The Potential and challenges of Off-grid Solar Photovoltaics in Resource-Challenged Settings: the case of Sub-Saharan Africa

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Standfirst: Solar PV has huge potential to address current gaps in electricity access for resource-challenged settings, such as Sub-Saharan Africa SSA. However, a rapid surge in installations and future growth will lead to an increase in waste from panels and batteries that needs to be tackled urgently. Innovative technical solutions and improved policies and standards and urgently required to address end-of-life challenges for solar PV in SSA.

[H1] Introduction

Access to sustainable and affordable energy is a driving force for prosperity and well-being with the potential to address all of the 17 Sustainable Development Goals defined by the United Nations[1]. Unfortunately, Sub-Saharan Africa (SSA) has the world's lowest per capita use of modern energy – defined as clean, safe, affordable and reliable electricity and cooking fuel supply - with 590 million people lacking access to electricity[2]. Despite efforts to boost electrification, there has been a decline in access trends in the region due to population growth outpacing gains made in electrification, the pandemic and the inflation and supply chain issues resulting from the pandemic and the Russian invasion of Ukraine [2]. This low access is critical to address as it has been correlated with poor productivity indicators[3;] For example, lack of electricity limits the ability to pump water both for irrigation and drinking purposes and perpetuates the use of fossil fuels such as diesel in generators[3]. Therefore, electrification is key for health, food production, livelihoods and economic wellbeing.

However, extending grid systems to rural settings - which are most affected by poor energy access – is difficult because of distance, challenging terrain and high costs of deployment. Globally, 1.1 billion people will need to be provided with access to electricity through off-grid systems, with nearly half of those users likely to be in SSA[4]. Because SSA has abundant solar resources, solar PV is a viable solution to electrify remote rural households, but this resource has remained largely untapped so far (**Fig. 1a and 1b**).

Prices of solar installations have dropped by around 90% in the last decade thanks to falling prices of panels and batteries, improved efficiencies of units and scale up of production especially in places like China. This solar PV a cost-efficient andviable solution[5] for off-grid electrification. Solar PV and in particular Solar Home Systems (SHS) which are portable in nature and easy to install in households, provide an excellent opportunity to leapfrog remote communities currently bypassed by grid systems to clean energy solutions. SSA has seen a surge in installed solar PV associated with the drop in solar PV prices (**Fig. 1c**). The price of solar PV module decreased by 88% from 2.15 to 0,27 $/W, while the cumulative Installed capacity in SSA increased from 22 MW to 8854 MW (Fig.1c.). However, this growth is also associated with environmental challenges and finding solutions to recycle, reuse and repair SHSs in SSA will be crucial to protect the environment during this period of rapid expansion[6]. Typically panels have 30 year life span and batteries range between 10 to 15 so the installations over a decade ago will be approaching end of life in the next few years especially with regards to batteries. Hence end of life solutions will need to be rapidly scaled up to meet both an increasing demand from existinging installations and future demand from the anticipated surge in installations. In particular given the shorter life span of batteries this is an area that needs rapid action.

Figure 1: a| Solar power potential (Source: Global Solar Atlas, World Bank, ESMAP and SolarGIS, https://globalsolaratlas.info/map?c=16.467695,-25.664063,2&s=16.017937,-22.851563&m=site). **b|** Share of electricity production from solar, https://ourworldindata.org/grapher/share-electricity-solar. **c|** Global average PV module price and installed capacity in SSA. Data source: PV module prices are from Nemet (2009)[7]; Farmer & Lafond (2016)[8]; International Renewable Energy Agency (IRENA)[9], PV installed capacity is from Climatescope 2022[10]. **d |** The estimated cumulative waste volumes (million t) of end-of-life PV panels in South Africa, Nigeria (left Y-axis) and global (right Y-axis). The data is from Weckend, 2016.[11] The assumed panel lifetime is 30 years. Both scenarios are modelled using the Weibull function with different shape factors, 2.4928 for early loss scenario and 5.3759 for regular-loss scenario[11].

[H1] Challenges for end-of-life management in sub-saharan Africa

The next decade will see a surge in the number of panels reaching end of life, and SSA is expected to be a major contributor to worldwide solar panel waste by 2030 (**Fig. 1d**). As noted in Figure 1d countries such as South Africa have seen a 90% increase in solar installations. Currently SSA imports solar panels and batteries from markets such as China and Germany with non-existent recycling facilities in the region. The recycling of solar panels requires high temperature thermal processing and silicon etching processes to recover aluminium, glass and plastics. These are energy intensive processes for which capabilities need to be grown in SSA. Hence there is an urgent need to accelerate research, innovation and enterprise to support businesses in the region to be able to reuse materials from solar panels.

This situation is exacerbated by the fact that off-grid solar expansion needs to be accompanied by energy storage solutions which is viable if localized manufacturing can be scaled up. Current energy storage options viable at scale are Li-ion batteries (LIB) and lead acid batteries (LAB), with most off-grid providers switching to LIB as their lifetime costs are lower than LAB. Both PV[13] and batteries[14] waste can contaminate soil and water through heavy metals, such as Ag, Cu and Co, and toxic chemicals including $LiPF_6$ and dimethyl carbonate, but both PVs and batteries can be recycled. For example, a typical LIB battery recycling process consists of its collection, shredding into small pieces, separation, recovery of heavy metals and disposal of hazardous materials such as $LiPF_6$ and organic solvent including ethylene carbonate, ethyl methyl carbonate and dimethyl carbonate[12]. However, this process is especially challenging in SSA as the region lacks the industrial infrastructure for the safe handling and disposal of large volumes of waste. In addition, LIBs are more expensive to dispose of safely, as the recycling of LIBs requires proper disassembly of the battery with a combination of physical and chemical processes. In particular, the toxic organic electrolytes used in LIBs should be handled without exposing it to the environment[15]. To the best of our knowledge, LIB recycling facilities are non-existent in SSA. Most of the LAB recycling facilities in SSA are informal where the battery acid is drained in an unregulated manner or smelting is used thereby polluting the environment. There needs to be investment in setting up battery manufacturing and recycling facilities in SSA as currently most batteries are imported and recycling facilities are limited.

[H1] Solutions for end-of-life management for Solar PV in sub-Saharan Africa

These difficulties do not mean that we should stop using solar panels as using solar has huge benefits for climate action and reducing emissions but we need to look into the reduction of material use at the outset and then subsequent recycling facilities at end-of-life. For example, The 2023 Queen Elizabeth Prize for Engineering was awarded for the invention of PERC Solar Photovoltaic Technology, which introduces an additional layer to reflect unused photons into the silicon thereby increasing the efficiency of solar panels with the same surface area. This strategy reduces the amount of material required for panels from the outset, and thus could help in reducing pressure on the limited recycling facilities in SSA. VeraSol is a quality assurance program launched for off-grid products that have recently expanded its scope to include solar home systems. They provide guidance to industry on how to test product quality, certification and technical assistance for governments to implement policies to ensure that end users have access to high quality solar products. This is relevant in the SSA market which gets flooded with poor quality products with reduced life span thereby generating additional waste. So higher quality at at the outset can reduce downstream waste.

Companies like ROSI are applying circular economy principles for end-of-life solar panels and batteries. However, key barriers for the scale up of these solutions include the lack of standardized recycling processes, policy gaps around national and regional standards for waste disposal and reuse and the high cost of recycling. A key intervention required would be to create an enabling environment for local manufacturing, recycling and safe reuse of materials from off-grid solar. The lack of policies on waste disposal and resuse of materials and lack of investment to this end becomes a barrier for local SME's and off-grid solar providers to scale up safe disposal and reuse facilities for solar panels and batteries. The initiatives and solutions set out here provide hope for the solar off-grid sector.

Research on business models to scale up solar and end-of-life solutions would help attain the sustainable development goals and targets for energy, water and climate by increasing resilience to climate-related impacts, and reducing emissions by reducing dependencies on diesel-powered systems. Now is the time to invest in research and innovation, quality assurance and certification, policies and regulations and technologies for recycling, reusing and safely disposing batteries and panels. We need local solutions for SSA with incentives and clear guidines for SME's in the region to deliver on end of life sustainability for off-grid solar. Decent living standards are directly linked to access to electricity so addressing the end-of-life issues for the solar off-grid market is crucial[16].

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Author contributions

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Competing interests

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