AE4H Working Paper:

Areas for Technology Innovation in the East African Off-grid Energy Sector

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Circadian Energy Inc. for Affordable Energy for Humanity

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Executive Summary

This paper aims to provide technology developers with an overview of existing energy access solutions. Alongside this, it highlights areas for future innovation that could reduce overall cost solutions, with the overall goal of achieving impact at a broader geographic scale.

Table 1 summarizes current off-grid energy access solutions, their applications, cost to manufacture, retail price, and challenges faced by companies providing these solutions.

Table 2 summarizes areas for technology innovation discussed in this paper.

Some background on energy access is given for context. Existing energy access solutions are described including a detailed breakdown of their component costs and overview of selected technical and non-technical challenges they face. Finally, some suggestions for areas where technology innovation might be particularly fruitful.

Table 1: Summary of off-grid energy access solutions

Solution	Tiers Served	Typical Applications	Cost to produce	Customer price	Challenges Faced
Pico-solar devices	1	Task and room lighting, phone charging, radio	11 USD[1]	5–20 USD	Market saturation, distribution logistics
Solar home systems	1–2	Multi-room lighting, phone charging, entertainment, air circulation, refrigeration	80 USD[2]	20–80 USD + 5–20 USD/month (1–3 years)	Market saturation, customer acquisition cost, distribution logistics, loan default, foreign exchange risk
Microgrids	2–4	Multi-room lighting, phone charging, entertainment, air circulation, refrigeration, light-industrial applications (carpentry, food-processing)	Varies significantly by project	0.50–2.00 USD/kWh	Uncertain revenue stream, foreign exchange risk, site selection, policy barriers, fluctuating fuel prices

Table 2: Summary of areas for technology innovation

Technology Innovation	Description	Solutions Affected
Productive-use applications	Income-generating appliances. Increases customer revenue and affordability of higher tiers of energy access.	Solar home systems, microgrids
Improved microgrid demand estimation	Reduces project risk, making new projects more attractive investments and leading to their greater penetration.	Microgrids
Controllable loads & demand response	Control energy demand to reduce operating expenses, increase component lifetime and lower capital costs.	Microgrids
Accessible generation and storage technologies	Lower cost energy storage and small-scale alternative renewable generation technologies (e.g. wind and hydro).	Pico-solar devices, solar home systems, microgrids
Efficiency improvements for solar panels	Dust repellent surfaces and low cost, reliable axis tracking improve effective solar module efficiency.	Pico-solar devices, solar home systems, microgrids

[1] Median for a solar lantern (3 Wp PV panel, 14 Wh battery, and 75 lm LED)

[2] Median for a small system (35 Wp PV panel, 136 Wh battery, and 500 lm LED)

1 Introduction

Electricity access is a necessity of the 21st century; it is a cornerstone of economic and social growth. In remote and unconnected parts of the world, access to even the smallest amount of electricity can have dramatic effects on quality of life. Here, access to electricity is not a simple matter of convenience, but a gateway to dramatic improvements in health, education and economic prosperity.

Providing electricity access is a complex problem due to factors such as the immense cost of centralized infrastructure, low household income, slow pace of electricity adoption, and small communities separated by large distances and/or harsh terrain. While the cost of renewable energy technologies is falling, the many other barriers facing organizations seeking to provide energy access to unconnected communities mean that cost reduction is still of paramount importance.

This paper aims to provide technology developers with an overview of existing energy access solutions and highlight areas for future innovation that could reduce overall cost of these solutions significantly, therefore leading to their potentially greater penetration. Some background on energy access is given for context. Existing energy access solutions are described including a detailed breakdown of their component costs as well as some technical and non-technical challenges they face. Finally, some suggestions for areas for impactful technology innovation are made.

2 Background

This section aims to provide context for the off-grid energy sector. The data in this paper is specific to the East African context, especially Kenya and Tanzania. However, many of the insights and problems discussed here can be extrapolated to other remote and developing regions of the world.

2.1 Energy Access Tiers

The Energy Sector Management Assistance Program (ESMAP) created a comprehensive tier system to formalize energy access [1] which has become standard in the off-grid energy sector. Most energy access solutions can be described in terms of this framework. There are six tiers ranging from Tier 0 (no access) to Tier 5 (full access). Access is measured with respect to seven attributes: capacity, duration, reliability, quality, affordability, legality, and health and safety. Table 3 shows a simplified version of the matrix used to evaluate household electricity supply.

2.2 The Importance of Cost Reduction

Cost reductions of any amount are of paramount importance in increasing the penetration of off-grid energy systems. The Rocky Mountain Institute estimates the value of the potential off-grid energy market in four sub-Saharan countries (Senegal, Kenya, Tanzania, and Uganda) at 750 million USD in annual revenue, and that reducing costs by 50% doubles the market size to 1.5 billion USD [2].

Table 3: Simplified Multi-tier Matrix for Access to Household Electricity Supply (Capacity & Duration)

		Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Capacity	**Power**	Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
	OR Services	Lighting of 1000 lmhrs per day and phone charging	Electrical lighting, air circulation, television, and phone charging are possible			
Duration (Minimum)	**Per day**	4 hrs	4 hrs	8 hrs	16 hrs	23 hrs
	Per evening	1 hr	2 hrs	3 hrs	Min 4 hrs	4 hrs

3 Current Solutions

This section provides more detail on current energy access solutions, their cost and the cost of their components, and technical challenges they face.

Depending on geographical location, targeted energy access tier, and solution, the Levelized Cost of Electricity (LCoE) can vary greatly [3]. While extensive research has been conducted to choose the most cost-effective energy access solution, this paper simply aims to provide an overview of the existing solutions and the circumstances in which they are normally employed.

Customers choose a solution primarily based on the following priorities [4, 5]:

1. Durability (reliability)
2. Price (affordability)
3. Light intensity/capacity[3]

Therefore, these criteria should be taken into consideration in the design of any device destined for the off-grid energy market.

3.1 Standalone Solutions

Many companies have adopted a bottom-up approach to electrification, providing standalone solutions to individuals or individual households. This approach allows these companies to expand more quickly than those providing solutions that require infrastructure to be built. Collectively, these companies have provided electricity access to millions of people. In H1 2018 alone, 3.66 million off-grid solar products were sold by affiliates of the Global Off-Grid Lighting Association (GOGLA) [6]. These standalone solutions can be divided into two major categories: pico-solar devices and solar home systems.

3.1.1 Pico-solar Devices

Pico-solar devices are extremely rugged, portable devices providing Tier 1 energy access. They are purchased outright at a price between 5–20 USD [6, 7]. Solar lanterns, phone chargers and radios are the most common devices in this category. Solar lanterns have displaced kerosene lamps in many regions, providing cost savings and health benefits. These devices are the best selling by volume, however sales of higher power devices such as solar home systems are expected to dominate in the future [4].

Technical Description

These devices are very simple. They are comprised of a small photovoltaic panel (0.1–10 Wp), a battery, a charge controller, and some output (LED array, USB phone charger, etc.).

Monocrystalline and polycrystalline photovoltaic panels are used. Monocrystalline cells offer better efficiency and a smaller form factor at a higher cost compared to polycrystalline cells. Most pico-solar devices use lithium-ion batteries due to their high energy density.

Cost Breakdown

The median cost of producing a typical solar lantern (3 Wp PV panel, 14 Wh battery, and 75 lm LED) is around 11 USD. Figure 1 shows the decomposition and forecast of solar lantern component costs. While components costs are expected to fall, increasing labour costs will prevent the total cost of these devices from falling as drastically as the cost of their components [4].

[3] Although this is specific to products providing lighting, it indicates that customers value what energy access allows them to do, not energy itself.

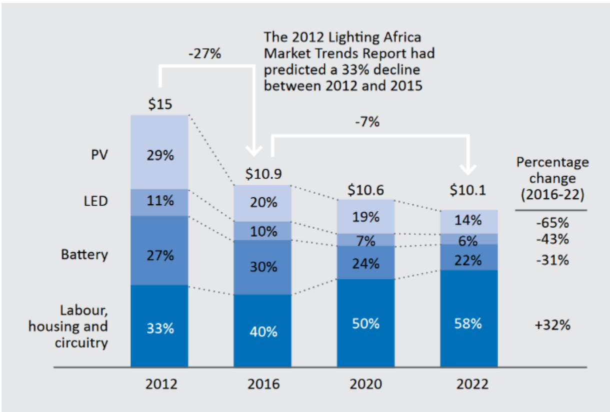

Figure 1: Decomposition and forecast of solar lantern component cost [4]

Challenges Faced

Lack of product differentiation and lack of customer loyalty makes it difficult for any company to dominate in the crowded pico-solar device market. Some pico-solar device companies offer entry-level solar home systems in an attempt to retain their customers as their energy demand grows (as they climb the "energy ladder").

Pico-solar device companies also face the logistical challenges of building robust distribution channels in rural and remote areas.

3.1.2 Solar Home Systems

Solar home systems are off-grid PV panel and battery systems that provide a single household or business with Tier 1 and 2 energy access. They provide multi-room lighting, phone charging and are often packaged with super-efficient DC appliances such as televisions, radios, and fans.

One of the most impactful innovations in the standalone solution space was the introduction of pay-as-you-go, or "PAYG" financing, to these products. This leasing model allowed customers with very little upfront capital and an uncertain revenue stream to finance the purchase of a solar home system over several years. Lease payments can also serve as the foundation of a credit history for these customers. This model is facilitated by prevalent mobile phone-based payment systems (for example, M-PESA). A PAYG customer pays for their lease by adding credit to their account using mobile payments. The solar home system can be remotely deactivated if a customer fails to make payments. Lease terms range from 1–3 years with deposits of 20–80 USD and monthly payments of 5–20 USD depending on system size.

Technical Description

Solar home systems are made up of a photovoltaic panel (10–200 Wp), a battery, charge controller and additional power electronics. Most feature cellular antennas used for remote monitoring/control and mobile payments. Figure 2 shows an excerpt from a patent for a solar home system with pay-as-you-go technology.

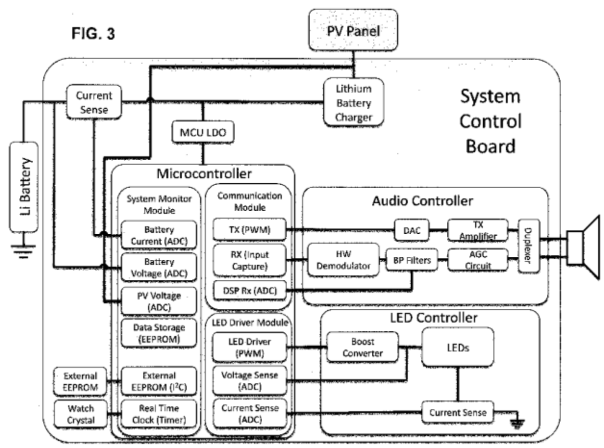

Figure 2: Solar home system block diagram [8]

Mostly polycrystalline photovoltaic panels are used. Both lead-acid and lithium-ion batteries are used in solar home systems. Lithium-ion batteries offer a longer lifetime than their lead-acid counterparts, however they have a higher upfront cost. Some literature indicates that systems using lithium-ion batteries have a lower Levelized Cost of Electricity (LCoE) than those using lead-acid batteries [9]. The falling cost of lithium-ion batteries also makes them an attractive choice. However, lead-acid batteries are more readily available in the market and local recycling facilities exist [10].

Cost Breakdown

The median cost of a small solar home system (35 Wp PV panel, 136 Wh battery, and 500 lm LED) is around 80 USD. Figure 3 shows the decomposition and forecast of the component costs of both systems. The total cost of these systems is predicted to continue to fall.

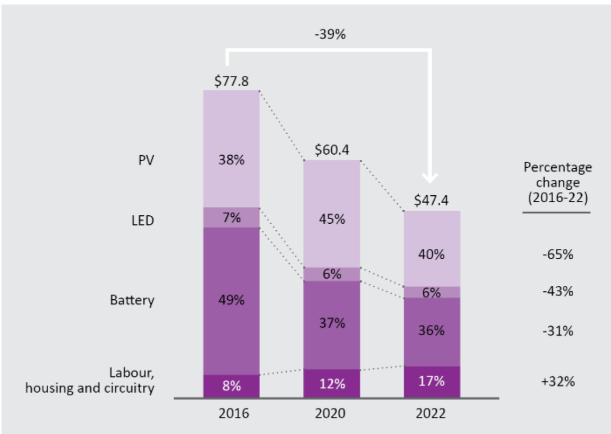

Figure 3: Decomposition and forecast of small solar home system component cost [4]

Challenges Faced

In addition to the same challenges faced by companies selling pico-solar devices, companies providing solar home systems struggle with very high customer acquisition cost (quoted as high as 40 USD per customer in interviews with salespeople), relatively low revenue per customer, and risks associated with the PAYG model (such as loan default, fluctuating exchange rates, mobile payment transaction costs). In addition to the logistical challenge of distributing their products, these companies often offer warranties and repair services, which bring additional risk and challenges.

From a technical perspective, solar home systems use generation and storage assets less efficiently than microgrids because they cannot benefit from load aggregation. For example, one study showed that 30% less PV capacity was required to supply the demand of a village of 50 households with a microgrid compared to solar home systems [11]. However, the most cost-efficient energy access solution for a given site depends on many factors including population density, community energy demand, local component and resource availability etc. [3].

3.2 Microgrids

Microgrids (the term 'minigrid' is often used interchangeably) are electricity networks that use some form of local generation to provide energy access to an immediate area. They can operate while connected to the centralized grid or independently. They offer a cost-efficient solution for providing higher tiers of energy access to densely populated areas [3] owing to economies of scale and improved asset utilization due to demand diversity. Microgrids typically provide Tier 2 to 3 access (but can provide up to Tier 4 access) to anywhere from 20 to more than 100 customers [12]. In addition to lighting, phone charging and small appliances such as televisions, microgrids have capacity to support applications with high power requirements, such as carpentry, tailoring, food-processing (milling of grains, freezing) etc.

Modern microgrids often use smart meters, which allow operators to remotely monitor and control energy consumption at the customer level. Many operators employ a pay-as-you-go model where customers add credit to their meters using mobile payments. Smart meters allow microgrid operators access to a variety of tariff structures, such as quantity-of-use, capacity-based, time-of-use, and customer-type based structures [13]. The price of energy on a microgrid is usually much higher than on the national grid but service can be more reliable. Due to varying tariff structures the actual price per kWh can vary significantly: tariffs for productive-use applications range from 0.50 USD/kWh to almost 2.00 USD/kWh (median of 0.90 USD/kWh) [14].

3.2.1 Technical Description

Many microgrids use primarily solar generation, which can be supplemented by diesel generation to meet peak loads. Solar only, diesel only, and hydro-electric microgrids exist. Due to the intermittent nature of renewable energy technologies some sort of energy storage is almost always present in these microgrids. Deep-cycle lead-acid batteries are most common, but lithium-ion batteries are also used. Some research exists on hybrid systems as well – energy storage systems combining multiple energy storage media [15] – but these are uncommon in practice.

Distribution networks can be AC, DC or a combination of the two. For example, distribution at the household level can be DC while distribution over longer distances is AC. Above ground distribution networks are common because new customers can be added to the network easily. Buried networks are also possible depending on local policies.

Generation, storage, central controller and power electronics such as charge controllers, inverters (for AC microgrids), breakers and protection circuitry are installed in a single location. This makes maintenance easier. If present, interconnection with the national grid is handled here as well. Smart meters are wirelessly connected to the central controller and to the cloud to enable remote monitoring and control.

3.2.2 Cost Breakdown

The cost of a microgrid is heavily dependent on the type of load it will serve. Most microgrids are tailored to a given community. As the generation and storage requirements vary significantly between installations, a cost breakdown in terms of the total cost is not meaningful. However, a cost breakdown per component can be given. While initial component costs can be quite low, a variety of factors can drive final installed costs up. These are logistical challenges such as the availability of components in a given region, and the price for labour charged by contractors. Table 4 shows the decomposition of microgrid component installed costs.

Table 4: Decomposition of microgrid component installed costs [2, 13, 16]

Component	Lifetime [years]	Installed cost [USD/unit]	unit
PV generation & structure	20	1.30–3.00	Wp
Charge controller	20	0.20–0.40	W
Inverter	10	0.2–1.00	W
Storage (deep-cycle lead-acid batteries)	7[4]	0.15–0.50	Wh
Diesel generation	10[4]	0.40–1.00	W
Diesel fuel	-	1.00–1.30	l
Distribution network	-	2.00–5.50	m
Smart meters	10	30.00–40.00	meter
Power house & civil costs	-	0.40–0.60	W

3.2.3 Challenges Faced

Microgrid suffer from long payback periods (often exceeding 5 years [13]) due to high upfront cost and low energy demand. Furthermore, uncertain demand and uncertain demand growth introduce additional risk to new projects.

Some of this uncertainty can be mitigated in the sizing and financing structure of the project [17]. Nevertheless, microgrid developers prefer sites with more certain electricity demand. Sites with "anchor customers", such as a cell-phone tower or light industry, fall into this category. They provide a well-defined load and constant revenue stream. Communities with high population density and established electricity demand (for example, communities where solar home systems are already common) also make attractive targets. Unfortunately, these sites are also targeted for national grid expansion projects. Microgrids are

[4] Depending on system design and community demand, the lifetime of some components can vary significantly.

unable to compete with the price of energy offered by the national grid.

Another approach to mitigate risk associated with uncertain demand is to focus on building scalable systems and install additional capacity once sufficient demand has been observed. For example, a diesel generator can be used to cover some demand until it becomes cost effective to install additional PV capacity.

Policy barriers prevent microgrid developers from fully leveraging the technologies at their disposal. DC microgrids provide several advantages (cost-saving and technical) over AC ones [18] yet policy barriers prevent them from becoming prevalent. For example, if microgrid developers hope to mitigate the risk of national grid encroachment by planning to connect their microgrids to the national grid, many national power authorities require that the microgrid to be built to the same standard as the national grid (for example, an above-ground AC distribution network).

4 Areas for Technology Innovation

The following section aims to highlight areas of future innovation that have the potential to reduce overall cost of off-grid energy systems significantly and ultimately lead to the potentially greater penetration of these systems. However, even if one of these innovations is realised there may be many other barriers to implementing it in the field.

4.1 Productive-use Applications

While lighting alone provides communities with some opportunities for economic growth [5], the key to dramatic growth lies in "productive-use applications" of electricity access. These are appliances that unlock new economic opportunities or greatly improve the efficiency of existing activities due to access to electricity. Innovations in productive-use applications are likely to have a high impact on the off-grid solar industry [4].

Note on cooking: Cooking with electricity is infeasible below Tier 3 energy access. However, several super-efficient wood-burning and charcoal cook stoves exist in the market.

4.1.1 Low-tier Applications

Applications with low power requirements such as entertainment (e.g. televised sports matches), barbershops/salons, and phone charging promote economic growth and in turn, access to higher tiers of energy access. These applications are prevalent, with companies providing "business-in-a-box" kits [19].

4.1.2 Light-Industrial Applications

Some examples of light-industrial productive-use applications are shown in Table 5. Payback periods are calculated using a microgrid tariff of 0.90 USD/kWh. While tailoring, egg incubation, and water treatment & sales offer the best opportunities for revenue generation, electric milling, ice-making, and carpentry are in the most need of cost-saving and efficiency-increasing innovation to make them more attractive businesses.

Table 5: Productive-use business cases [14, 20, 21]

Application	Payback period [months]
Refrigeration (ice-making, cold drink sales)	10
Electric milling for grains	Very high
Carpentry	11
Egg incubation	3
Water treatment & sales	4
Tailoring	1

Electric Milling for Grains

Electric milling is an excellent example of a business that is potentially lucrative, but unfeasible with current machinery. Current diesel mills are much more profitable than electric mills. Due to the high power requirements of electric mills and high microgrid tariffs, the initial investment in an electric mill may take a very long time to pay off or may never pay off. For electric milling on a microgrid to be cost-competitive with diesel milling, electric mills require an efficiency increase of 184% [14] (equivalent to reducing the average microgrid tariff to 0.32 USD/kWh).

4.1.3 Agricultural Applications

Many standalone solar agricultural products exist, such as solar irrigation pumps. However, the African Postharvest Loss Information System estimated 14 to 18% of grains are lost during post-harvest handling and storage on-farm [22]. There is a need for accessible storage media such as refrigeration and better processing techniques.

4.2 Improved Microgrid Demand Estimation

Improved demand estimation can de-risk microgrid projects (see Section 3.2.3). Microgrids that have been in operation for 5–10 years have collected an appreciable amount of data regarding the demand and demand growth of their communities. Machine learning techniques can be applied to these datasets to predict the demand and demand growth of similar sites. Smart meters simplify access to the volume of data required to apply machine learning techniques. Surveys can also be used. Improved demand estimates would allow microgrid developers to size new projects with increased certainty, ultimately reducing the risk in these projects and encouraging investment in microgrids.

4.3 Controllable Loads & Demand Response

It could be very beneficial to exert some level of control over energy demand in a microgrid. This could lower operating expenses, extend component lifetimes, improve service and ultimately reduce capital costs. This is enabled by smart meters, which allow monitoring and control at the customer level.

For example, refrigerator and freezer compressors have high power requirements when turned on but are only turned on intermittently with a well-defined schedule. Figure 4 shows the load profile of a standard refrigerator (under no activity). Refrigerators targeted at the off-grid energy market have similar average power requirements [20]. Adding these load profiles in-phase leads to very high demand at some times and zero demand at others, which places unnecessary stress on the microgrid –unnecessary cycling of batteries or running a diesel generator at an inefficient operating point. If these loads could be controlled some could be shifted out-of-phase with the others, preserving the level of service without stressing the microgrid.

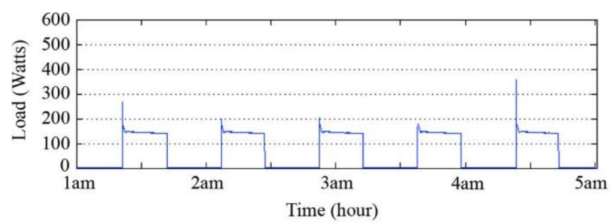

Figure 4: Maytag MSD2641KEW refrigerator load profile [23]

This is an illustrative example and only represents one example of demand response. Even LED lighting performance can be gracefully degraded to reduce stress on a microgrid network.

4.4 Accessible Generation and Storage

Customer energy demand is highest in the evening [12], so most of the solar energy captured during the day must be stored. Currently batteries are the most common energy storage media, and their cost often makes up a significant fraction of the cost of an off-grid energy system. While battery costs are falling, the cost of energy storage remains a large technological barrier to the prevalence of solar off-grid energy access. In addition to low cost, criteria for off-grid energy storage include: retention of capacity over many cycles, deep-cyclability, and low maintenance requirements.

Other forms of renewable generation would be an asset, especially in the microgrid context. Aggregating generation profiles from different sources, for example wind or micro-hydro, could lead to better matching generation and demand profiles, reducing reliance on energy storage and overall project costs. Currently both wind and hydro are competitive at large scales, but do not scale well with cost into the sub-megawatt range. For example, the cost for a hydro project scales with $C \propto P^{0.7}$ [24], where C is the cost of the project in USD and P is the capacity of the project in kW. This means that a 10 kW project costs 5 times more than a 1 kW project, and a 100 kW project only costs 25 times more.

4.5 Efficiency Improvements for Solar Panels

4.5.1 Dust-repellent Surfaces

Dust poses a large problem for solar panels, reducing output by up to 25% in regions where air pollution is particularly acute, like Northern India [25]. Nanotechnology and micro-manufacturing can be applied to create dust-repellent coatings or surface finishes for solar panels. A dust-repellent coating would increase a solar panel's effective efficiency, lowering the cost of standalone solar devices and microgrids.

4.5.2 Axis-tracking

Axis-tracking could significantly increase effective solar panel efficiency. An axis-tracking solution for this market must be low cost, reliable, and simple to install and maintain. Some solutions using expanding paraffin wax exist [26].

Simulations of a 0.3 kWp solar panel using a fixed 20° tilt roof mount[5], 1-axis, and 2-axis tracking solution in Kisumu, Kenya were calculated using System Advisor Model (SAM) and Typical Meteorological Year (TMY) data [27] for the region. Figure 5 shows the effect of single and double axis tracking on the monthly energy production.

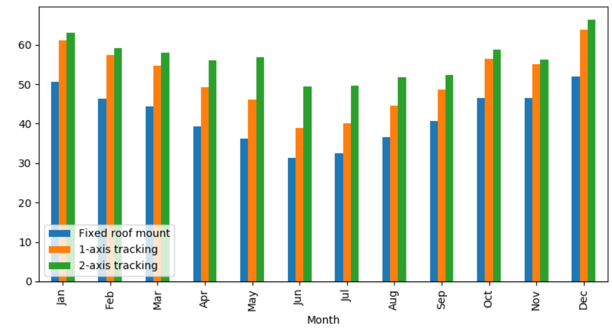

Figure 5: Monthly energy from a 0.3 kWp PV panel in Kisumu, Kenya

Not only does axis tracking improve the effective efficiency of a solar array, but it also reduces the seasonal variability in energy production, simplifying solar energy system design. Seasonal variability is the range of monthly energy production as a percentage of the mean. Table 6 summarizes this.

Table 6: Effect of axis tracking on a 0.3 kWp PV panel

Tracking	Mean monthly energy [kWh]	Seasonal variability [%]
Fixed 20° tilt	41.91	49.45
1-axis	51.35	48.72
2-axis	56.49	30.10

Axis tracking also offers the potential to easily shed accumulated obstructions such as snow or sand. The increased average monthly energy production for single and double axis tracking represent effective efficiency increases of 25 and 35% respectively.

[5] This is not the optimal configuration for the region but represents a typical roof-mounted solar panel.

References

[1] M. Bhatia and N. Angelou, "Beyond Connections: Energy Access Redefined," Energy Sector Management Assistance Program, 2015.

[2] J. Agenbroad, K. Carlin, S. Doig, C. Henly and E. Wanless, "Energy within reach: growing the minigrid market in Sub-Saharan Africa," Rocky Mountain Institute, 2017.

[3] F. F. Nerini, O. Broad, D. Mentis, M. Welsch, M. Bazilian and M. Howells, "A cost comparison of technology approaches for improving access to electricity services," *Energy,* vol. 95, pp. 255-265, 2016.

[4] Lighting Global, "Off-Grid Solar Market Trends Report 2018," Lighting Global, 2018.

[5] S. Wheeldon, E. d. Dinechin, G. d. Chorivit and O. Reynolds, "Powering Opportunity: The Economic Impact of Off-Grid Solar," GOGLA, 2018.

[6] GOGLA, "Global Off-Grid Solar Market Report: Semi-Annual Sales and Impact Data," GOGLA, 2018.

[7] I. Nygaard, U. E. Hansen and T. H. Larsen, "The emerging market for pico-scale solar PV systems in Sub-Saharan Africa: From donor-supported niches toward market-based rural electrification," UNEP DTU Partnership, 2016.

[8] Marincola, L. Silverthorn, B. Silverthorn, F. Iannce, K. Kuhlmann, B. Duggan and P. Zullo, "Solar lighting with pay-as-you go technology". United States of America Patent US20130212005A1, 15 August 2012.

[9] S. P. Ayeng'o, T. Schirmer, K.-P. Kairies, H. Axelsen and D. U. Sauer, "Comparison of off-grid power supply systems using lead-acid and lithium-ion batteries," *Solar Energy,* vol. 162, pp. 140-152, 2018.

[10] R. G. Charles, M. L. Davies, P. Douglas, I. L. Hallin and I. Mabbett, "Sustainable energy storage for solar home systems in rural Sub-Saharan Africa – A comparative examination of lifecycle aspects of battery technologies for circular economy, with emphasis on the South African context," *Energy,* vol. 166, pp. 1207 - 1215, 2019.

[11] A. Chaurey and T. Kandpal, "A techno-economic comparison of rural electrification based on solar home systems and PV microgrids," *Energy Policy,* vol. 38, pp. 3118 - 3129, 2010.

[12] N. J. Williams, P. Jaramillo, B. Cornell, I. Lyons-Galante and E. Wynn, "Load characteristics of East African microgrids," in *2017 IEEE PES PowerAfrica*, Accra, 2017.

[13] T. Reber, S. Booth, D. Cutler, X. Li and J. Salasovich, "Tariff Considerations for Micro-Grids in Sub-Saharan Africa," NREL, 2018.

[14] S. Booth, X. Li, I. Baring-Gould, D. Kollanyi, A. Bharadwaj and P. Weston, "Productive Use of Energy in African Microgrids: Technical and Business Considerations," NREL, 2018.

[15] S. Hajiaghasi, A. Salemnia and M. Hamzeh, "Hybrid energy storage system for microgrids applications: A review," *Journal of Energy Storage,* vol. 21, pp. 543-570, 2019.

[16] M. Taylor and E. Y. So, "Solar PV in Africa: Costs and Markets," IRENA, 2016.

[17] N. J. Williams, P. Jaramillo and J. Taneja, "PV-array sizing in hybrid diesel/PV/battery microgrids under uncertainty," in *2016 IEEE PES PowerAfrica*, 2016.

[18] A. Hirsch, Y. Parag and J. Guerrero, "Microgrids: A review of technologies, key drivers, and outstanding issues," *Renewable and Sustainable Energy Reviews,* vol. 90, pp. 402-411, 2018.

[19] SolarNow Uganda, "Small Business Solutions," SolarNow Uganda, [Online]. Available: https://www.solarnow.eu/solar-solutions/small-business-solutions/. [Accessed 10 April 2019].

[20] GIZ, "Photovoltaics for Productive Use Applications," GIZ, 2016.

[21] C. Kirubi, A. Jacobson, D. M. Kammen and A. Mills, "Community-Based Electric Micro-Grids Can Contribute to Rural Development: Evidence from Kenya," *World Development,* vol. 37, pp. 1208 - 1221, 2009.

[22] M. Sheahan and C. B. Barrett, "Review: Food loss and waste in Sub-Saharan Africa," *Food Policy,* vol. 70, pp. 1 - 12, 2017.

[23] M. Pipattanasomporn, M. Kuzlu, S. Rahman and Y. Teklu, "Load Profiles of Selected Major Household Appliances and Their Demand Response Opportunities," *IEEE Transactions on Smart Grid,* vol. 5, pp. 742 - 750, 2014.

[24] G. Aggidis, E. Luchinskaya, R. Rothschild and D. Howard, "The costs of small-scale hydro power production: Impact on the development," *Renewable Energy,* vol. 35, pp. 2632 - 2638, 2010.

[25] M. H. Bergin, C. Ghoroi, D. Dixit, J. J. Schauer and D. T. Shindell, "Large Reductions in Solar Energy Production Due to Dust and Particulate Air Pollution," *Environmental Science & Technology Letters,* vol. 4, no. 8, pp. 339 - 344, 2017.

[26] F. J. Doyle, "Solar Tracker for Solar Energy Devices". United States of America Patent US20120097149A1, 29 12 2011.

[27] European Commission Joint Research Center, "Photovoltaic Geographical Information System (PVGIS)," European Commission Joint Research Center, 2017.