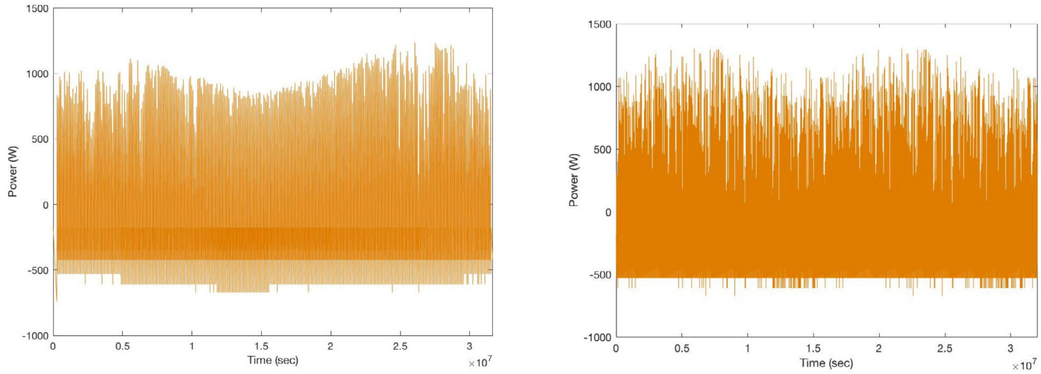

Figure 2: Yearly demand profile for a single rural household in Zimbabwe (left hand panel) and Uganda (right hand panel). A negative power indicates discharge while positive power indicates PV charging.

3. Analysis of Lithium Ion Battery Degradation

Considering the electricity usage data presented in Section 2, a 3 kWh system is required to meet the electricity demands for a rural Sub-Saharan home. Although this is in the upper boundary of existing PV systems in Africa, 3 kWh is consistent with commercially available PV systems such as Tesla's Powerwall system or Moixa's Maslow system [20]. In this work, we assume a 125 Ah battery pack with a nominal voltage of 24 V. Assuming a cost of USD 2 per Ah, the total replacement cost of the PV battery system is assumed to be \$250 (USD).

The Lithium Ion battery degradation model used in this work is based on an Equivalent Circuit Model (ECM) approach presented in Ref. [21]. The ECM parameters are parametrised for calendar ageing and capacity throughput over various temperatures (T), states of charge (SoC), depths of discharge (DoD) and currents (I) using data collected for commercially available 3 Ah $LiNiCoAlO_2/C_6$ cells over 500 days of storage and cycling. The battery ageing model is validated with a highly dynamic annual usage cycle, akin to an automotive battery connected to the electricity grid. Such a highly dynamic usage cycle was chosen for validation because under these circumstances, the battery model is operating at its boundary. In addition, the ambient conditions chosen for the validation cycle corresponds to Dallol, Ethiopia, an urban environment with the highest ambient temperature in the world. This condition was chosen because elevated temperature is expected to lead to the most aggressive degradation of the battery. The validation results are summarised in Table 1. Details of the battery ageing model will feature in a forthcoming publication.

Table 1: Capacity fade and resistance rise validation results for the ageing model after 1 year of cycling. Note, the errors are calculated using discrepancies in absolute capacity and resistance values and not change in capacity and resistance values.

	Initial	**67Ah**	**128Ah**	**189Ah**	**250Ah**
Capacity loss measured (Ah)	0	0.273	0.317	0.33	0.347
Capacity loss estimated (Ah)	0	0.206	0.267	0.306	0.339
Error in total capacity estimate (%)	**0**	**2.05**	**1.51**	**0.72**	**0.24**
Resistance rise estimated ($m\Omega$)	0	8.75	11.84	13.84	15.2
Resistance rise measured ($m\Omega$)	0	7.76	11.38	13.38	14.23
Error in total resistance estimate (%)	**0**	**2.21**	**0.96**	**0.92**	**1.89**

Applying the annual load profile shown in Figure 2 to the battery degradation model developed by the authors, capacity fade (CF) and power fade (PF) was estimated, where CF and PF are defined as

$$CF = 1 - \frac{Q - \mu_{CF} Q_{rated}}{Q_{rated} - \mu_{CF} Q_{rated}} \quad (2)$$

$$PF = \frac{1}{\mu_{PF} - 1}\left(\frac{R_0 + R_{CT}}{R_0(0) + R_{CT}(0)} - 1\right) \quad (3)$$

where Q is the 1C discharge capacity of the cell, Q_{rated} is the manufacturer's rated cell capacity, R_0 is the cells internal resistance and R_{CT} is the charge resistance (the sum $R_0 + R_{CT}$ is the total cell resistance), μ_{CF} is the factor of the cells rated capacity at which point the battery is considered deficient (taken to be 0 for this work) and μ_{PF} is the factor of the cells total resistance at which point the battery is considered not fit for purpose (take to be 2 in this work, although this is arbitrary for SHS applications).

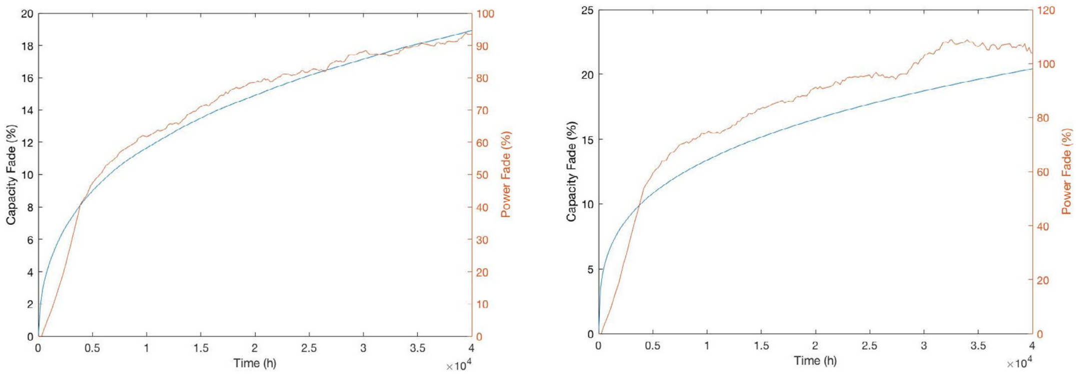

Figure 3: Showing capacity fade (blue) and power fade (red) for 4.55 years of cycling under a typical residential load in Zimbabwe (left hand panel) and Uganda (right hand panel)

After 4.5 years of cycling, CF and PF is 18.9% and 93.8% for Zimbabwe and 20.4% and 104% for Uganda. An impedance rise of 100% means that the impedance has double from the beginning of life. These values of CF and PF equates to a loss of \$47.25 and \$51 for Zimbabwe and Uganda, respectively. The marginally larger degradation observed for Uganda is attributed to its higher energy throughout (3.8 MWh annually compared to 3.3 MWh annually for Bulawayo in Zimbabwe) and higher ambient temperature (see Table 2) which is knows to degrade the battery through the growth of the Solid Electrolyte Interface (SEI) at the negative electrode/electrolyte boundary. The growth of SEI irreversibly consumes lithium leading to capacity fade and impedes the intercalation of lithium into the host electrode leading to power fade [22].

Table 2: Average annual temperature for Bulawayo in Zimbabwe and Najjeera village in Uganda

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bulawayo, Zimbabwe	21	21	20	19	16	14	13	16	19	21	22	21
Najjeera, Uganda	22	23	22	22	22	21	21	21	21	21	21	21

Given that the residential homes considered in this paper have little or no access to electricity, the addition of PV-battery systems will lead to social benefits. Battery degradation over 5 years was found to be important over 5 years; although a degradation cost of \$50 is estimated (based on ambitious battery replacement cost estimates), the impact of >20% CF will be noticeable. An important question around the added benefit of electricity storage compared with direct PV energy usage needs to be explored in more detail. This will form a part of further work.

4. Conclusion

Solar Home Systems which employ lithium ion-batteries can meet the electricity requirements for rural homes is Sub-Sharan Africa. The cost of Lithium Ion battery degradation is arguably small when considering the benefit of electricity accessibility. Although the cost of battery degradation is not preventive to the deployment of PV systems in rural Sub-Saharan Africa, the initial investment of $7k-$21k for installing such PV systems can be a barrier. This work is an initial investigation, further work will consider the degradation of PV cells and the impact of electricity access of rural communities in Sub-Saharan Africa.

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References

[1] I. Energy Agency, "World Energy Outlook 2016," 2016.
[2] G. Legros, I. Havet, N. Bruce, and S. Bonjour, "United Nations Development Programme THE ENERGY ACCESS SITUATION IN DEVELOPING COUNTRIES A Review Focusing on the Least Developed Countries and Sub-Saharan Africa," New York, 2009.
[3] I. E. Agency, "The Impact of Higher Oil Prices on the Economy," Paris, 2004.
[4] M. S. Kahsai, C. Nondo, P. V. Schaeffer, and T. G. Gebremedhin, "Income level and the energy consumption–GDP nexus: Evidence from Sub-Saharan Africa," *Energy Econ.*, vol. 34, no. 3, pp. 739–746, 2012.
[5] S. Karekezi and T. Ranja, *Renewable energy technologies in Africa.* London: Zed Books, 1997.
[6] V. B. Amatya, "Poor peoples' energy outlook," 2012.
[7] S. Brandt and P. Media, "A FOCUS ON ENERGY PROSPECTS IN SUB-SAHARAN AFRICA," 2014.
[8] International Renewable Energy Agency, "SOLAR PV IN AFRICA: COSTS AND MARKETS," 2016.
[9] S. M. Shaahid and I. El-Amin, "Techno-economic evaluation of off-grid hybrid photovoltaic–diesel–battery power systems for rural electrification in Saudi Arabia—A way forward for sustainable development," *Renew. Sustain. Energy Rev.*, vol. 13, no. 3, pp. 625–633, 2009.
[10] A. Chaurey and T. C. Kandpal, "A techno-economic comparison of rural electrification based on solar home systems and PV microgrids," *Energy Policy*, vol. 38, no. 6, pp. 3118–3129, 2010.
[11] I. Reda and A. Andreas, "Solar Position Algorithm for Solar Radiation Applications (Revised)," 2000.
[12] NREL, "PVWatts Calculator." [Online]. Available: http://pvwatts.nrel.gov/. [Accessed: 21-Feb-2017].
[13] G. Prinsloo, R. Dobson, and A. Brent, "Journal of Energy in Southern Africa.," *J. Energy South. Africa*, vol. 27, no. 3, pp. 11–27, 2016.
[14] A. C. Brent and W. J. L. Kruger, "Systems analyses and the sustainable transfer of renewable energy technologies: A focus on remote areas of Africa," *Renew. Energy*, vol. 34, no. 7, pp. 1774–1781, Jul. 2009.
[15] D. Tinarwo, "Design of Village Power and Micro-Grids for Rural Areas of Zimbabwe with Specific Attention to Voltage Regulation on Low Voltage Meshed Distribution Grids," University of Kassel, 2008.
[16] F. Sprei, "Characterization of power system loads in rural Uganda," 2002.
[17] S. A. Kalogirou, *Solar energy engineering : processand systems*. .
[18] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, "Solar cell efficiency tables (Version 45)," *Prog. Photovoltaics Res. Appl.*, vol. 23, no. 1, pp. 1–9, Jan. 2015.
[19] "Meteonorm: Irradiation data for every place on Earth." [Online]. Available: http://www.meteonorm.com/. [Accessed: 28-Mar-2017].
[20] L. Greene, S. Dunlop, and P. Barwell, "Solar Trade Association Position Paper on Energy Storage," 2016.
[21] K. Uddin, A. Picarelli, C. Lyness, N. Taylor, and J. Marco, "An acausal Li-ion battery pack model for automotive applications," *Energies*, vol. 7, no. 9, pp. 5675–5700, 2014.
[22] K. Uddin, S. Perera, W. Widanage, L. Somerville, and J. Marco, "Characterising Lithium-Ion Battery Degradation through the Identification and Tracking of Electrochemical Battery Model Parameters," *Batteries*, vol. 2, no. 2. Multidisciplinary Digital Publishing Institute, p. 13, 26-Apr-2016.