Review

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Decentralized Solar Energy Systems for Rural Electrification in Sub-Saharan Africa: Opportunities, Challenges, and Future Pathways

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Decentralized Solar Energy Systems for Rural Electrification in Sub-Saharan Africa: Opportunities, Challenges, and Future Pathways

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Abstract

Access to reliable electricity remains a pressing challenge in Sub-Saharan Africa, particularly in rural areas where over 600 million people live without power. This paper explores the potential of decentralized solar energy systems; such as solar home systems, mini-grids, and solar-powered appliances in addressing energy access challenges across rural Sub-Saharan Africa. While these systems offer clean, reliable, and scalable alternatives to conventional grid expansion, their adoption is constrained by regulatory uncertainty, limited financing options, and local capacity gaps. Drawing on case studies from five countries, the paper examines how recent innovations -including mobile-based Pay-as-you-go (PAYG) financing, hybrid renewable systems, and improved energy storage technologies are reshaping energy access models. It also outlines policy recommendations aimed at strengthening regulatory coherence, promoting regional cooperation, and enhancing sustainability. Ultimately, the study highlights how decentralized solar solutions can contribute to long-term environmental, financial, and social resilience, with direct implications for poverty alleviation and inclusive rural development in the region.

Keywords: decentralized solar energy systems; Sub-Saharan Africa; solar home systems; mini-grids; conventional grid expansion; Pay-as-you-go (PAYG); improved energy storage technologies; regional cooperation; hybrid renewable systems

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1. Introduction

1.1. Overview of Rural Electrification in Sub-Saharan Africa

Most parts of Sub-Saharan Africa rank among the least electrified areas in the world, and about 600 million people have no electricity (IEA, 2020). These areas, especially in rural settings, are the most affected by the lack of access to energy and almost all of the populations residing in the countryside lack trustworthy access to power (World Bank, 2017). This non-electrification has great ramifications with regards to the social and economic development. In rural communities, energy plays a critical role in ensuring basic needs and requirements such as lighting, cooking, communication and healthcare all of which are instrumental in upgrading living conditions, and growing local economies (Alstone et al., 2017).

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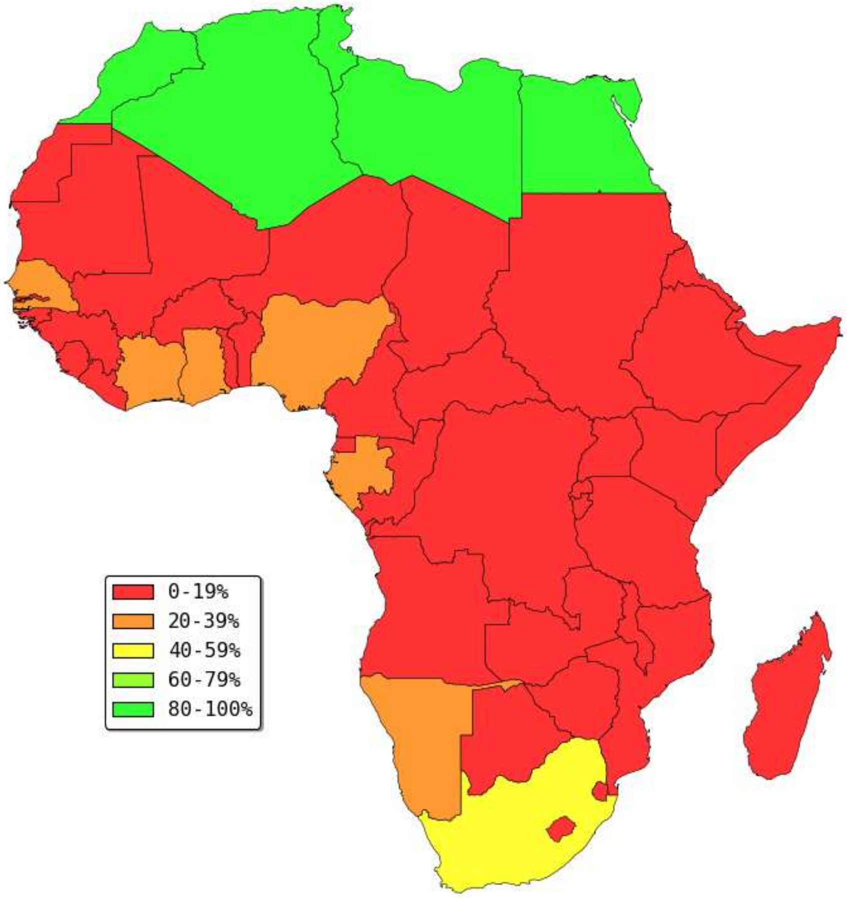

Figure 1. Rural Electrification Rates in Africa.

Rural electrification has a complex background in Sub-Saharan Africa. Geographically remote locations of rural areas limit the development of issues related to infrastructure in addition to financial issues (Bertheau et al., 2020). The expansion of the traditional electricity grid—characterized by high costs and slow implementation, faces significant challenges, including insufficient investment, weak governance structures, and the absence of a reliable power supply in many regions (IRENA, 2019). Consequently, the people living in rural areas are stuck with inefficient and pollution energy sources, such as kerosene lamps, firewood, and charcoal, which contributes to environmental degradation and health issues in areas (Dagnachew et al., 2017).

1.1.1. Energy Access in Rural Areas: Current Statistics and Challenges

Access to energy in rural Sub-Saharan Africa is among the trumped developmental challenges. The International Energy Agency (IEA) also claimed that almost 72 percent of people who reside in rural Sub-Saharan Africa have no access to electricity, which is further complicated by poor infrastructure, low household income, and insufficient sustainable finance sources (IEA, 2020). In addition, electricity access remains highly uneven in rural areas, with shortages being more acute in some countries than in others. Indeed, in Nigeria and Ethiopia, over 90 percent of the rural population remains off-grid. (IEA, 2020). Such deprivation of the modern energy services retards the economic growth, restricts education as well as inhibiting the social progress, adding to the disparity in the regions (UNDP, 2018).

Obstacles to rural electrification do not only have economic origins but are logistical as well. A great part of the rural areas, are located in distant locations where it is hard and expensive to expand the traditional power delivery networks (Khandker et al., 2012). Moreover, there are no strong local

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energy markets, and rural communities have little purchasing power. As a result, large-scale energy solutions, which do not meet people's needs, are difficult to deploy. (Hoffman et al., 2020). These problems indicate the necessity to apply decentralized energy tools, which are able to offer affordable, reliable, and sustainable energy to rural populations.

1.1.2. Significance of Decentralized Solar Energy Systems in Rural Electrification

Due to these difficulties, decentralized solar systems have come up as a possible means of ensuring rural electrification in Sub-Saharan Africa. The use of solar energy as a solution to provide the energy requirements to the rural population is flexible, scalable and cost-effective (Nichter et al., 2020). Systems like mini grids and off grid solar home systems, Decentralized systems are attractive because they enable energy access without requiring a costly and complex expansion of the grid. In these systems, some of the benefits are less-intensive upfront costs, little maintenance, and the capacity to customize to needs of various communities (Sovacool, 2017).

The above-said rapid reduction in the prices of solar panels and energy storage technologies has enabled the solar power to become cheaper and available to all, which helps it to become one of the options in rural locations, which would be cost-prohibitive to connect to the grid (IRENA, 2020). Also, solar energy will enhance climate change resilience since it is a renewable energy source that does not release any greenhouse gases as conventional biomass and traditional fossil sources (IEA, 2019). Furthermore, one must not forget that solar energy is especially applicable in Africa because there is a lot of sunshine during the year, which makes it a perfect candidate to be fully powered by the sun (Alstone et al., 2017).

1.2. Purpose of the Review

This review seeks to address how partially decentralized solar energy technology is changing the way in which rural people in Sub-Saharan Africa get access to electricity. It will scrutinize the engagement of off-grid and mini-grid solar system in bridging the energy access gap in rural communities with respect to the socio- economic and environmental effects of these systems. The review will also involve pointing out the major opportunities and challenges to scale levels of decentralized solar energy solutions in the region.

This review is concerned with off-grid and mini-grid solar systems that have increasingly been viewed as the best points of solution to bring electricity to rural communities. Such solar systems that are off-grid include solar home systems (SHS) and small-scale appliances powered by solar battery and are normally implemented in homes that are not connected to the main grid. In contrast, mini-grids can be used to serve multiple households, businesses, and public institutions since they serve an entire community. The two categories of systems are effective in bringing electricity to places that are remote and their scalability is a major selling point since they are quick to reach the rural energy demand (Sovacool, 2017).

Social effects of decentralized solar energy systems are noticeable as well since the implications are not only related to electricity availability. Better access to energy will develop education, healthcare, and productivity, triggering economic progress and the social wellbeing of people (Alstone et al., 2017). The solar energy solutions are also environmentally friendly, providing the possibility to minimize the consumption of biomass and kerosene, therefore, reducing air pollution and deforestation, among other aspects of climate change mitigation (IRENA, 2020).

In the review, the main opportunities and challenges of the use of decentralized solar systems in Sub-Saharan Africa will be determined. Examples of opportunities are potential solar energy that leads to rural development, employment opportunities, and becoming climate change resilient. Nevertheless, there are still issues, including a huge initial investment, access to financing, and regulatory uncertainties, which should be covered to introduce solar energy solutions to the mainstream. The future directions of the decentralized solar energy will also be addressed in the review by including technological progress, policies, and funding mechanisms that will require furthering the scale of the application and its sustainability.

1.3. Scope of the Review

This review utilizes case studies from five Sub-Saharan countries: Ghana, Kenya, Nigeria, Ethiopia, and Malawi. These were chosen because these countries used different degrees of adopting solar energy and their progressive style of energy access to rural regions. The review will concentrate on the importance of Pay-as-you-go (PAYG) and community ownership models that have received immense popularity in such countries as an innovative way to find funding for decentralized solar energy systems (Nichter et al., 2020). The review will also look at the regulatory policies which have facilitated or even obstructed the development of solar energy markets in these countries, whether there is need to harmonize the policies and cooperate regionally in the endeavor to catalyze the growth of solar in Sub-Saharan Africa.

2. The Role of Decentralized Solar Energy in Rural Electrification

Both economic and logistical constraints have been the obstacles to the supply of reliable electricity to rural regions of Sub-Saharan Africa. Off-grid and mini-grid solutions to solar energy are a possibility of centralization of energy, which will help to fill the energy gap, revolutionize rural electrification and help to achieve social-economic progress in a country. These meshed systems play a crucial role in addressing the limitations of traditional grid infrastructure while offering sustainable, reliable, and affordable options for energy access in remote areas.

2.1. Defining Off-grid and Mini-grid Solar Systems

Decentralized solar energy systems are generally classified as having two major categories, these include; off-grid solar systems and mini-grid systems. Both are conceived to supply power in unconnected territories to the national grid although they differ in magnitude, infrastructure and the plan of deployment.

2.1.1. Off-Grid Solar Systems: Stand-alone Solar Units for Rural Households

Off-grid solar systems are normally standalone systems, which deliver power to an individual household or tiny enterprise. They are mostly applied in rural places where it is uneconomic to extend the grid. These off-grid solutions comprise Solar Home Solutions (SHS) and appliances powered by solar energy that form the main source of power at home. Off-grid solar systems are generally intended to energy meet the basic electricity demands of households, like light, phone charging, and small appliances (Burgess et al., 2019).

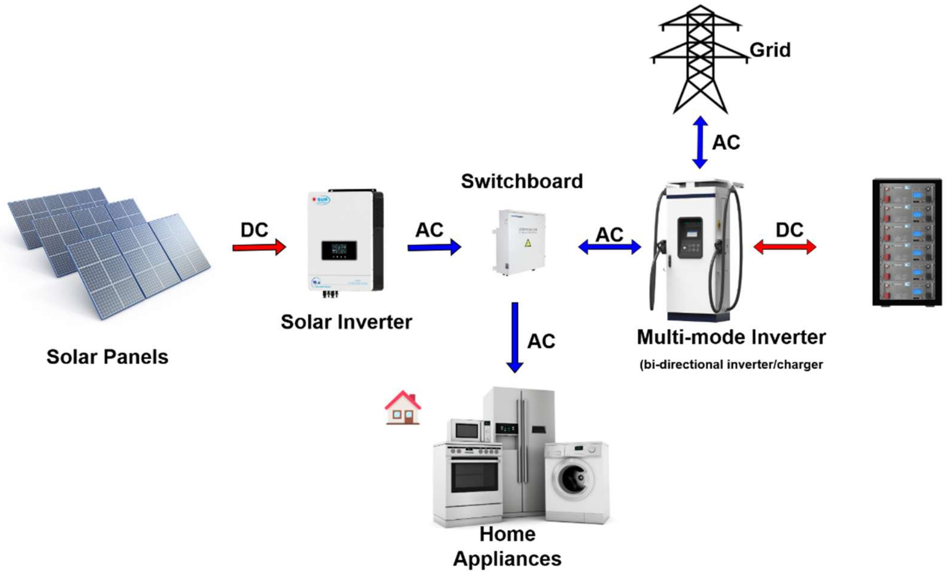

Figure 2. Guide to designing off-grid and hybrid solar systems.

The introduction of off grid solar systems has had a rather specific effect on rural areas where people could not access a grid connection or the price would be prohibitive. These systems help improve the quality of life as they provide reliable and affordable energy that offers a cleaner and more reliable source of energy than the customary sources like kerosene which is frequently accessed in the rural society to be used as a lighting fuel (Sovacool et al., 2016). A major reason as to why off-grid solar systems could work so well in supporting rural households that are located in remote areas is that the systems are flexible and scalable. It would not be logistically or economically feasible to extend the grid to such areas.

This is one of the main particularities of off-grid solar systems when Pay-As-You-Go (PAYG) financing models become widespread. Through these models, the cost of installing solar system which consumes lots of initial capital can be avoided and village households can gain access to solar energy. Mobile money platforms are frequently utilized by PAYG models to trigger small and incremental payments, therefore, reducing the costs and accessibility of solar energy to the low-income population (Branger et al., 2020).

2.1.2. Mini-Grid Systems: Larger-Scale Networks for Communities

Unlike off-grid systems, mini-grids solar systems make use of solar power to supply power to a group of households, or a community as a whole. They are usually more complicated as they include a centralized solar generating facility, energy storage, and a distribution grid locating together various households and companies in a certain area. The proposed mini-grids are viewed as an important rural electrification technique, particularly in regions with greater concentrations of people or in circumstances where greater electricity services are needed than only the basic one (Zeng et al., 2021).

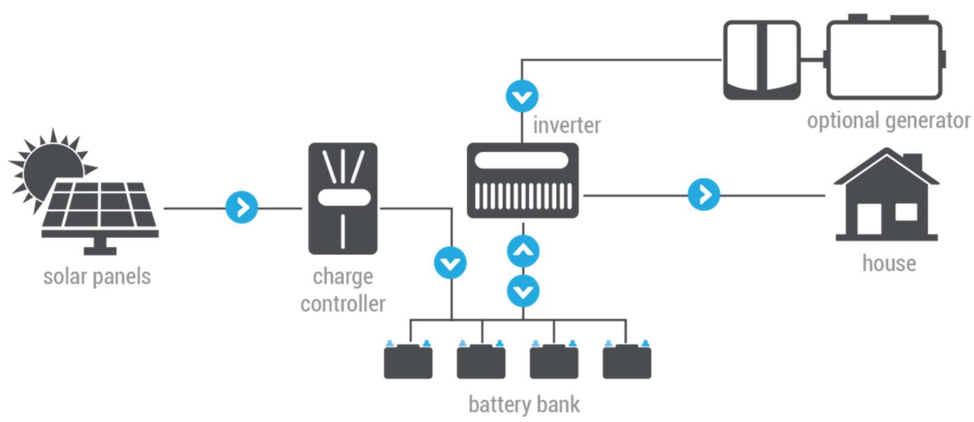

Figure 3. Mini Grid Hybrid solar-systems.

Mini-grid systems unlike the off-grid systems which are normally installed on household basis are meant to benefit the energy needs of a community or village as it delivers energy to lighten up, pump water, process agricultural products or to run very small businesses. Mini-grids best suit the rural location that will experience increased demand of electricity or areas where households can be clustered in order to share infrastructure (Okello et al., 2018). Mini-grid systems involve bigger investments than off-grid systems because more infrastructure has to be developed including energy storage and connection points to grid.

Another benefit of mini-grids is that it promotes economic growth of rural societies. As an illustration, small businesses like food processing, water pumping and local industries can be powered by mini-grids, a factor that greatly elevates the lives of people living in rural settings. Also, such systems can be connected with national grids during their expansion, therefore, providing an ultimate entry into electricity markets of greater sizes (Liu et al., 2020).

2.2. Technological Advancements in Solar Energy

The development of improved solar technology is one of the factors that have contributed to decentralized solar systems. There has been a rise in improvement of the photovoltaic (PV) technology, energy storage technology and system efficiency, all of which have led to rise in solar energy distribution in rural locations as solar energy continues to develop.

2.2.1. Improvements in Photovoltaic (PV) Technology

Over the last 20 years, there have been significant developments in photovoltaic technology that resulted in solar panels becoming more efficient and cost-effective. The most significant contributor to this trend has been the drop in the prices of PV modules that have made solar energy more and more accessible to people in the rural areas (Cory et al., 2020). There also has been an incentive in cost reduction due to technological advancements, manufacturing economies of scale, and a larger number of international suppliers (Narula et al., 2020). Consequently, solar energy has proven to be an alternative in off-grid and mini-grids.

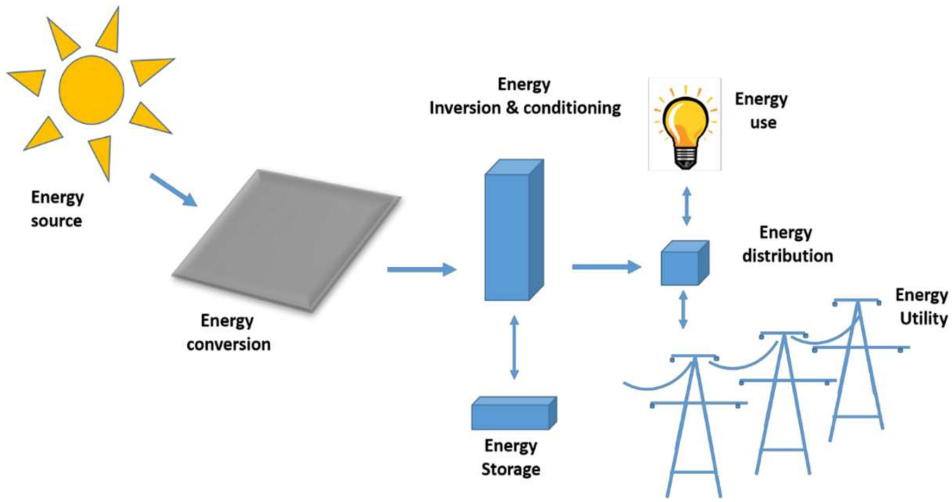

Figure 4. Recent advances in solar photovoltaic materials and systems for energy storage applications.

Efficiency of PV panels have improved as well with newer technologies bringing the signified optimal theoretical efficiencies of solar cells near to real world values. The developments in materials, including perovskite solar cells and bifacial solar panel, have created new avenues through which the potential of capturing energy in the form of sunlight can be amplified thereby boosting the capacity of the solar energy systems (Li et al., 2018). These developments in the PV technology had enabled the production of more energy with less installation, thus decreasing the cost and location space to install solar systems further in rural regions (Liu et al., 2021).

2.2.2. Energy Storage Solutions and Battery Technology

One of the largest obstacles encountered with solar energy systems is energy storage, especially in off grid and mini-grid systems where storage of energy must be available 24 hours a day. Better battery technology has resulted in energy storage being more efficient, economical, and scalable, so solar systems can deliver a steady supply of power, even on cloudy days. Lithium-ion batteries, now standardized in solar energy storage, are much higher in efficiency and can provide longer lifetime than the ancient counterparts, like lead-acid batteries (Zhou et al., 2021).

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Moreover, recent innovations on Battery Management Systems (BMS) have contributed to the reliability of solar power storage battery through its monitoring and managing control over the battery health and performance conditions (Wang et al., 2020). The use of renewable energy sources such as solar and wind can also be integrated with the grid and energy storage technologies allow the integration to be stable because they use renewable forms of energy. The introduction of energy storage in off-grid and mini-grid has resulted in the excess energy produced during the day to supply at night or at a time of limited solar radiation thereby enhancing the reliable performance and affordability of decentralized solar systems (Jain et al., 2020).

2.2.3. Innovations in System Efficiency and Cost Reduction

Advances in system design, installation and operations have also led to the increase in the efficiency of solar energy-based systems. To illustrate, smart grid technologies and highly efficient monitoring systems are now possible to have a more efficient control on energy production, distribution, and utilization in off-grid and mini-grid systems. They will allow operators to maximize the performance of the solar systems and minimize waste and the overall efficiency of the system (Cao et al., 2019).

Also, the price of installing solar energy system has been reduced because of the invention of new manufacturing methods, automated production lines, and using cheaper material (Bose et al., 2021). Solar-powered mini-grids and home systems are observed to be more affordable thus they are getting widespread amongst households and enterprises in rural areas. Additionally, the increasing accessibility of fewer components and plug-and-play frameworks has made the process of installation less challenging, and the possible simplicity to roll out and service solar energy services to the remote regions (Kipp et al., 2020).

2.3. Solar Energy Potential in Sub-Saharan Africa

Sub-Saharan Africa has massive potential in solar energy. Thus, it is a good candidate that can derive maximum benefits by using solar energy solutions particularly in rural communities. It also gets a lot of sunshine during both seasons and most regions are characterized by high levels of solar radiations hence making it a conducive environment to solar energy systems. Based on these natural advantages, the rural rollout of solar energy technologies is a tough task to accomplish because of various factors such as high costs of implementation, issue of logistics, and accessibility to technology, among others. In this section, the potential of solar irradiance in Sub-Saharan Africa and the availability of solar technology to the rural populations elsewhere are discussed, offering some knowledge regarding opportunities and challenges when it comes to the use of solar energy in Sub-Saharan Africa.

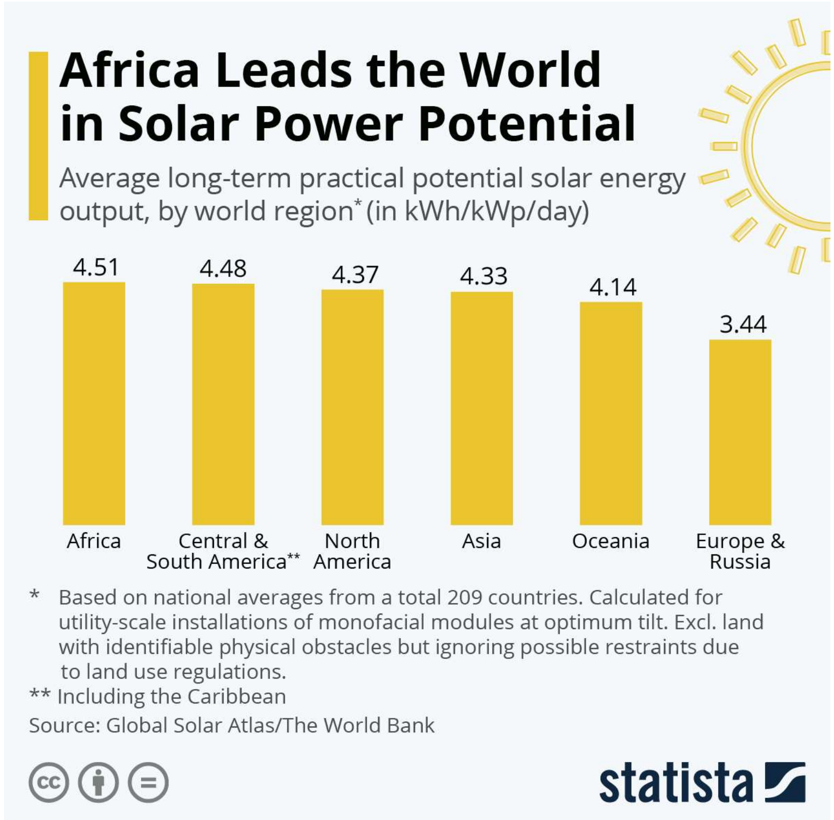

Figure 5. Africa's solar energy potential.

2.3.1. Solar Irradiance in the Region

A reference to solar irradiance should draw an amount of solar power at a specific site per unit area. The region of Sub-Saharan Africa is one of the best places in the world to produce solar energy because it has high solar irradiance. The area has an average amount of solar irradiance of approximately 5.5 kWh/m 2 /day, much more than the world average (IEA, 2020). This is attributed by the fact that, most of the countries within this region are near the equator which boasts of direct and uniform sunlight all year round.

The immense solar irradiance potential is distributed differently in the various regions of the territory; the countries of the Sahara Desert and Sahel region, comprising Mali, Chad and Niger are the ones that receive most sunlight. The regions receive more than 6 kWh/m 2 /day, which means that their solar irradiation is favorable to produce solar energy in large volumes (Alfaro et al., 2018). Conversely, other regions in the South, including Southern Africa and East Africa, also enjoy high levels of solar irradiance only that they are generally slightly low with a mean value of between 4.5 and 5.5 kWh/m 2 /day (Muthoni et al., 2020). Although these differences are present, the region in general has a lot of solar assets that can be tapped to provide electricity.

Consistency of sunlight is one of the major benefits of the solar irradiance in the Sub-Saharan Africa. In contrast with other areas, which experience seasonal changes in the generation of solar power, Sub-Saharan Africa has sunshine all through the year, especially during the dry season, which guarantees constant sunshine to solar energy systems. Such predictability plays an imperative role in the functioning of off-grid and mini-grid solar systems which cannot operate without energy generation to satisfy the needs of rural populations (Shem, 2019).

Sub-Saharan Africa has developed an interest in small-scale and large-scale solar energy projects against this background of a high solar potential. With the price of photovoltaic (PV) technology ever-dropping, there is an untapped potential in the region that can be used to both provide access to

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energy and economic growth through the high solar irradiance of the region. Nevertheless, despite the availability of natural resources, it is the right environment, full of technological advances and investment as well as sound policy frameworks, that the country is in need of in order to release the full potential of its natural resources.

2.3.2. Accessibility of Solar Technology for Rural Communities

The accessibility to solar technology has been a significant challenge to the utilization of the solar energy in the rural Sub-Saharan Africa despite all the solar irradiance present. Despite the certain extent of adoption of the solar technology in the region in uptake in the urban areas, the rural areas have experienced setbacks in the same due to the issues of cost, supply and infrastructure. Expensive cost of solar system is one of the biggest deterrents to utilization of solar energy in the rural scenario. Costs of solar and other similar technologies are declining through the decades, still, there is no possibility to afford the idea of placing the off-grid and mini-grid systems by a vast majority of rural populations due to the high upfront costs (World Bank, 2020).

However, recently over the past few years there has been availability of non-traditional sources of financing the solar technology that has made solar technology affordable to the rural communities through the Pay-As-You-Go (PAYG) model. The use of PAYG model allows users to pay off the cost of the solar systems in very little payments as opposed to paying huge sums of money to access solar technology. This model has been gaining immense popularity in the likes of Kenya where systems of mobile money like M-Pesa are used to bring payments of solar systems (Foster et al., 2020). Through these outlets, families in rural areas can buy solar systems without substantial initial capital, and the price of solar power is reduced and affordable to low-income households.

In addition to the finance problems, also exists the logistics issue of accessing the solar technology in Sub-Saharan Africa for its rural locations. The rural areas lack most of the infrastructures that would assist in the distribution and installation of solar energy systems. This will include transportation problems, availabilities of quality workforce, and availability of local suppliers who will provide after sales and repairs services. This requirement, consequently, leads to the fact that access to solar technology results in the rural settlements being dependent upon external aid to Non-Governmental Organizations (NGO's) or International Aid Organizations (Nielsen et al., 2020). In other cases, such communities could also be utilized to access solar systems which are government sponsored but it has been reported that coverage of such schemes is very poor in most instances.

The solutions, which have been adopted to deal with them include using solar kits / modulars that are easy to carry and deploy to less developed part of the country. The systems will also be small-scale and adaptable in order to be adjusted to meet a specific energy need of a small business or a single household. Additionally, the solar kits typically come with simple installation instructions, therefore, reducing the extent of necessary technical savvy (Gupta et al., 2018). These systems are also more scalable in terms of modularity whereby more panels and batteries are merely added as the energy needs increase in response to the sustained increase in energy demands.

Another important component that defines the availability of technology is the commencement of local supply chain and local technician training. Most of the regions in Sub-Saharan Africa do not have trained personnel who can install and maintain solar energy systems. The need to remove such a gap has led to the implementation of various solar technology training models across the globe to build domestic capabilities in solar technology and build durable domestic markets in the country (Gulfam et al., 2019). These programs offer the hope of continuing the solar technology in the rural areas by enabling the local communities to grow their capacities in terms of installation and maintenance of the solar systems.

And, finally, the relevance of policy and regulatory frameworks must be cited in enabling the availability of the solar technology. Government policies supporting the usage of solar can only promote the use of solar power even further through subsidies, tax holiday, and tax exemption on duty on imports of solar technology to the rural areas in the effort of making solar energy cheaper and affordable. To illustrate, Rwanda implemented the policies that contributed to the provision of

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solar appliances in the country through networks of local retailers that facilitate the expansion of solar systems in the jungle (Venkatesan et al., 2020). However, lopsided and fragmented policy frameworks could continuously act as a stumbling block to the blanket annexation of solar energy to the countryside.

3. Case Studies on Rural Solar Electrification in Sub-Saharan Africa

Decentralized solar systems have now concentrated on Sub-Saharan Africa largely in rural parts where it is still not affordable or viable to have the conventional grid infrastructure system. This aspect of off-grid solar systems, such as mini-grids and Pay-as-you-go (PAYG) systems has helped millions of people in rural settings gain access to electricity. This section proposes case studies on Ghana and Kenya, which are countries that have done a lot in harnessing the power of the decentralized solar energy system in order to enhance electrification in the rural areas. The case studies examine the achievements and challenges and special initiatives these countries have made to scale solar energy solutions among communities in the rural locations.

3.1. Ghana: Success and Challenges in Mini-Grid Deployments

Ghana has been a leader in adopting solar energy initiatives to meet the needs of its rural population. Of particular interest is the country's approach to rural electrification through its solar mini-grids strategy, where Ghana expects renewable solar energy to help solve its power shortages while also stimulating economic growth in deprived regions.

3.1.1. Policy and Institutional Framework for Solar Energy in Ghana

The Ghanaian government has undertaken significant initiatives aimed at creating an enabling environment for the exploitation of solar energy, particularly in rural areas. The importance of renewable energy in achieving sustainable development is pointed out by the national energy policy of the country. The primary source of the energy policy of Ghana is the Act 832, Renewable Energy Act of 2011, and the 2010 National Energy Policy that seeks to diversify the energy mix and increase the share of renewable sources of energy on the national grid. Ghana has set ambitious targets of meeting renewable energy, and the country is scheduled to supply 10 percent of the power through the assistance of renewable energy resources by the year 2030 (Mills et al., 2018).

The government has developed many initiatives to encourage the scale-up of solar power energy, besides the Renewable Energy Act. Rural Electrification Project (REP), which was initiated in the 1980s, has played the role of helping to make electricity available in the rural environment. These efforts include an attempt to improve the off-grid solutions in remote areas where it is uneconomical to extend the grid through new programs such as the Solar Mini-Grid Program. They have been a significant force in ensuring that policies are developed as well as the project set up in a bid to enhance access to solar energy via the Energy Commission of Ghana and the Ministry of Energy (Owusu et al., 2020).

In May 2025, the Government of Ghana officially launched a landmark renewable energy project, the Scaling-Up Renewable Energy Program (SREP), aimed at significantly expanding electricity access in some of the country's most underserved communities. According to the Ministry of Energy and Green Transition, the SREP initiative will involve the construction of 35 mini-grids and the installation of 1,450 solar home systems across the Bono East, Oti, and Savannah regions. In addition, 12,000 net-metered rooftop solar PV systems will be installed nationwide to support Ghana's transition toward a greener energy mix

Ghana has also established various institutional frameworks in boosting the process of the use of solar energy, like the Sustainable Energy for all (SE4All), which shall hopefully lead to the universalization of accessibility to clean, affordable, and reliable energy. Another avenue through which the government supports solar energy initiatives is by securing funding from international

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partners, including the United Nations Development Program (UNDP) and the World Bank (Agyemang et al., 2017).

3.1.2. Case Study: Off-Grid Solar Solutions in Rural Communities

Off-grid solar systems have undergone exponential success, particularly in rural Ghana, where people have erected solar mini-grids in remote settlements. One example of such a project is the Ghana Solar Energy Project that is focused on the electrification of rural Ghana with the use of solar-powered mini-grid. Such photovoltaic power plants managed micro grids that run on an array of batteries have provided a stable and renewable power to a series of different villages in Ghana particularly in the Northern and Western ends where growth of a grid is merely inadvisable.

Dzorwulu, one of the villages in the Northern region has been able to benefit by the solar mini-grid technology that has introduced light, irrigation power, and electricity of small businesses. The implication of this project has been imminent since, not only electricity is made accessible but the socio-economic status of the community has also been improved through the medium of this project. Energy stability has significantly boosted the output of businesses and institutions of learning now stand the chance to expand and operate longer hence making education available (Abrokwah et al., 2019).

Mini-grid scalability in rural areas, however, even though it is good news, is a matter of concern. One of the issues that determines this sustainability is its financial viability. There are some mini-grids already facing operational and maintenance difficulties due to lack of local capacity, and tariffs have proved a challenge in certain initiatives since they may not be affordable by the citizens living in rural settings (Rashid et al., 2018). There has also been issues with regards to technical problems of energy storage and grid integration of the operational challenge. Some of the challenges that will be crucial to tackle in the future are technical and financial as Ghana continues to launch an increasing number of solar mini-grids.

3.2. Kenya: Leveraging Pay-as-You-Go (PAYG) Systems for Rural Access

Kenya has led in adopting Pay-as-you-go (PAYG) solar systems especially in electrification of the rural areas. The PAYG systems offer a modern form of financing that can make solar technology accessible, without the request of high up-front payments, to households with low income. This enables customers to be able to access solar energy services on a power-by-power basis and in many cases via mobile money applications.

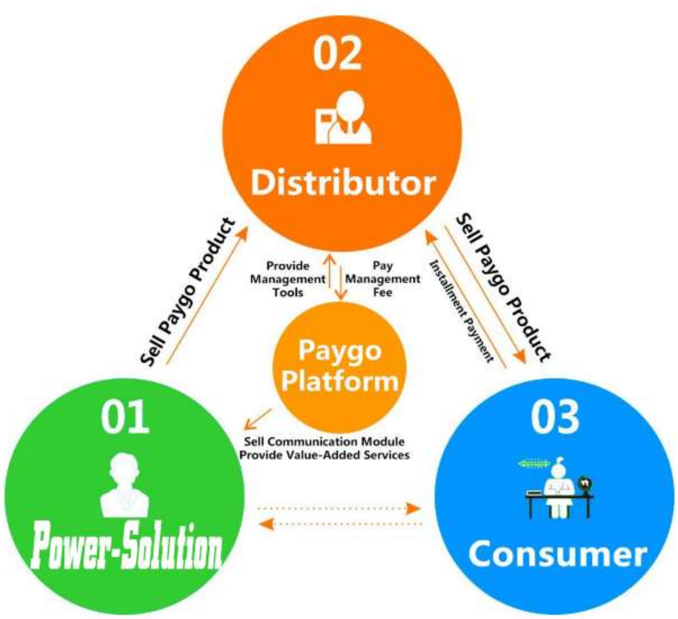

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Figure 6. Illustration of the PAYG model.

3.2.1. The Role of PAYG Models in Scaling Solar Energy Access

The model has been useful in spreading the sunlight energy to the residences in Kenya. Among the factors which have facilitated the PAYG systems successively is the popularity of the mobile money services, especially M-Pesa, which has transformed the financial transactions in Kenya and all over. The PAYG solar systems allow the customer to pay small, affordable installments of their solar units through mobile money, and they do not need to pay hefty capital costs at their own end (Burgess et al., 2020).

In Kenya, this model has proven especially effective as it alleviates the affordability feat which in most instances the rural household usually finds in investing in this solar technology. PAYG systems have opened the way to make the solar home systems affordable to a significant number of households with low income, especially in rural communities where grid extension is either absent or out of reach, by making them too costly (Awerbuch et al., 2017). Besides, the PAYG models usually have flexible payment schedules where households can pay at times in their income cycles; this makes the solar energy to be affordable to the rural poor.

Some of the factors that have contributed to the success of the PayAsYouGo systems in Kenya are technological improvements through the use of solar panels, cheap cost of solar energy solutions, and the availability of mobile money infrastructure that can easily receive payments. The PAYG companies including M-KOPA Solar, Off Grid electricity, and Sun King have been on the frontier to roll out these systems and has resulted in millions of people having access to electricity (Karekezi et al., 2020).

3.2.2. Case Study: PAYG Systems for Individual Solar Home Systems

Probably the most famous PAYG solar case study in Kenya is the M-KOPA Solar initiative, which has served off-grid households in Kenya with affordable solar energy ever since the turn of this century. M-KOPA Solar strategy has involved laying individual solar home systems (SHS) to households in the rural areas so that the households can make small and manageable payments of the systems through mobile money. More than 750,000 homes in Kenya, Uganda, and Tanzania were given solar kits by the company; this has greatly increased access to solar power in East Africa (Foster et al., 2020).

The solar home systems of M-KOPA aim at making the necessary household applications to run on charge e.g., lights, phone charging and small devices, and this comes at a basic level of power which enhances the living standards of rural households. This system comprises a solar panel and battery storage and has LED lights and these are facilitated by a mobile based payment system that gives customers the option to make payments using M-Pesa. This model has not only made access to energy better, but also helps improve the economic situation of the rural houses since they are less dependent on costly and polluting kerosene lamps (Gordon et al., 2019).

Although the PAYG model has proved to be successful in increasing access to solar, it has never been rosy either. Requirements of constant mobile payment infrastructure are one of the key obstacles, as the smooth transactions are to be provided. Moreover, mobile network coverage is also a challenge of some customers in the remote areas, which may hinder their payments. In addition, financial sustainability of PAYG firms is another issue since means of stable cash flow and payment defaults should still be addressed (Burgess et al., 2020).

3.3. Nigeria: Community Ownership Models and Their Impact

Nigeria is one of the most energy-scarce and populous countries in Sub-Saharan Africa where the growth of solar power in the form of community ownership has seen tremendous growth. The model will enable more local people to own the energy resources through sustainability, economic growth and energy independence. Considering the size of the population in Nigeria yet to be connected to the national grid, decentralized solar energy applications with particular reference to mini-grids have become a huge prospective solution to rural electrification.

3.3.1. Case Study: Solar-Powered Mini-Grids for Remote Villages

One of the brightest examples of the implementation of solar powered mini-grids in Nigeria is the project implemented in the rural villages of the Northern and Central part of Nigeria where the availability of electric power is poorly coordinated. Nigerian government and International Development Agencies have subsidized some pilot projects which involve the implementation of solar mini-grids in off-grid community. Such mini-grids supply electricity to households, schools, and micro-enterprises and bring the life of people in remote settlements much to an improved condition.

To cite an example, a small village in the Northern part of Nigeria (Bunyadi) had a solar mini-grid project that had a positive impact on the people because it could provide reliable, cheap, and clean electricity. Before the establishment of mini-grid, residents had to make do with kerosene lamps and small diesel generators to supply them with light which besides being costly also caused health hazards and environmental problems. The village had completely changed after solar powered mini-grid was implemented. The availability of electricity has enabled the local industries to work longer hours, students can study at night and the healthcare sector does not have to switch off the fridges to conserve electricity to stock the needed medicine (Aminu et al., 2021). It also worked to reduce dependence on the expensive fossil fuels and reduced the carbon pace at the local community level.

Though this project was successful in terms of its electricity output, it has challenges such as the long-term continuous funding of the project and technical maintenance of solar system. It also emerged as one of the major issues that there is no experienced labor and financial funding to carry out routine maintenance activities and unless something is done to overcome this problem, it can threaten the sustainability of such solar systems (Oluwaseun et al., 2020). Therefore, it is crucial to raise the capacity in order to preserve the region and it is essential to provide access to long-term financing instruments of such projects.

3.3.2. Community-Led Initiatives for Energy Ownership and Sustainability

It has been established that social projects are effective in driving sustainability of solar energy endeavors in Nigeria. Such programs empower the local communities not only to appreciate the outputs of solar energy but also to own and control their own renewable energy networks and this leads to improved ownership and sustainability. The other development is the creation of energy cooperatives or associations by localities to oversee the installation, maintenance and use of solar systems in various regions of Nigeria. These types of cooperatives tend to work with governmental agencies, non-governmental organizations, and businesses to finance and implement solar programs.

One such project is the Nigeria Electrification Project (NEP) Tech currently targeted at providing off-grid solar mini-grids and home solar systems to unserved and underserved urban rural areas. The NEP has also developed models of community ownerships in which the communities are likely to participate in governance and finance management of mini grids. This has led to locally built capacity and ownership with a feeling that it is ours and it has enabled maintaining that the solar systems are well fed and sustainable financially (Amadi et al., 2020).

One of the major advantages of these community led projects is that the ways in which the communities want the solar projects to work can be customized. Decisions concerning solar energy solutions should be made locally so that they are tuned to suit challenges facing different communities. Moreover, the participation of the communities in the management of the systems will build the domestic capabilities and generate employment opportunities and the feeling of empowerment. Nevertheless, even though the community ownership models have proven successful, some remaining issues include the cost of initial capital investments, insufficient training opportunities, and ineffective financial access (Ogunlade et al., 2019).

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3.4. Ethiopia: Integrating Solar Energy into Rural Development

Ethiopia, characterized by large rural population has taken giant steps in integrating solar energy in its rural development in its broader scope to encourage sustainable development and ease the level of poverty in the country. With energy demand growing in Ethiopia, the government realized the need of using renewable energy sources towards accomplishing its development objectives, especially in electric power to the rural areas. In this strategy, an important place belongs to solar energy as an economical and environmentally friendly source of power.

3.4.1. Government Support and Policy Incentives for Rural Electrification

The Ethiopian government has implemented a range of policies aimed at promoting the expansion of renewable energy, particularly in rural areas. Notable among these policies is the Rural Electrification Program (REP), which seeks to provide reliable electricity to rural communities using sustainable energy sources such as solar, wind, and hydroelectric power. The government also developed the Ethiopia Energy Access Program, which focuses on scaling up renewable energy technologies, including solar energy, to achieve universal access to electricity by 2030 (Berhanu et al., 2020).

In order to realize these endeavors, Ethiopia has offered accommodating policy platform, which comprises of incentives on solar technologies, tax holidays on importation of renewable energy and motivating the involvement of the private sector. Government and the international organizations, the world bank, the European Union and the United Nations Development Program (UNDP) have worked together so as to obtain funds and technical assistance regarding the rural electrification program. With this partnership, Ethiopia has documented an impressive milestone in adopting the solar energy solution especially in the rural areas where the grid is difficult to expand (Abdi et al., 2019).

Furthermore, the National Electrification Program (NEP), the Ethiopian initiative, that started in 2018 is expected to intensify the use of solar energy in the off-grid and rural populations. The program is centered on decentralized solar in the form of solar home systems and mini-grids to deliver clean-reliable electricity to the underserved populations. Pay-as-you-go (PAYG) solar systems are pushed by the government as well in order to make it more affordable to the low-income population (Gedefaw et al., 2021).

3.4.2. Case Study: Solar Solutions for Health and Education Sectors

Renewable energy can support development activities, as in Ethiopia, where solar energy is used to improve healthcare and education in rural areas. A very good example is the use of solar-powered energy devices in health facilities and schools in the distant parts of the country. Such systems especially in places where connection to the national grid is either not available or unreliable.

Solar power is used to operate refrigerators for vaccines, provide lighting for medical staff, and power other essential medical equipment in rural health centers. For example, in the Southern Nations, Nationalities, and Peoples' Region (SNNPR), the energy supply of several health facilities has been converted to solar power, ensuring that vaccines are stored at the required temperatures; an essential factor for the effectiveness of immunization programs. In another example, solar-powered systems used on health posts in the rural areas have assisted in mitigation of expensive diesel generators, a less expensive and sustainable alternative solution (Gedefaw et al., 2021).

Solar has been utilized in the education sector to increase the learning hours in schools in rural areas, introduce lighting in evening studies, and in the usage of the computer in the digital learning process. The installation of solar systems in schools has provided students with electricity for lighting, which is particularly essential in areas without access to the grid. As an illustration, the Ethiopian Ministry of Education together with international donors has put a program in place to install solar systems in more than 1, 000 schools in the country that are in rural areas and enhancing education opportunities in these disadvantaged areas (Berhanu et al., 2020). These solar solutions have not only led to a stable source of energy but also boosted general efficiency levels of schools and health facilities as they require less use of expensive polluting fossil fuels.

3.5. Malawi: Innovations and Partnerships in Solar Energy Distribution

Malawi (one of the least electrified and smallest nations in Sub-Saharan Africa) has achieved substantial advances towards using solar energy in order to solve its energy access issues in rural areas. Having more than 80 percent of the population residing in the rural settings and where grid extension serves as a very challenging exercise due to the geographical, cost, and technical constraints, the country has resorted to the use of decentralized solar energy systems. Rural Malawi has experienced increased energy access due to solar-powered solutions especially mini-grids, solar home systems, and solar-powered water pumping systems. This section briefly discusses the innovations and collaborations that have defined the solar energy scene in Malawi, especially in the positive impact of international partnerships and the success of solar millions of farmers that depend on solar-driven agricultural irrigation systems in the country.

3.5.1. Role of International Partnerships in Scaling Solar Projects

The success of the solar projects in the country of Malawi plays a pivotal role in international relations and cooperation. Distribution of solar energy in the country has been significant in the scale up of solar energy distribution with the input of international organizations, bilateral development agencies, and investors in the private sector. These arrangements have not only provided funding, but also technical knowledge, capacity building and policy making which has brought in a momentum to implement the technologies of solar in a faster pace.

The relationship between the government of Malawi, World Bank and the United Nations Development Program (UNDP) is one of the most conspicuous ones and has assumed the form of Malawi Rural Electrification Program (MREP). The collaboration has brought an opportunity to intensify the use of an off-grid solar capacity that suggests an establishment of a solar mini-grids and a solar home system in places where the grid-connection might be impossible. The MREP has played a significant role in allowing families to access an avenue to cheap and clean energy to rural area and specifically to the Southern and Central parts of Malawi. With the assistance of the World Bank and UNDP, the government of Malawi has been capable of employing enterprises that include capacity-building of the local authorities and solar technicians, installation of the decentralized energy systems, and the incorporation of the solar energy into the national electrification strategy (Chinsinga, 2021).

Furthermore, Malawi has been living under the crutches of the Africa Development Bank (AfDB) and the German Developmental Agency called GIZ. Technical assistance has been implemented through such groups to install solar mini-grids and business model development which could allow the locals to be involved in the energy value chain. As an example, GIZ has facilitated the operation of Energizing Development (EnDev) in Malawi whose aim is to encourage the use of solar energy in electrifying the rural region where the power is distributed using decentralized systems to serve settlements that are far-flung (Moffat, 2020).

Global financing facilities (e.g., Global Environment Facility (GEF) and Green Climate Fund (GCF) have been pivotal in provision of seed capital needed to finance large scale solar. This capital has enabled the establishment of solar power plants by the local and international companies that helps in poverty alleviation in Malawi, employment, and nature conservation. The global cooperation has also helped facilitate development of transnational partners to perpetuate renewable energies efforts towards establishing synergies between Malawi and other countries in its vicinity that they can be in a position to combine regional energy platforms (UNDP, 2020).

In addition, partnerships with entities in the private sector have helped commission off-grid solar systems and mini-grids. In recent years, various privately owned companies, including BBOXX, Off Grid Electric, and d.light, have collaborated with the Government of Malawi to ensure that the rural population has access to affordable solar home systems through innovative financing mechanisms, such as Pay-As-You-Go (PAYG) model. Such alliances have been critical to scale solar energy access to their long-term sustainability (Bertheau et al., 2019). These alliances lower the price of solar technologies, make these technologies more accessible, and enable the local distribution of solar products providing the country with a functioning market of solar solutions.

3.5.2. Case Study: Solar-Powered Water Pumping and Agricultural Irrigation

Agricultural irrigation is one of the key sectors where solar energy has brought a transformative change in Malawi. Agriculture forms the backbone of Malawi's economy, with more than 80 percent of the population relying on it for their livelihoods. The country also encounters a big challenge in maintaining regular water supply to undertake irrigation activities as rainstorms patterns are uncertain and irrigation channels are weak. Against this background, solar powered water pumping systems have emerged to be a game changer to the rural farmers as they can have access to water to irrigate their farms sustainably, affordably, and reliably.

An illustrative case in point is the Malawi Government-led solar-powered irrigation program which is run in collaboration with the International Fund for Agricultural Development (IFAD) and the GIZ. The project undertaken was supposed to increase agricultural output in rural areas by empowering the smallholder farmers to use the solar-powered water pumps to irrigate their farms. The project focused on parts of Central and Northern Malawi where agriculturalists have worked under rain-based farming that is primarily compromised by seasonal rain occurrences (Jumah et al., 2021).

The introduction of solar-powered water pumping systems has enabled farmers to significantly increase crop yields and generate income by irrigating their fields during the dry season. For example, the solar-powered pumps installed within the districts of Mchinji and Dowa have enabled farmers to irrigate maize, vegetables, and fruits, hence remediating food security and increasing the capacity of the rural population living to change climate. These systems also have the benefit of lessening the use of the costly diesel-powered pumps, as the systems work on the energy harvested by the sun, thus giving the needed solution to their pumping needs and in a cost-competitive manner that is not harmful to the environment (Saha et al., 2020).

A solar-powered water pumping system was installed in the village of Nsanje, providing water for both household use and irrigation of agricultural fields. The World Bank and the Government of Malawi, through its Ministry of Agriculture, have successfully implemented the project. By directly pumping water from a nearby river, the system has helped boost agricultural productivity and alleviate water scarcity that typically affects farmers during the dry season. Another benefit of the solar-powered irrigation system is that farmers are no longer forced to rely heavily on chemical fertilizers and pesticides, as they now have the means to grow crops more sustainably (Nkhoma et al., 2020).

The effects of solar-powered irrigation have gone beyond the production of more agricultural output. It has also given farmers greater autonomy to their livelihoods and has aided in improving the local economy. The implementation of the systems has also enabled women, who are the usual targets of providing water, to save time and direct their efforts to more economic acts including agriculture and nano industries. Small agro-processing businesses, which tend to generate some possible employment, have also been powered with solar-powered irrigation systems in some other instances, boosting local economic developments (Moffat, 2020).

Nevertheless, while solar-powered irrigation can be considered one of the most effective solutions for supporting smallholder farmers in Malawi, it faces several challenges. Despite the availability of financing options, the high initial cost of solar irrigation systems remains a significant barrier for many farmers. In addition, maintaining these systems requires technical expertise, which is often lacking in rural communities. To address these issues, the government and international partners should continue to invest in training programs, affordable financing mechanisms, and reliable after-sales services for rural communities (Chinsinga, 2021).

4. Socioeconomic Impacts of Decentralized Solar Energy Systems

The implementation of decentralized solar energy mechanisms, such as solar home systems, solar-powered mini-grids, and water pumps: plays an important role in shaping the socioeconomic structure of rural populations in Sub-Saharan Africa and other developing countries. These systems provide access to affordable, reliable, and sustainable energy, which in turn fosters economic development, improved healthcare, and enhanced educational opportunities. The following section examines the health- and education-related impacts of decentralized solar energy, with particular attention to how such systems are improving the quality of life in rural communities.

4.1. Health Impacts

Improved access to reliable, good-quality electricity is essential for enhancing health outcomes in rural communities. Solar power has also played a major role in enhancing provision of essential health services by facilitating the energy provision of health institutions, decreasing the dependency on hazardous fuel sources and the ability to provide improved lighting on medical procedures. Since the rural regions usually do not have access to a stable and uninterrupted source of power, the decentralized solar energy sources seem to be the cheapest and sustainable way out of the issues.

4.1.1. Improved Access to Lighting and Health Services

Enhanced access to lighting as one of the most expedient results of decentralized solar systems manifests itself into better capacity of conveying necessary health services in the rural setting. In many rural settlements, health facilities lack access to reliable electricity, which constrains their ability to provide essential services such as emergency care at night, vaccine refrigeration, and the operation of critical medical equipment. The lighting systems in the health centers run on solar power enabling the medical workers to continue with their operations effectively at night time which increases the overall quality of health services offered.

Examples of applications of solar energy in health posts and rural hospitals include the provision of light to medical personnel, the possibility of conducting health services at night, and the running of key facilities of health services (Gedefaw et al., 2020). Applications of solar energy in maternal and child healthcare have provided significant benefits, particularly through the provision of reliable lighting during childbirth and infant care. For example, in rural hospitals in Tanzania, solar technology has been used to provide strong lighting, enabling midwives and medical professionals to deliver safe birth services even at night. This has significantly reduced maternal and infant deaths associated with home deliveries, where households often relied on inadequate lighting sources such as kerosene lamps or candles (Mdee et al., 2020).

There is also solar energy that is useful to the refrigeration that is vital in the preservation of the vaccines and medicines. Solar-powered refrigerators were also installed in numerous rural health clinics in Sub-Saharan Africa to provide safe and adequate temperature conditions to keep vaccines stored, which means that it is possible to conduct immunization campaigns successfully (Ngugi et al., 2020). Through their use in refrigerating vaccines, solar energy can aid in increasing the vaccination rate in hard-to-reach places which is a big step in preventing such preventable diseases and consequently improves the overall health of the population.

4.1.2. Reduced Reliance on Kerosene Lamps and Mitigation of Indoor Air Pollution

The other significant health implication of decentralized solar energy is the mitigation of the dependency to the use of kerosene lamp and other deleterious lighting methods. Kerosene lamps are used as the main source of light in most rural areas, nevertheless, they are highly hazardous to the health of the inhabitants. Use of kerosene lamps emits indoor air pollution which may be in the form of carbon monoxide, particulate matter, volatile organic compounds, linked to respiratory diseases, including asthma, bronchitis, and more chronic disorders (Roth et al., 2020). In addition, kerosene lamps generate fire, which leads to injury of households and damage of their property.

The adoption of the use of solar powered lighting systems to replace the kerosene lamp has offered a solution on this issue effectively. Lights which make use of solar energy are clean, safe and environment friendly. They also exclude indoor air pollution that kerosene entails, and minimize the chances of fire in the household (Bensch et al., 2019). In the communities where solar lighting has been implemented, households claim to have fewer cases of illness found in the respiratory system, and also exposure to toxic indoor air pollutants is lower. To give an example, a household survey conducted in rural Kenya revealed that the air was considerably cleaner when people used solar lamps, and it improves both childhood and adult air health outcomes (Mekonnen et al., 2020).

Besides the better health outcomes, the use of kerosene has also decreased which has an economic advantage. This is because households do not have to use a large percentage of the income on kerosene thus bringing resources to other priority needs like food, education, and medical expenses.

4.2. Education Impacts

Reliable and affordable energy that is provided by decentralized solar systems means transformative changes in education in rural locations. Availability of electricity can help students study in the evenings, the teachers utilize digital learning devices and increase the schools operating time, and all that play an important role in the enhancement of education. Solar energy has been demonstrated to serve as an important aspect in improving the quality of education in Sub-Saharan Africa as well as dealing with some of the critical problems affecting the rural schools.

4.2.1. Enhanced Learning Opportunities with Better Lighting

One of the most immediate effects of solar energy on education is the extension of learning hours, particularly in rural settings where access to electricity and adequate lighting is limited or entirely absent. In a majority of schools in the countryside, pupils do not even have time to study beyond the setting of sun because there is no proper source of lighting. The lighting facilities by solar power enable students to study during the night, thus enhancing their success in learning (improving academic achievement).

An example of this is the way the children in rural communities in Malawi have been able to study in the evenings with the introduction of solar lighting in the schools allowing the rural population to close the gap between access to education in the rural and urban areas. On the one hand, students of the rural schools whose lighting system was powered by solar energy showed better academic results than those in the schools lacking electricity (IIED, 2019). Besides, the application of solar light in such schools can allow teachers to develop lesson preparation and delivery done during evenings, which improves the overall level of education both in students and educators.

The gender equality in education has also been enhanced by the provision of solar powered lighting. Girls are ill-off compared to their male counterparts in most of the rural communities, mainly because of household responsibilities and the fact that they have no source of light during the nighttime studying. Electricity powered by the sun has also enabled girls to continue accessing education at night making them more likely to attend school in their rural locations (Lloyd et al., 2020). This has greatly enhanced better educational levels and equality in education between the genders through the capacity to study at night.

4.2.2. Solar-Powered Educational Infrastructure in Rural Areas

In addition to enhancing lighting, the development of more sturdy educational setups in the rural regions due to solar energy has also been achieved. Solar-powered systems have already been installed in most schools to supply computers and digital learning tools among other technologies which make learning experience to be enhanced. The use of computers and the internet powered by solar has opened the doors to rural schools to join in the digital education programs allowing students

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to have access to a cornucopia of online tools and sources that did not exist in the past (Nelson et al., 2020).

For example, solar energy has brought the internet and computer use in schools in rural parts of Uganda, having extended access of students to learning resources beyond the textbooks. The advent of digital means of learning has assisted in killing down educational gap between urban and rural environment enabling students in remote regions to enjoy online courses, e-learning, and education videos. This move has made the process of education more exciting, especially when it comes to the study of science and technology which always demand demonstrations and online materials (Ochieng et al., 2020).

Infrastructure facilities made out of solar energy have also assisted in the betterment of school facilities. Water pumps serving sanitation facilities are also provided by solar energy systems so that schools have a drinking and sanitation water supply. Water pumps powered by solar energy have caused an uprise in the level of hygiene in schools in some regions where sanitary water is lacking, leading to the increased health levels of both students and staff (Loughnan et al., 2020).

4.3. Economic Impacts for SMEs and Rural Businesses

Deployment of decentralized solar energy systems such as; solar home systems, mini-grids, and solar-powered appliances has manifested significant economic effects of small and medium business and rural enterprises in Sub-Saharan Africa. Arguably, access to dependable energy at an affordable cost is essential to the growth and sustainability of businesses especially in the rural places where traditional energy infrastructure is unreliable or does not exist at all. Solar energy has also emerged as a low-cost alternative, not only providing businesses with the energy required for their operations but also contributing to economic development by encouraging new enterprises and strengthening locally driven economic activities.

4.3.1. Empowering Small Businesses with Reliable Energy Access

The constant availability of electricity is one of the basic criteria of business activities but most small businesses in the rural regions of Sub-Saharan Africa suffer intermittent or lack of access to electricity. The solar energy systems offer a low cost and dependable solution to expensive and many times unreliable grid electricity and therefore rural business is in a position to improve its profitability and productivity. In Kenya, Tanzania and Uganda, the use of solar-powered systems has seen the small enterprises increase their operating hours, power machines and lower their reliance on diesel generators that have high costs and produce pollution.

As an example, small shops such as barber salons, shops, and food sellers in rural Kenya have managed to maintain their businesses until the late evening hours because of the solar-based solutions available in the country. Such businesses have gained access to consistent lighting through solar energy, which also powers refrigerators and other small-scale machinery essential to their operations (Tschirley et al., 2021). Solar energy application in the rural part of Uganda have eased agricultural business activities because such sources power irrigation fans, mills, and other relevant devices (Kigozi et al., 2020). The cost savings involved in avoiding the use of diesel fuel or kerosene lamps along with the availability of inexpensive solar technologies has allowed the rural businesses to minimize their operation cost, increase their competitiveness and their profitability as well.

Solar-based systems are also used to boost the reliability of operations of businesses. Its operations in the case are an example because the majority of the rural villages are laden with power cuts alongside their unreliable grid connections and hence may lead to loss of income and increased cost of operation. By utilizing solar energy, a person gets a solid and dependable source of energy, which is quite crucial to businesses that require energy to cool, illuminate, or power machines on a regular basis (Barrett et al., 2020). The presence of a source of energy that is dependable can also allow the SMEs to maintain constant operations, risk, and even presence of business due to the installation of solar systems.

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4.3.2. Growth of New Local Enterprises Supported by Solar Energy

In addition to strengthening the assets of existing firms, simple solar energy systems have also led to the formation of new companies. The solar energy solutions have provided pleasant environment of doing business and more so in the rural settings where the energy infrastructure is not well developed. The availability of the affordable solar energy has led to the emergence of new businesses supplying solar products, installation, and the solar maintenance solution and this has helped to stimulate commerce.

In Sub-Saharan Africa, regional entrepreneurs have appeared as resellers and as installers of solar-powered systems in, among others, Ghana and Nigeria. This has opened up new markets of solar technologies, created employment and led to increase in the green economy. As an illustration, in Nigeria, there is an increase in small businesses that are selling solar installation and repair services by taking advantage of the fact that more individuals in the rural communities need solar home systems and mini-grids (Awotide et al., 2018). Such new businesses help not only grow the economy but also improves the knowledge and local capacity in the realm of renewable energy which further boosts the spread of solar technologies.

Besides generating employment opportunities in the energy industry, solar energy has also facilitated expansion of new enterprises in other industries, especially the agricultural sector. The availability of solar-powered irrigation systems has enabled farmers to develop the corresponding businesses connected with the production of vegetables and fruits since the latter was constrained previously by the lack of access to consistent water supply (Sommerville et al., 2019). Solar agricultural irrigation systems have further led to the rise of agro-processing industries in the form of food-drying and milling businesses, which are highly dependent on the availability of steady energy sources (Ajayi et al., 2020). By doing so, solar energy is important in enhancing economic diversification and encouraging local businesses especially in the rural development where economic growth opportunities are usually scarce.

4.4. Women Empowerment and Social Inclusion

Installation of decentralized solar energy systems has significantly affected the socially inclusiveness, namely gender equality and empowerment of women. Women in the rural areas can greatly be helped by increasing the availability of reliable energy to facilitate the lives of women by saving their time spent in household chores, health conditions, and income generation. Solar power has thus been an important tool as far as easing gender inequality and women empowerment is concerned since it enables entrepreneurship among women and employment opportunities.

4.4.1. The Role of Solar Energy in Empowering Women Through Entrepreneurship

The availability of solar energy has given the women certain entrepreneurial prospects particularly in the rural set up where they have a challenge of getting electricity. Firewood or kerosene for lighting has posed a big problem to women who traditionally get involved with this activity. This is because most of them have domestic chores. They have saved these traditional forms of energy by installing solar powered systems that have accorded women more time to carry out other economic activities like running small businesses, undertaking agricultural activities or to go into the labor market.

In rural Kenya, solar-powered systems have enabled women to establish small businesses, including mobile phone charging stations, which not only generate income but also enhance energy access within their communities (Kigozi et al., 2020). Solar energy has further allowed women to engage in activities such as food processing and handicrafts, which require the continuous use of electricity-powered machinery. By reducing reliance on firewood and other traditional energy sources, solar power has empowered women to improve their livelihoods and gain economic independence (Bensch et al., 2020).

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Additionally, the growth of solar energy has led to the emergence of women-led solar enterprises. For example, in Uganda, women have taken the lead in solar distribution and business development, helping to address the gender gap in the renewable energy market. These women entrepreneurs not only increase their personal income but also contribute to the expansion of the renewable energy sector, making solar products and services accessible to previously underserved communities (Sommerville et al., 2019).

4.4.2. Gender-Inclusive Benefits of Decentralized Energy Systems

Decentralized solar energy systems offer highly gender-inclusive benefits, particularly in enhancing women's well-being and contributing to community development. The adoption of solar energy has empowered women by reducing the time and effort they spend on domestic activities. For instance, solar lighting allows women to perform cooking, cleaning, and caregiving tasks at night; activities that were previously constrained by the lack of reliable lighting (Karekezi et al., 2017). The time saved can then be invested in income-generating ventures or other community development activities.

The health benefits of solar energy for women and children are also significant. The use of clean solar lighting mitigates indoor air pollution, which disproportionately affects women and children due to kerosene-based lamps and traditional cooking stoves (Roth et al., 2020). Solar energy contributes to a healthier indoor environment by improving air quality, enhancing the safety of women and their families, and reducing the risk of respiratory illnesses, burns, and other accidents associated with inadequate or hazardous lighting.

Moreover, solar energy is also influential in ensuring that different people are socially included based on their energy requirements. In many cases, women especially living in rural and remote locations do not enjoy the fruits of economic growth and development since access to electricity is also limited. These women can more actively engage in economic, social, and cultural operations due to access to decentralized solar energy, which means increased social equality and inclusion (Zhou et al., 2019).

The gender-sensitive benefits of solar energy are further enhanced by women-focused energy initiatives. Programs that involve women in solar energy projects and decision-making processes ensure that their voices are heard regarding the future of energy in their communities. Such initiatives not only equip women with technical skills to operate solar power systems but also enable them to create employment opportunities and contribute to the local economy (Gordon et al., 2019).

5. Financial Models for Scaling Decentralized Solar Energy

Various financial models have been developed to increase access to decentralized solar energy solutions among underserved populations. These models aim to overcome the high financial barriers associated with solar energy, including the substantial initial capital costs of installation and the limited access to finance for low-income households. Among these instruments, the Pay-As-You-Go (PAYG) system and community ownership models are considered particularly promising. Both approaches provide innovative mechanisms to fund solar energy projects and ensure their long-term sustainability. This section discusses the PAYG and community ownership models, examining how they operate and their impact on scaling decentralized solar energy systems in Sub-Saharan Africa and other developing regions.

5.1. Pay-as-You-Go (PAYG) Model

Pay-as-you-go (PAYG) system has been deemed as a revelation in overcoming financial hurdles, which stands as a barrier in the implementation of solar power systems in off-grid communities. In the pay-as-you-go model, the consumers afford and purchase the solar systems without the up-front cost which is clearly out of reach to most of the households in the rural areas. Instead, the payments

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are done in small portions over time usually by means of mobile money, thus providing a financially viable method to fund the solar energy solutions.

5.1.1. Introduction to PAYG and Its Mechanisms for Affordability

The Pay-As-You-Go (PAYG) model is a financial mechanism that enables individuals, particularly in low-income communities, to access solar energy without the need to pay high upfront cost typically associated with solar systems. Through the PAYG model, solar products such as solar home systems, solar-powered lights, and mini-grids are leased to customers on a lease-to-own basis. Customers make small, manageable payments over time, which can be paid via mobile money platforms such as M-Pesa in Kenya. This model allows customers to pay for the solar products in installments, typically based on their energy usage, making it affordable and accessible for even the most financially vulnerable groups. The prepaid nature of the system ensures that those who may not have the means to finance a full solar system upfront can still access reliable, renewable energy. PAYG thus provides a sustainable and flexible solution to the challenge of energy poverty, especially in rural areas where access to electricity is limited or non-existent (Foster et al., 2020).

The main rationale underpinning the affordability of PAYG model is the capacity to generate payments that are pegged onto the energy consumption of the system. Customers normally get charged on the use of energy like an electricity bill and payments are spread out over time to make the payments affordable. This framework helps customers to make payments depending on their income patterns where the solar products will be affordable and accessible. Furthermore, the mobile money facilitates payment by customers without having to go to the physical bank which is not viable in the rural areas where services of the bank are not readily available.

There is some security given by PAYG models to the consumer and provider as well. The model addresses the financial risk that consumers have to take due to a hefty initial payment and, on the other hand, it can be considered by the providers as a method of financing the up-front cost of solar installations and ensuring affordability to the consumer (Liu et al., 2021). Also, since payments are made over a period of time, the system thence changes to the ownership of the consumer once paid in full, and this guarantees the clean and cheap energy over a longer term.

One of the main strengths of the PAYG models is the aspects of scalability. The PAYG model, through alliances between solar power companies, mobile money systems and financial institutions, becomes able to expand across huge geographic locations, and provide millions of individuals off the grid with access to solar power. Such a model has been successfully utilized especially in Sub-Saharan Africa, where many people have no access to electricity.

5.1.2. Case Study: PAYG Impact in Kenya and Other Countries

Kenya has been a leader in the uptake of the pay-as-you-go (PAYG) approach to rural access to solar energy. It can be said that the popularity of PAYG systems in Kenya is because of the popularity of mobile money services such as M-Pesa, which has enabled consumers to pay small frequent payments towards solar systems. M-KOPA famous provider of PAYG solar systems in Kenya had brought at least 750,000 households in Kenya access to solar power using its PAYG model (Foster et al., 2020). The solar home systems distributed by the company usually serve to provide light, phone chargers and small appliances whose provision has tremendously enhanced the quality of life of millions of people living in off-grid regions.

Effects of the PAYG Systems in Kenya are not only in breach of electricity. It has been demonstrated that the health impact of solar systems is positive through the limitation of the use of kerosene lamps, which results in the development of indoor air and respiratory issues. There is also an increased access to solar energy allowing students to study even at night thus, the educational system has shown better results (Ochieng et al., 2018). The smaller companies have also been served as they have been able to spread out the time of operations as well as cut down on the use of expensive diesel generators and destroying diesel fumes because of the availability of certain solar energy.

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The success of PAYG system in Kenya has encouraged like models in other nations in the Sub-Saharan Africa. PAYG Solar solutions have seen Tanzania rise in the remote areas that have better access to electricity. Other examples are Off Grid Electric and d.light, which collaborate with mobile money providers to increase the availability of solar energy in Tanzania, Uganda and Rwanda with significant effects on the rural economy due to access to low-cost energy sources (Njeru et al., 2020).

Although the PAYG model has been successful in various African markets, it still has its difficulties. The costly nature of solar equipment production is one of the significant obstacles, and even though with incremental payments the poorest households might overcome the cost barrier as well, it still remains a significant factor. Moreover, the sustainability model of PAYG model relies on the constant increase in mobile money services and on the companies to assume the responsibility to maintain and offer after sales measures.

5.2. Community Ownership and Cooperatives

Another possible solution that has been implemented to scale decentralized solar energy systems is community ownership of those systems. In contrast to the PAYG system that is commonly based on the ownership and payments of one individual, the community-based ownership models aim at collective responsibility and commonality of solar systems. Such models can enable rural communities to gain control over their energy assets and energy management so that the solar power yields may be distributed among the whole community.

5.2.1. Solar Cooperatives and Community-Led Models

Communal-driven energy models and solar cooperatives aim at jointly managing solar energy systems, their operation and maintenance by the community. Within this arrangement, a community of people or households forms a collective to share among them and invest in a solar energy infrastructure. The investment, installation and maintenance of the system is done by the community and any profits resulting to the sale of energy or providing services are used to replenish the cooperative to fund a community growth project.

The main benefit of solar cooperatives is that they have a potential to decrease the expenditure spent by people on energy and at the same time create its capacity and develop a sense of ownership and empowerment by a community. As an example, in some countries such as Ghana and Uganda, rural communities have established cooperatives to run solar mini-grids, electricity produced on which is consumed domestically and also applied in local businesses. Such cooperatives have typically been furthered by international development organizations and governments and offered financing, technical knowledge, and policymaking assistance to grow the model (Kammen et al., 2021).

Community-based solar in Ghana has been promoted through the development of the community-based solar programs under the Energy Commission of Ghana where rural communities can engage in energy management. Through these efforts, the local economy has expanded with the activities of small-scale farming and food processing enabled by the presence of a reliable source of energy, namely irrigation, milling, and refrigeration (Agyemang et al., 2020). Also, there is the establishment of employment opportunities whereby through a community-driven solar project, local technicians and workers who have trained to install and maintain solar systems have been employed to create sustainability and self-reliance in the long-term.

5.2.2. Benefits of Collective Ownership in Mini-Grid Systems

The mini-grid systems led by the communities provide a number of advantages to the communities that live in remote areas. First, it offers a steady and cost-effective energy supply capable of electrifying homes, schools, healthcare institutions, and small companies that increases the living standards of the area in general. The economies of scale can also take place through sharing of resources where a community can pool its resources to allow the cost of installation and maintenance to occur.

Local control: Mini-grid systems are also used to promote shared responsibility and inclusion, wherein communities are in charge. Keeping energy infrastructure in local ownership will allow decisions to be made locally based on local needs and priorities and positions energy systems that are fit to local environments. This has brought about innovation in energy services, in some instances, to the advantage of local farmers, smaller manufactures and providers of services because they have access to stable power to satisfy irrigation, refrigeration and similar services needs when previously they did not have power at all (Gulati et al., 2019).

Furthermore, collective ownership structures empower communities to take control of their energy future. These models provide a platform for community interaction and participatory decision-making, which strengthens social cohesion and supports local governance processes. The success of such models depends on active community participation and the establishment of clear governance structures to ensure transparency, accountability, and proper management of the solar systems. When well-structured and effectively managed, community ownership models not only enhance access to renewable energy but also promote a sense of shared responsibility and long-term sustainability (Agyemang et al., 2020).

However, community ownership models face challenges related to governance and effective management, which are often complex in nature. To ensure the long-term success of such projects, strong local institutions must be established to oversee operations and maintain accountability. In addition, the high initial capital required for these projects remains a significant barrier for many rural communities. To address this, financial support from local governments and international stakeholders is essential, ensuring that communities can access the necessary resources to implement and sustain these solar energy initiatives.

5.3. Financing Mechanisms and International Partnerships

In rural and underserved regions of Sub-Saharan Africa, the widespread deployment of decentralized solar energy systems relies heavily on effective financing mechanisms and cross-sector collaborations. Given the high upfront capital costs of solar technologies and the financial constraints faced by local communities, innovative funding solutions are essential to support the broad adoption of solar energy. These solutions include financial aid from development banks, impact investments, crowdfunding, and partnerships among diverse stakeholders such as international organizations, governments, and private sector entities. This section of the paper examines the roles of financial institutions, development banks, crowdfunding initiatives, and impact investments in promoting and sustaining solar energy projects.

5.3.1. Role of Financial Institutions and Development Banks

The financing of renewable energy project, which is mainly solar energy systems in the developing countries is a familiar and critical engagement of the financial institutions and the development banks. It is these institutions that provide the needed capital risk management tools as well as financial instruments hence facilitate implementation and investment on solar energy projects. According to the information, there exist very high barriers to solar diffusion in the governments of various countries in the Sub-Saharan Africa region, where installing a solar system is quite costly. Examples of the development banks that have been paramount in terms of their financial contributions to such projects are the African Development Bank (AfDB), World Bank and European Investment Bank (EIB).

The African Development Bank (AfDB) is a good example of such relationship as it sponsors events of the so called, Desert to Power project, which aims to harness solar energy along the Sahel corridor that stretches across a few countries in Sub-Saharan Africa. The AfDB in conjunction with the use of concessional loans and grants has enabled the establishment of solar projects, which would otherwise not be funded individually by the efforts of the private players (AfDB, 2020). These

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financial institutions are offering finance at long term that causes less cost of capital and proposing fair terms of repayment to solar energy ventures in rural areas. They can also come in handy in mitigating risks taken during venturing into such types of investments by making guarantees and insurances.

Development banks have also collaborated with governments to establish friendly policies and financial environments to develop the renewable energy projects. They tend to offer technical support, capacity building initiatives as well as policy advising services in order to make sure solar energy initiatives are executed in a productive expedient manner. In Kenya, the World Bank, on the other hand, has helped the government in such a move by providing loans and grants to allow it put in place off-grid solar systems and mini-grids to ensure that solar energy plays a role in its rural electrification strategy (World Bank, 2019). Such engagements have resulted in the effective scaling of solutions around solar energy as well as the creation of sustainable financing models, which are replicable in other African regions.

5.3.2. Crowdfunding and Impact Investments for Solar Projects

Crowdfunding and impact investments have played a greater role in the financing of decentralized solar plants. The alternative sources of financing are especially applicable when financing smaller projects or where funding has become unavailable, possibly due to the size of the project. Crowdfunding has facilitated ordinary people and organizations to raise funds to install solar energy systems by seeking donations or investment in a mass network of donors or investors, some of whom might be willing to support the environmental sustainability cause and social justice.

SunFunder is both a leading debt-financing provider and a prominent crowdfunding platform for distributed solar projects in Africa and other emerging regions, facilitating energy access and long-term climate investments. The organization has disbursed over USD 150 million in loans to 57 solar companies involved in off-grid solar, mini-grids, agri-solar, and other commercial and industrial (C&I) solar projects. As a crowdfunding platform, SunFunder has enabled investors to lend capital to small-scale solar energy systems, with repayments made as the projects generate revenue. Crowdfunding initiatives have also been successfully implemented in countries such as Tanzania, Kenya, and Uganda, where local communities have financed solar home systems and mini-grids directly, bypassing traditional financial institutions. This approach has expanded investment in solar energy and increased community participation in energy access projects (Guevara et al., 2020).

Impact investing, which aims to generate both financial returns and positive social or environmental outcomes, has been crucial in scaling solar energy solutions in Sub-Saharan Africa. The potential benefits of solar energy projects, including improved energy access, climate change mitigation, and economic growth, attract impact investors. These investors often collaborate with local business owners or solar energy companies to finance projects that bring tangible changes to rural communities. Notable impact investors, such as the Acumen Fund and the Shell Foundation, have actively supported solar energy enterprises, contributing significantly to the provision of clean energy for off-grid populations (Roberts et al., 2018).

A mix of crowdfunding with impact investments has contributed to filling the funding gap that has restricted solar projects. These financing mechanisms are helping realize solar energy systems in locations that otherwise would not be part of the traditional investments by cashing in the popularity of sustainable investing and social impact.

5.4. Government and Donor Funding for Solar Energy Expansion

This role has been impacted by the government financing and donor financing to facilitate the rise of solar energy within the rural community within the Sub-Saharan Africa. This aspect highlighted by the compensation of the cost of the solar system and issuance of the project and concessional loans to the solar firms has been eminent in the mechanism of sponsoring of the solar systems particularly by both the governments and international donors. These funding instruments contribute significantly to the resolution of the cost impediments against solar energy technologies,

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which arise at front, enabling country applications of universal clean energy to gain roots in the rural setting.

5.4.1. Subsidies, Grants, and Concessional Loans for Solar Initiatives

The use of solar energy to achieve the rural energy access goals and sustainability in development has become a major issue of governments of the Sub-Saharan Africa. In an attempt to increase the application of the solar technologies, different governments have introduced subsidies, grants and concessional loans seeking to reduce the costs of the solar systems so as to reduce the costs to consumers. The financial instruments lowered the entry costs of the solar energy and it had become an attractive option to both the low-income households and the rural businesses.

This could be illustrated by the time the Kenyan government initiated the solar home systems subsidy program whose purpose was to reduce the number of solar installation costs among the rural home owners. The World Bank funded program would be targeted at availing solar energy companies with funds to align the prices of solar products to become affordable to the low-income families. The subsidized loans have also been provided to the solar companies in order to help strengthen their operations and reduce the price of solar manufactured products to their customers (Adams et al., 2020).

Donors have also funded solar projects in a very profound manner. Organizations such as the Global Environment Facility (GEF) and the Green Climate Fund (GCF) have mainly funded the grants and low-interest loans in the solar energy projects especially in rural setup. This capital is employed in the process of adding solar infrastructure, primarily mini-grids and solar irrigation, in underserved markets. The example of Solar initiatives in Uganda financed by the GEF, in that case, has already made it possible to implement solar mini-grids in local populations that helped to enhance the lives of thousands of people (GCF, 2020).

5.4.2. Partnerships Between Governments and Private Sector Actors

In Sub-Saharan Africa the factors that have contributed to the development of solar energy have been significant public- private investment in solar energy. Governments are presented with a chance to exploit expertise, technology, and funds needed to scale up solar energy operations through the assistance of the players in the private sector. Governments use such partnerships to provide the policy and regulatory framework crucial in offering solar energy development and the technology and capital required to initiate the projects come in through the private corporations.

The other successful Public Private Partnership (PPP) in the solar power business is between the solar companies in the country and the Zambian government in the development of solar mini-grids in the rural locations. In the process implementing the idea and installation of solar powered mini grids to supply power to off grid communities, the government of Zambia has collaborated with external solar firms including First Solar and Enel Green Power. By doing so, it has facilitated the expansion of the solar energy in rural Zambia, which took place at an accelerated pace, as the government has developed financial and policy benefits, whereas the private sector has delivered the required infrastructure and technology (Mbewe et al., 2020).

The private sector in renewable energy also tends to favor Public-Private Partnerships, as the long-term sustainability of solar projects often depends on such collaborations. These partnerships allow the government to contribute by creating a conducive environment for solar energy, including the provision of supportive policies and subsidies, while private firms bring necessary investment, innovation, and expertise to address the energy needs of rural communities. Moreover, these alliances help ensure that solar projects align with national energy plans and development goals, maximizing their potential impact on poverty alleviation and sustainable economic growth.

6. Policy and Regulatory Challenges in Scaling Solar Energy

Although the potential of decentralized solar energy systems in Sub-Saharan Africa is enormous, numerous policy and regulatory issues are impediments to scaling the systems. Such issues may inhibit the mainstream usage of solar technologies, and thus remote villages can still not take enough advantage of renewable energy options. Regulatory and policy conditions are central factors in defining the extent to which solar energy may be deployed to serve the energy requirements of underserved populations to a sufficient extent at the required scale. This part excepts the regulation obstacles that the decentralized solar system faces, policy support that solar energy pioneers need, and the necessity of aligning regulations across the borders to allow go-ahead with regional energy integration.

6.1. Regulatory Barriers to Decentralized Solar Systems

Regulatory frameworks inconsistency and intransparency of the decentralized energy system is one of the major problems that would challenge scale up of the solar energy systems in Sub-Saharan Africa. There are regulatory constraints to the implementation of these systems, the off-grid solar home systems, mini-grids and appliances powered by solar systems, and these systems are halted in their effective use especially in the rural setting. Some countries lack clear policies and regulations to facilitate easy operation of solar energy companies and could also result in delay in implementation of projects.

6.1.1. Lack of Clear Regulatory Frameworks for Off-Grid Solar Energy

Legislations regulating the usage of the off-grid systems of using the solar energy in the majority of the nations in the Sub-Sahara Africa are nonexistent or could be ambiguous. The policies that certain nations have introduced to promote the use of solar energy lack rigidity and regulations required to spread the concern of pursuing decentralized solar collection in a big way. As an example, the mini-grids and off-the-grid solar in Nigeria and the country of Zambia have to take some time before compensating based on the regulatory structure that has ambiguous roles, responsibilities, and technical specifications in relation to the energy firm under solar power (Asante et al., 2020).

The uncertainties in the sector are largely anchored in the absence of a regulatory framework guiding off-grid solar systems. This gap poses a significant concern, as it can discourage private sector investment in rural solar energy projects. The lack of pricing standards, quality control, and mechanisms for ensuring customer satisfaction means companies are less likely to risk investing in solar systems due to the potential for insufficient returns on their capital (Foster et al., 2020). Additionally, the absence of legal protections leaves consumers without recourse in cases of poor service or faulty installations, which can damage both the reputation of solar companies and consumer trust.

The need for clear regulation of decentralized solar energy has been highlighted by several countries, yet progress has been slow. Governments should develop comprehensive regulatory frameworks addressing critical areas such as licensing, quality standards, pricing, and consumer protection. The primary goal of these regulations is to promote investment, safeguard consumers, and integrate off-grid solar systems effectively into the national energy infrastructure (Iha et al., 2021).

6.1.2. Inconsistent Grid Connection Standards and Licensing Requirements

Other than the absence of regulatory systems of off-grid systems, variable standards regarding connectivity to grid and the inconsistency of licensing is another major challenge to expansion of solar energy systems in rural locations. Some countries have specified procedures in which establishments of a national grid connection (of the decentralized solar systems call mini-grids) is not clear, the standards are different, and the approval processes are long. Incongruent licensing regulations among various regions may also pose a problem to both solar energy companies and the local governments resulting to delay in the implementation of the projects.

Grid connection standards do not have uniformity to make the integration of solar mini-grids with the national grid is quite complicated. The integration of existing mini-grids and the main grid represents a rather definitive process that becomes complex and notorious due to a series of bureaucratic procedures used by many rural communities. In the absence of technical standards of connecting to the grid, there can be a delay or ineffectiveness of the connection and failure to have interconnection between decentralized systems and the grid (Khan et al., 2020).

Moreover, solar energy companies may have quite distinct licensing requirements in different countries, including, and especially, the countries that possess different regions in one country. In others, solar energy businesses are faced with the challenge of going through complicated and expensive licensing processes, which have the potential to undermine the process of solar projects implementation in underserved regions. Such confusion and inconsistency to licensing needs weaken the development of the decentralized solar sphere, keeping away investments of the non-state sector and delaying the process of rural electrification (Foster et al., 2019).

6.2. Policy Support for Solar Energy Initiatives

Solar energy systems require the support of policy to help in their successful scaling, especially among rural communities where energy access is scarce. The government has to make policies that have financial incentives, enable environment to boost solar energy companies and most importantly deploy solar energy system on a sustainable basis. The policy support to solar energy initiative ought to aim at removing obstacles to entry, establishing consistent marketplaces to solar energy publicity and to make sure that the solar energy supports the national development goals.

6.2.1. National and Regional Policies Promoting Solar Energy in Rural Areas

The attempts to push the use of solar energy in Sub-Saharan Africa have seen a number of national policies tried and implemented in the respective countries, especially those found in the rural parts. Examples of incentives under such policies may be subsidies on solar systems, tax free on solar products, and encouragements on investment in the renewable energy in the private sector. As one illustrative example, in Kenya, the government has implemented diverse policy instruments such as tax exemption on solar products or a subsidy of solar home systems, which actually encourage people to use solar energy (World Bank, 2020).

Scaling solar energy projects is highly dependent on regional policies. A notable example is the African Union's Agenda 2063, which emphasizes the development of renewable energy resources, including solar, as a key strategy for Africa's future development. Energy access challenges in Sub-Saharan Africa can be mitigated through the regional integration of policies, as coordinated approaches that promote cross-border energy trade, infrastructure development, and the integration of solar energy into national grids can collectively contribute to sustainable solutions (AfDB, 2021).

At the national level, policy frameworks have encouraged large-scale solar projects in countries such as South Africa and Morocco, while smaller nations have focused on decentralized solar initiatives, such as mini-grids. Regional organizations have also played a role in supporting solar energy adoption through policies that promote integration, knowledge sharing, capacity building, and technical assistance. Examples of such organizations include the East African Community (EAC) and the Economic Community of West African States (ECOWAS) (Karekezi et al., 2020).

6.2.2. Harmonizing Regulations for Cross-border Energy Trade

With a scaling up of solar energy efforts in Sub-Saharan Africa, there seems to be a growing importance surrounding the harmonization of regulations to cross-border trade in energy. Regional power pools have been established in many countries of the region and in order to integrate effective decentralized solar energy systems into these regional grids, coherent technical standards, normative frameworks, policies are required. Setting of uniform standards related to energy trading is necessary in order to make sure that solar energy will be able to be successfully traded across nations and included in the regional grid.

ECOWAS region, as an example, has done a lot towards the encouragement of cross-border energy trade with the ambition of having an attempted West African Power Pool (WAPP), designed to include the national grids into a regional energy market. To incorporate the usage of solar energy into these power pools, the regulations on the grid connection, pricing of energy, and power purchase agreements must be aligned. The harmonization of laws and norms will make transnational energy trade more effective and reliable, which will enable the distribution of solar energy in many countries (Togo et al., 2021).

The convergence of rules of a merchant energy trade across the border also creates the chance to incorporate the private sector investment in regional solar systems. Uniform regulations, as well as tariffs, across countries may be lacking and hence put some investors off as they bring another risk and uncertainty in the picture. Through developing a harmonized regulatory environment in the trade in solar energy, the countries will be able to mobilize more investment in solar energy, enhance reliability of energy at the time of its supply, as well as enable the popularization of solar energy to urban and rural aspects.

6.3. Institutional Capacity and Governance Issues

Whether or not decentralized solar energy systems can be successfully scaled in Sub-Saharan Africa under the aegis of financial resources and the regulatory frameworks is also reliant on the capacity and governance provisions of a given country. Institutional capacity is defined as the capacity of the local governments, organization, as well as communities to control, realize, and maintain solar energy projects. Issues of governance that are likely to impede the process of solar energy developments are corruption, incompetency, and poor coordination among various players. The next section describes issues related to local capacity building of solar energy projects, the role of the local governments in facilitating the rural electrification and some general institutional problems in the solar energy sector in Sub-Saharan Africa.

6.3.1. Challenges in Local Capacity Building for Solar Energy Projects

One of the major problems that the Sub-Saharan African countries have encountered in relation to the growth of solar energy systems is the inability to drive and implement the local activities on the solar systems. This involves insufficient technical labor, poor training skills in addition to the incompetency in the technical skills in installation, operation and maintenance of solar systems. Renewable energy is highly under development in most of the primordial countries and the difference in terms of knowledge and skills to execute a big solar project is mammoth (Alemu et al., 2020).

It is especially evident in the situation of limited skilled workforce especially in the rural community where most solar projects are being initiated. Despite the various efforts that they have put in capacity-building programs, governments have been unable to do a lot in response to the magnitude of the problem. One illustration would be the fact that the demand of having solar technicians and engineers is well above the trained individuals in any given country like Ethiopia and Nigeria. This large pool of unskilled laborers has constituted an obstruction to the development of solar conjecture since there is no availability of educated labor to install, repair and maintain the solar systems (Gurung et al., 2020).

Besides, the lack of the relevant regimes of educational and vocational training is also likely to stimulate the local capacity building. In most of the countries in the Sub-Saharan Africa, solar energy training programs have not been established yet therefore, there is no guarantee of one-on-one training in the renewable energy sector because most of the educational institutions lack the financial support (World Bank, 2020). The lack of such capacity does not allow the local capacity to possess the opportunities of developing the solar energy industry in the region.

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Besides, the implementation of the project is also quite inefficient as a means of reaction to poor institutional frameworks. In certain scenarios, there is a lack of alignment between the government agencies, the non-governmental organizations (NGOs) and the players in the private sector, and this leads to poor efficiency and slow development of solar project (Karekezi et al., 2020). The efficient method to fight those adversities is to build local capacity through the formation of particular training, opening vocational schools on renewable energy, and involving international connections with solar energy organizations.

6.3.2. Role of Local Governments in Supporting Rural Electrification

Local governments have a very significant role to play in supplementing the rural electrification processes involving a decentralized mode in the use of solar energy. These kinds of governments contribute to having solar energy projects established under favorable policies and long-term sustainability of projects. It is unveiled that the local governments act as mediators among international donors, companies in the private sector as well as the rural communities in most cases in ensuring that solar energy programs fit the national and local developmental objectives.

The national government in countries like Kenya has played a crucial role in expanding electrification by promoting solar mini-grids and off-grid solar systems, particularly in regions located far from the national grid. The Kenyan government has fostered a supportive environment for decentralized solar energy through policies that encourage private sector participation and provide incentives for solar companies to invest in rural electrification (Kariuki et al., 2021). For example, local governments in Kenya are actively involved in determining the locations for solar mini-grid installations, selecting distributors, and overseeing the delivery of solar-powered solutions to remote communities (Ngugi et al., 2020).

Local governments are also able to aid in the policy support through their assistance in establishing a sense of involvement in the community to join the solar energy projects. This can include educating the masses among the locals about the utility of the solar energy, marketing of the public-private networks and creation of cooperatives or community relating to solar ventures or enterprises. The integration of communities in the process of developing and actualizing solar projects can be useful in ensuring that the same systems meet individual demands of the populace and are embraced by the community and promote the likelihood of the extended success of the project within the local government.

However, in the majority of the cases, the factors such as the lack of financial resources, technical skills, and effective governance extensively threaten local governments in Sub-Sahara Africa. This can also act as an obstacle to the successful management of local governments in solar energy projects and sustainability. This could contribute to the electrification of the rural setting in terms of the capacity of the local government (training and the capacity-building processes and enhancing accessibility to funds) to ensure the development of electrical infrastructure including the implementation of solar system in underserved areas (Sovacool et al., 2021).

6.4. Regional Cooperation and Harmonization of Policies

The widespread adoption of solar energy in Sub-Saharan Africa requires regional cooperation and harmonization of policymaking. Energy challenges faced by a single country often have cross-border impacts, affecting neighboring nations. Collective regional efforts can help address shared issues such as limited funding, inadequate infrastructure, and gaps in technical skills. By aligning policies and regulations, countries can create a more favorable environment for cross-border solar energy projects, which in turn promotes greater energy integration and more efficient utilization of renewable resources across the region.

6.4.1. The Role of the African Union and Regional Economic Communities

African Union (AU) and Regional Economic Communities (RECs) play a crucial role in promoting regional integration and policy harmonization within the energy sector. The AU's Agenda 2063 emphasizes the importance of renewable energy for achieving sustainable development goals across the continent. In parallel, the African Renewable Energy Initiative (AREI) serves as a platform for African nations to collaborate on renewable energy programs, share knowledge and expertise, and mobilize financing for large-scale solar projects. Together, these continental and regional frameworks support coordinated efforts to scale solar energy deployment, enhance cross-border energy trade, and accelerate the transition to sustainable energy systems in Africa (AU, 2020).

Other regional economic communities such as the economic community of the West African States (ECOWAS) and the East African Community (EAC) and the Southern African Development Community (SADC) have also contributed significantly in increasing the prospect of energy integration and cooperation besides the AU. These RECs have provided regional energy policies, structures and initiatives with the objective of eradication of regional energy issues similar in central or southern African energy issues and the coming up with renewable energy technologies like solar. This might be supported in the case of ECOWAS who has established the West African Power Pool (WAPP) which is in the process of establishing the electricity market in the region including the use of solar energy, which will be incorporated into the existing energy grid in West Africa. Through such programs, RECs facilitate the establishment of a common arena in terms of designing solar energy resources and trade at the cross-border scale (EAC, 2019).

Through collaboration, nations in these areas will be able to maximize collective resources, and share their costs of energy infrastructure, as well as improving the reliability and sustainability of solar energy initiatives. Regional cooperation gives countries an opportunity to get improved financing terms and draw on international expertise available through technical facilities of the globally-based institutes, like the World Bank and United Nations Development Program (UNDP), to encourage the regional renewable energy initiatives.

6.4.2. Policy Integration for Facilitating Large-Scale Solar Adoption

The use of solar energy has an immense potential and, therefore, to take full advantage of its potential, it is important that countries in Sub-Saharan Africa should introduce solar energy into its national energy discourse and make its policies congruent with regional guidelines. Policy integration means that the national energy strategies, regulations, and incentives, which are recognized as effective within their scope should be integrated into the regional objectives, and the cross-border solar energy projects must be developed and scaled-up efficiently.

Fluctuations in regulatory frameworks across different countries present a major challenge to policy integration for solar energy. In Sub-Saharan Africa, while some countries have made significant progress in developing supportive solar energy policies, others still lack the legal and regulatory institutions necessary to foster solar energy development. This lack of harmonization creates barriers for cross-border projects and restricts the movement of energy across national boundaries. To address this issue, regional cooperation aimed at harmonizing standards, technical specifications, and regulations for solar energy can be pursued, allowing all countries in the region to adopt a consistent framework.

To illustrate, ECOWAS Renewable Energy policy (EREP) aims at ensuring that energy policy framework is common to all which would offer and offer universal energy policy at the regional level and help ECOWAS member states trade power among themselves as well as increase the level of investments on solar energy projects (ECOWAS, 2020). The East African Community (EAC) on the same note has developed regional energy policy that supports the use of renewable energy technologies including solar that forms a major source of energy to increase energy accessibility in the region. These policies will create a localized solar energy market and reduce tariff barriers as well as allow the development of large-scale solar energy projects which have the capacity to benefit more than a single nation.

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Besides the policy integration at regional level in operations, the national governments should integrate their policies with those of the region. This is based on the fact that favorable legal and regulatory environments of the solar energy projects, granting incentives that facilitate usage of solar energy activities and inclusion of the solar energy systems in national development strategies should be established (AfDB, 2020). Improving the integration of policy and making the region more collaborative, the countries of Sub-Saharan Africa can create an even more sustainable and stronger market of solar energy, which will pave the way of further accessibility to energy and economic prosperity in the region.

7. Future Pathways for Decentralized Solar Energy in Sub-Saharan Africa

The future of decentralized solar energy in Sub-Saharan Africa looks promising, with rapid technological advancements, innovative financing models, and supportive policies paving the way for widespread adoption. The potential for solar power to provide affordable, clean, and reliable electricity to rural communities is significant. To fully realize this potential, continued progress in technology, financing mechanisms, and scalable business models is essential. The next section explores the future directions of decentralized solar energy, focusing on emerging technological innovations, the growth of digital platforms, and the expanding use of the Pay-as-you-go (PAYG) model.

7.1. Technological Innovations and Their Potential Impact

The innovations of bolstering, small-scale, hybrid solar energy systems, and other technological gains in the capacity of storing solar energy, efficiency, and storage are going to have far reaching consequences in the scalability, and efficiency of decentralized solar energy technologies within Sub-Saharan Africa. Innovations surrounding these fields will also be vital in enhancing energy availability in off-grid locations as the demand of clean and reliable energy will keep increasing in these locations.

7.1.1. Emerging Technologies in Solar Energy Storage and Efficiency

The discovery of better energy storage systems is one of the most important technological advances that will bottle neck the future of decentralized solar energy. Solar power, in itself, is erratic, it is only produced during the day. To make solar the primary energy source in off-grid regions, it must solve efficient storage so that electricity becomes stable and constant even when the sun has disappeared or the weather clouds it.

Recent advancements in battery technology, particularly with lithium-ion and flow batteries, have significantly improved solar energy storage. These batteries offer much higher energy densities and longer lifespans compared to traditional lead-acid batteries, which have long been used in off-grid solar systems. As the cost of these batteries continues to decrease, solar storage has become more affordable, making it accessible to a broader range of rural populations across Sub-Saharan Africa (Hossain et al., 2021). Further innovations, such as the development of solid-state batteries and energy storage systems that incorporate local materials, could further reduce costs and improve storage efficiency. These advancements could bring solar energy to new levels of affordability and reliability, making it viable for both off-grid households and commercial establishments (Olsson et al., 2020).

Besides better storage, the current increase in solar panel efficiency is also contributing immensely in making decentralized solar more viable. Bifacial solar panels and perovskite solar cells, a new technology that uses sunlight reflected on the back of the panel and a new technology that gives higher efficiencies at a lower cost could be revolutionary in solar power generation (Chirag et al., 2020). Such innovations might actually reduce the price-per-watt of solar-generated electrons and make it more cost-competitive with other forms of energy, as well as more affordable to less-populated groups in Sub-Saharan Africa.

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Such technological gains do not only reduce the cost of solar energy, but also, reliability. Since solar energy can be shifted in storage and production efficiency, on-demand solar energy can be achieved unlike solar power which is intermittent, thereby allowing solar energy to be a more reliable source of power especially to off-grid locations.

7.1.2. Future of Hybrid Solar Systems Combining Other Renewable Sources

The second innovation with significant potential for the future of decentralized solar energy is the combination of solar power with wind and hydropower energy. A hybrid solar system, which integrates solar power with wind or hydroelectric generation, can substantially improve the reliability and sustainability of energy supplies in rural areas. This solution directly addresses the intermittent nature of solar power, as wind and hydropower can supplement solar energy by providing electricity during times when solar generation is unavailable, such as at night or on cloudy days. By combining these energy sources, hybrid systems can create a more stable and continuous energy supply, making them a promising option for off-grid communities in Sub-Saharan Africa and other developing regions.

For instance, countries like Kenya and Ethiopia, where sunlight is abundant and wind resources are also available, can benefit from hybrid systems that combine solar panels with wind turbines. This integration would provide a more stable and reliable energy source, especially for off-grid locations. In such areas, hybrid systems are particularly effective because they can meet the dynamic energy needs of local populations by leveraging multiple energy sources. Additionally, these hybrid systems reduce reliance on fossil fuels for backup generation, leading to cleaner energy solutions and a significant reduction in greenhouse gas emissions (Yaya et al., 2021).

Integration of solar and the other renewable sources also presents the possibility of energy diversification that increases energy system resilience. Hybrid systems may in some cases be attached to other infrastructures like mini-grids, and thus widen the energy mix that becomes accessible to off-grid communities. This opens the possibility of developing hybrid systems, which will necessitate the creation of more sophisticated energy management systems able to effectively aggregate the various sources of energy, although the potential these hold to revolutionize how decentralized energy access can be achieved is immense.

7.2. Expanding the PAYG Model and Digital Platforms

Pay-as-you-go (PAYG) model has become one of the most effective financial solutions to expanding solar energy access in Sub-Saharan Africa especially with the off-grid segment. Customers can use this model to pay in phases, usually via mobile money mechanisms, which decreases the cost of solar energy to low-income earners. With the development of the mobile money ecosystem, and digital solutions in general becoming more sophisticated and simplifying daily tasks, the PAYG model is likely to experience a much larger expansion, further opening the door to the rural population to adopt solar power as a form of energy.

7.2.1. Growth of Mobile Payment Systems and Digital Solutions for Energy Access

In the Sub-Saharan region of Africa, mobile payment systems have played a crucial role in making solar energy accessible and affordable to the masses. Mobile money platforms, such as M-Pesa in Kenya, have revolutionized the way solar products are purchased by enabling small, flexible payments. This has removed the barrier of high upfront costs, which often deter low-income households from adopting solar solutions. The rise of mobile money systems has significantly contributed to the success of the Pay-As-You-Go (PAYG) model, allowing millions of off-grid households to access clean, reliable, and affordable electricity (Foster et al., 2021).

In future, the growth of mobile payment systems will allow one to increase the scalability of the PAYG model to an even greater extent. The Mobile money platforms keep getting better with more refined payment systems like the smartphone compatibility and digital wallets. This combined

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approach will further simplify the process of using solar energy solutions and user experience with customers being able to pay more conveniently, monitor their energy consumption, and make payments conveniently through digital means. Moreover, the rise of mobile internet in rural locations would help in accessing and digital management of the solar energy units by more of its users, which in turn would extend the penetration of solar energy in the off-grid population (Gikunda et al., 2020).

Growth of digital solutions like energy management platforms, which have capabilities of surveilling the performance of solar systems even when one is not physically present in the location, will also be instrumental in increasing access to energy. They can present real-time data regarding the generation of solar energy and the consumption of them, which will enable customers as well as the suppliers of solar energy to control and optimize the use of energy. With the possibility of integrating these digital solutions and mobilizing payment systems, solar energy service providers will increase customer satisfaction by providing more flexible and personalized payment methods and decrease payment defaults (Sarr et al., 2021).

7.2.2. How Technology Can Facilitate the Scaling of Decentralized Energy Solutions

Technology plays a pivotal role in advancing decentralized solar energy systems, making their expansion more feasible and increasing their efficiency. As solar systems become more sophisticated, they will integrate smart meters, sensors, and digital platforms, which will enhance the management and distribution of energy. For instance, smart meters are a game changer as they allow for the automatic measurement of energy consumption, enabling adjustments to payments in real-time. These meters also have the capability to remotely control solar systems; switching them on or off based on the status of the payments.

This technological integration reduces the administrative costs associated with Pay-As-You-Go (PAYG) systems, while also decreasing the risk of fraud and non-payment, which are common challenges in decentralized energy solutions. In essence, by improving tracking and payment management, technology not only streamlines the financial aspects but also enhances the sustainability and scalability of solar energy initiatives (Kariuki et al., 2020).

Moreover, the application of blockchain technology is becoming a possible decision to increase transparency and effectiveness in the field of solar energy financing. The method of Blockchain can be utilized in tracking payments and energy exchanges in a secure way which would provide the customer as well as the solar energy companies with records that can be verified regarding energy consumption and payment history. This may enhance the compatibility of solar energy providers and customers, improve access to finances and lower operation expenses (Nguyen et al., 2021).

Technological advancements, particularly in solar energy storage, will be crucial in scaling up decentralized solar systems. As more efficient and affordable batteries are developed, surplus energy generated during the day can be stored and used during off-hours, such as at night or on cloudy days when solar generation is low. This ensures a steady and reliable energy supply, addressing one of the major concerns of solar energy adoption, the intermittent nature of power generation.

For households and off-grid businesses that have been hesitant to adopt solar energy due to concerns about reliability, the ability to store energy will provide greater confidence in the system. With reliable storage solutions, these users can rely on consistent energy access, regardless of environmental conditions. This advancement could significantly increase solar energy uptake, especially in regions where grid access is limited or non-existent (Denton et al., 2020).

7.3. Policy Recommendations for Overcoming Challenges

Despite the fact that decentralized energy systems using solar energy as a source have the potential to be one of the solutions to the energy access challenge in Sub-Saharan Africa, there are a number of barriers that still remain to be addressed in order to scale up these systems to their full capacity. The issues range from poor regulatory policies to a lack of coordination between governments, the private sector, and international institutions. With sensible policy suggestions, these barriers can be minimized, and governments and stakeholders can enable solar energy

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solutions to be implemented smoothly. This section outlines policy proposals aimed at enhancing regulatory frameworks, fostering regional integration, and promoting the overall sustainability of decentralized solar energy systems in the future.

7.3.1. Proposals for Improving Regulatory Frameworks

Scaling up decentralized solar energy systems in Sub-Saharan Africa is dependent on the formulation of transparent, uniform and strong regulatory frameworks. Lack of clearly determined standards governing off and mini-grid systems is a major concern, which inhibits the development of solar power in the region. Such systems usually exist in regulatory grey space, which prevents the private sector investors execute large projects. Another thing that governments should do to fill such a gap is to develop complex legal and regulatory frameworks to promote the advancement of solar energy particularly in the decentralized forms.

In order to enhance regulatory frameworks, first, the governments must come up with and enforce policies that bring coherent understanding of roles and responsibilities that the stakeholders should play, which include solar energy companies, consumers, and the local governments. Transparency and clarity in terms of licensing, tariffs, technical standards and quality control outlines are important in establishing a stable investing environment that is secure. The introduction of uniform standards in solar equipment, including the solar panels and batteries, would also contribute to the adequate quality of systems and their proper performance in the long-term perspective (Dixon et al., 2020).

Besides standardization, citizens should emphasize on the development of policies that promote investment in the solar energy sector by the private sector within the countries. This might involve tax relief, subsidization of the solar technology and streamlined process of getting permits and licenses. Governments may simplify the process of setting up solar energy projects by decreasing the bureaucratic red tape and providing financial incentives, which will finally result in electricity access by off-grid populations (Bennett et al., 2020).

Another important factor of an enhanced regulation system is the condition in which policy environment can be flexibly changed and adapted to the new technological developments. Technology in solar is continuously growing and this will require regulation to remain futureproof in allowing the advancements in energy storage, efficiency, and grid interface. The process of policymaking should not leave room to disengage the private sector and technical experts to maintain a reasonable amount of relevance and efficacy in regulating scaling solar energy (Georgieva et al., 2020).

7.3.2. Strengthening Regional Cooperation for Cross-border Solar Energy Networks

Since energy markets in Sub-Saharan Africa are closely linked, regional collaboration towards the expansion of solar energy in this part of the world is important. Although solar energy projects can be carried out within the confines of individual countries, neighboring countries can share more energy and improve reliability and efficiency through cross-border networks. Energy trade agreements, the creation of regional energy pools, and common infrastructure projects integrating solar power into national and regional grids may facilitate regional cooperation.

Some economic regions (RECs) of the Economic Community of West African States (ECOWAS), the East African Community (EAC) and the Southern African Development Community (SADC) have already started to develop energy cooperation efforts. Nevertheless, progress remains a long way off when it comes to aligning regulations and establishing a system of coordinated regional energy markets on which solar power can easily transfer across the boundaries. Policy makers are advised to enhance the infrastructure in support of regional energy trade including transmission lines, energy storage units, which form a vital part of sharing solar energy between countries neatly (Sogoudjou et al., 2021).

Regional cooperation can be enhanced through mutual conditions of policy building jointly to be used in resolving the challenges facing the region in areas of energy. As an illustration, the

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ECOWAS Renewable Energy Policy (EREP) is a significant step in ensuring the unification energy should be regulated in West Africa. Governments must drive to unify their national policies with the regional frameworks so that solar energy is successfully integrated into the regional energy markets (AfDB, 2021). Sharing resources, knowledge, and negotiating better terms of financing large-scale solar, countries would create a more integrated energy market by cooperating.

Besides enhancing a cross-border regulatory harmonization, the regional cooperation ought to focus keenly on the collective financing channels, in as well as solar infrastructure construction through collective efforts. Through the combination of the financial resources and technical expertise, the countries are able to eliminate the costs of large-scale solar energy projects and spread the received energy benefits equally. Another danger that regional cooperation could counteract is the volatility of solar energy, especially when it comes to energy generation which could be overcome via the utilization of a more diversified energy portfolio that encompasses the production of solar energy in a neighboring region (IEA, 2020).

7.4. Achieving Sustainability and Long-Term Impact

To ensure a sustainable financial and environmental effect on electrification of rural Africa, decentralized systems of solar energy plants need to be financially and environmentally sustainable. Besides technical and policy issues, social and cultural acceptance of the solar energy system is a key indicator in their long-term success. The way to ensure sustainability over solar energy solutions is to reinforce all the aspects of financial viability, environmental, and socio-cultural context in which the solar energy solutions are implemented.

7.4.1. Ensuring Financial and Environmental Sustainability of Decentralized Solar Systems

Solar energy systems need financial sustainability to become sustainable and functional in the long term. The viability of a decentralized solar system in terms of finance is pegged not only on the availability of upfront capital but also on the capability to obtain sustainable revenue stream which is to be able to finance the operation and maintenance costs. In case of the PAYG model, it implies that customers will maintain timely payment that will serve to maintain and reinvest in its system. One of the aspects that solar firms could consider with the local governments to ensure sustainability in revenue generation is developing tiered pricing strategies that are fine-tuned to the local level of income (Liu et al., 2021).

To actualize financial sustainability, governments can give loan guarantee, as well as facilitate development of financial products that are destined to solar projects. The Microfinance institutions specifically contribute quite significantly to the funding of solar home systems and mini-grids to the low-income households. These institutions can contribute towards the likelihood of mass adoption and sustainability of solar energy solutions by creating access to financing to small businesses and households (Sovacool et al., 2021).

The other factor that should be considered in the long-term success of the decentralized solar energy systems is environmental sustainability. Though solar energy is clean and renewable per se, the environmental effects associated with the development of solar projects rely on the material that will be utilized to produce solar panels and battery production, and its disposal once its life has expired. With the increase in demand on the use of solar systems, the solar industry cannot ignore the best practices of managing electronic waste (e-waste) and recycling solar components (Vijay et al., 2020). Policymakers must consider putting measures to ensure the solar sector is in tandem with the environmental sustainability agenda, among them are regulation of recycling of the solar panels, the use of sustainable materials and others.

7.4.2. Social and Cultural Considerations in Implementing Solar Energy Solutions

When discussing the introduction of decentralized solar energy systems, social and cultural considerations should also be taken into account alongside financial and environmental parameters.

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Solar energy systems can be viewed as locally developed projects, which are a critical factor for success. This means they must be adopted by the locals, and community involvement is influenced by culture, local acceptability, and the perceived value of solar energy. For example, cultural relationships with energy sources or cultural attitudes towards them might pose obstacles to the implementation of solar technologies in certain communities. Therefore, companies supplying solar energy and governments should adopt a participatory approach when engaging with communities, creating awareness about the benefits of solar energy and addressing any concerns (Mbewe et al., 2020).

Additionally, the local community's involvement in the design, installation, and maintenance of solar energy systems can enhance ownership and ensure the long-term sustainability of the project. It is also possible to use the solar energy project to build local capacity and a sense of ownership by involving locals in decision-making and providing training, leading to higher maintenance and success rates (Karekezi et al., 2020).

Social considerations also suggest that solar energy projects must align with broader developmental goals to address other issues such as education, healthcare, and economic opportunities. Solar energy can improve the welfare of rural communities by providing electricity to schools, health clinics, and businesses. However, the benefits must be managed appropriately to ensure they reach all layers of the population, with particular emphasis on women and underrepresented groups (Karekezi et al., 2021).

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Abbreviations

The following abbreviations are used in this manuscript:

IEA	International Energy Agency
UNDP	United Nations Development Program
IRENA	International Renewable Energy Agency
PAYG	Pay-As-You-Go
PV	Photovoltaic
BMS	Battery Management Systems
NGO	Non-Governmental Organization
REP	Rural Electrification Project
SREP	Scaling-Up Renewable Energy Program
SHS	Solar Home Systems
NEP	Nigeria Electrification Project
NEP	National Electrification Program
REP	Rural Electrification Program
SNNPR	Southern Nations, Nationalities, and Peoples' Region
MREP	Malawi Rural Electrification Program
AfDB	Africa Development Bank
GEF	Global Environment Facility

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IFAD	International Fund for Agricultural Development
GCF	Green Climate Fund
PPP	Public Private Partnership
ECOWAS	Economic Community of West African States
EAC	East African Community
WAPP	West African Power Pool
AU	African Union
RECs	Regional Economic Communities
AREI	African Renewable Energy Initiative
SADC	Southern African Development Community
EREP	ECOWAS Renewable Energy policy

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