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Re-mapping sub-Sahara Africa for equipment selection to photo electrify energy poor homes

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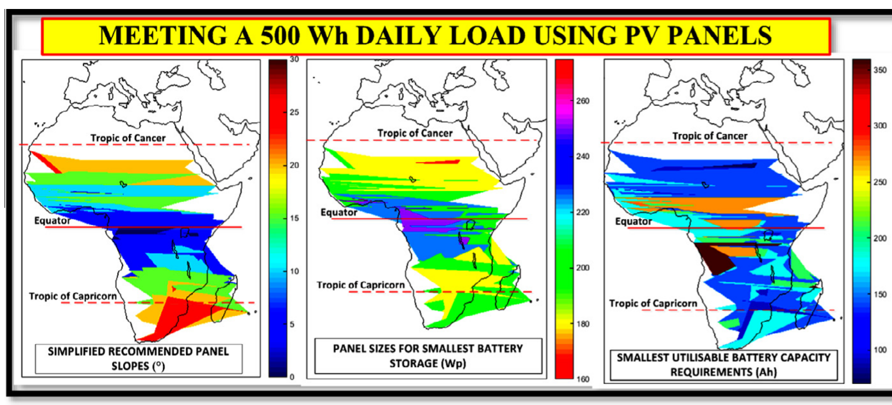
HIGHLIGHTS

- We estimate daily electrical energy requirements for start-up rural homes at 500 W h.
- We model PV panel and BOS components selection for optimisation to meet the load.
- We solve the model at 152 stations in sub-Sahara Africa and map the solutions.
- Optimal panel selections range between 160 and 275 Wp.
- Battery capacities range between 70 and 360 A h while 15 A charge controllers dominate.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper provides a missing integrated guide to budding middle class rural sub-Saharan Africa (SSA) homesteads trying to photo-electrify. It first estimates bare minimum requirements for these homes to start emerging from energy poverty. Guidance is given on optimal selection of the most important device for such homes: the light bulb. Along with other essential devices, this gives a daily electrical load of 500 W h, 42 A h at 12 V DC. Building on earlier experimental work on validating TRNSYS in Cape Town, it extends usage of the software to the rest of SSA, aiming to recommend panel and balance of system component sizes to meet the above load all year round. Use is made of panel slopes derived in a related piece of work to formulate an optimisation model for selecting panel–battery–charge controller combinations. A survey of South Africa-made panels and components is done. Then, a method of solving the model is demonstrated by an example in Uganda which selects from the surveyed components to satisfy two alternative technical objectives of 'least battery storage' and 'smallest panel size'. At each of the other 151 stations in SSA, the model is solved only for the first objective. The overall results are then mapped using MATLAB®. It is concluded that from a 'smallest battery storage' perspective, usable battery storage capacities in the region range between 70 and 360 A h, with the biggest being in equatorial/tropical rain forest areas of Congo basin and along the mid-western coastal areas. Panel sizes range between 160 and 275 Wp. The dominant recommendation on charge controllers is 15 A.

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1. Introduction

Tropical Africa's electric grid supply is miniscule not only by world standards but by those of the rest of the continent as well. For example, the 2014 International Energy Agency (IEA) report says that 620 Million tropical Africans have no access to electricity. This makes about half of the world's energy poor population [1] and is about 71% of the region's population [2]. Yet %ages for temperate Northern and Southern Africa are 1 and 14 respectively [1,3]. Many researchers and energy practitioners have pointed to self-generation using photovoltaic (PV) panels as a possible approach to enable homesteads access electricity [4–9]. The authors have also argued for this approach in the past on grounds of costs, health and safety, ease and speed of rollout among others [10,11]. Whereas these – and many more – works recommend photo electrification, and while the practice is taking root in some of the region's countries [12–15], there is as yet, limited recorded in depth research – based guidance on selection of equipment for the region. The paper therefore begins with a brief review of recent literature on work that comes closest to guiding these selections.

1.1. Economic viability

From within Africa, literature on photo-electrification in general is quite limited. That on system optimisation is even scarcer. In 2006 for example, Moner-Girona et al. [16] reported that not much was "very well-known" about the status of solar home systems (SHS) in sub-Sahara Africa. They did a review and found a necessity for local manufacture of the systems in the region. But in 2007, Wamukonya [17] reviewed the effectiveness of the systems as an option in helping develop Africa. She concluded that the option was unviable on account of costs. Ondraczek [18] pointed to the fact that most governments in Africa still regarded PV electricity as expensive. They reserved its usage for isolated rural installations. This was partly responsible for slow take up of SHS. But in another article, he cited the exception of Kenya [19] where a SHS market had developed fast and PV energy prices were beginning to be competitive by 2011. In that year, the grid supply cost reached US$ 0.21 per kW h. A year later, Rose et al. [20] confirmed that the economic value of PV electricity was higher than the total cost of acquisition and operation in the same country.

In 2009, Breyer et al. [21] did an economic analysis of small off grid PV systems in Ethiopia. The systems had been aligned to the basic needs of lighting, communication and entertainment. Even without a rigorous optimisation procedure, they determined a payback period of between 2 and 4 years for homesteads, depending on the energy demand by the homes (the larger the demand, the shorter the payback period). A few years later, Bazilian et al. [22] discussed the economics of PV electricity with intention of demystifying the costs to policy makers, investors and financiers. For example, they cited a 2012 US$ 0.85 per Wp rating for poly crystalline silicon panels from China as an example of how the prices were falling. Clearly, these and other works go to show that the economic viability of SHS in the region is now less debatable. What may not be quite clear however, are the technical details. Their literature is briefly surveyed next.

1.2. Technical gaps in optimisation for the region

Udoakah and Umoren [23] investigated monthly optimal tilts of PV panels at two cities in Southern Nigeria at latitudes 4.95°N and 5.64°N. They found that for 6 summer months, a zero slope was preferred. Adjustments were necessary each winter month. In the bigger system optimisation picture, these findings tackled only one part of the problem: how to maximise semi fixed panel energy yields at these locations. Excluded were issues of load optimisation, equipment selection and installation, and how the rest of the country and continent could make easy use of the findings. For example, despite the fact that many PV panels for households emerging from energy poverty are installed on roofs (e.g. see Fig. 1), the feasibility of monthly adjustments was not discussed.

Wansah et al. [24] addressed the load issue in remote places by studying performance of a stand-alone system in Eastern Nigeria. The system provided 3.3 kW h daily to a remote household. The load included a 21″ plasma TV, a satellite dish, and a refrigerator among other items. Itodo and Aju [25] studied a commercial application in which a 750 W rice thresher was powered by a PV system for 2 h a day. This required a string of 3 modules of 260 Wp, 4 series-connected 100 A h–12 V batteries, a 15 A charge controller and an inverter. From the loads handled by these two studies, it is clear that it was not the energy-poor's needs which were being addressed. And whereas, the studies demonstrated performance of the selected system components, they did not tell us whether the selections were optimised – and if so, how. Thus, the question of optimisation modelling for the poor still persists. And unfortunately, energy research work involving optimisation in less energy poor societies seems to be preoccupied with other issues now. We illustrate these with a few examples.

1.3. More electricity – different problems

At 85.4%, South Africa has the highest population access rate to electricity in SSA [26]. The focus now seems to be more on optimising energy resources usage for income generating activities and on carbon footprint reduction. Azimoh et al. [27] describe a mini grid approach to provide 300 remote households with an average 2.4 kW h per day each. They find that SHS as served by PV panels cannot optimally supply this load. Hence, they conclude that the system would work better where there is local small hydroelectric potential. In urban South Africa, the issue of consumer willingness to pay for green energy arises. Chan et al. [28] investigated it and found that willingness to pay depended on geography. It could not be generalised. In none of these two studies are the needs of the 14.6% energy poor South Africans addressed.

Outside SSA, documented work still focuses on the not so energy poor households. Not least, the reason being that there are very few energy poor people in most of the countries. Emphasis – like in South Africa – is on reducing the carbon footprint. In Argentina with 99.8% electrification, Reinoso et al. [29] evaluated energy costs of a 10 MWp PV power plant at the foothills of the Andes. In Mexico, with 99.1% electrification, Vidal-Amaro et al. [30] gave an optimisation model for a renewable energy-fossil fuel energy mix for the country. In Hong Kong, Ma et al. [31] optimised a solar PV-wind-water turbine/pump hybrid micro grid system to improve energy source reliability for remote communities. Their work addressed the problem of maintaining electricity supply reliability at close to 100%. On the other hand, the problem in most of SSA is to have this reliability take off from 0%.

In the UK, Rogers et al. [32] investigated, and demonstrated the feasibility of reducing home carbon emissions to 20% of a 1990 "typical house". That UK "typical house" is totally different from SSA's. The energy needs are different. In SSA, lighting needs dominate – as space heating in most of tropical Africa is not an issue. Perhaps the work elsewhere closer to what is addressed in this paper is that by Olcan [33] in Turkey. He optimised sizing of a PV powered water pumping system for irrigation. But even then, it is seen that it is not the energy poor's selection problems that are addressed.

In summary therefore, as of now, there is only limited documented guidance on optimal selection of load elements, power