Industry Science and Engineering Vol. 1 No. 6, 2024

Evaluating the Effectiveness and Exploring the Sustainable Development of Solar Lamps in African Region

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Abstract: With the transformation of global energy structure and the rise of renewable energy, solar lamps, as a clean and environmentally friendly lighting method, have been widely used in the African region. This paper focuses on evaluating the application effect of solar lamps in Africa and exploring their sustainable development prospects in the region. Firstly, through data collection and data analysis, we gain an in-depth understanding of the specific application of solar lamps in Africa, including the scope of use, user feedback, economic and environmental benefits. Secondly, qualitative and quantitative research methods are used to scientifically assess the application effects of solar lights, including analyses of lighting effects, energy efficiency, and impacts on local communities and ecological environments. Then, based on the evaluation results, the key factors for the sustainable development of solar lamps in Africa are explored, including technological progress, strategy support, popularisation of education and improvement of industrial chain. Finally, a series of strategic recommendations are proposed to promote the sustainable development of solar lamps in Africa, aiming to provide reference for relevant strategy formulation and practical work.

Keywords: Solar Lights; Africa Region; Sustainable Development; Energy Demand

1. Introduction

1.1 Research Background

The African region has insufficient access to electricity, with one-third of the population without access to electricity, 87 percent of whom live in rural areas. It is projected that by 2030, about 600 million people in sub-Saharan Africa will still lack access to electricity services [1]. In the past, Africa's long-term use of fossil fuels to generate electricity has not only brought huge financial burdens to African governments, but also brought climate problems [2]. Therefore, there is an urgent need to find sustainable and environmentally friendly energy solutions in Africa. Solar power technologies are widely used to meet the demand for electricity and combat climate change. The long sunshine hours and high radiation intensity of the African continent provide unique conditions for using solar energy. Solar lamps not only can be charged directly by solar energy without relying on traditional grid power but also do not produce pollution and greenhouse gas emissions during use, which is of great significance to environmental protection. Through the Lighting Africa program, the World Bank promotes the adoption of off-grid solar solutions to provide power to remote, impoverished areas in a fast, cost-effective and sustainable manner. The program is rapidly increasing access to solar products by creating and supporting sustainable markets, and as of December 2019, 52.4 million people have had their basic electricity needs met with Lighting the World quality-certified products. Solar power technology has been widely promoted and applied in Africa, and solar lamps, as an important lighting device, play an important role in solving the lighting problems of residents, improving the quality of life and promoting economic development.

1.2 Energy Profile of Africa

Africa is rich in energy resources and the region has high reserves of renewable energy as shown in Figure 1.

The region is blessed with excellent solar and bioenergy resources and the accessibility of modern energy facilities, although the growth in the region is still small. From the Figure 2 photovoltaic technology is still growing because it is the simplest technology to utilize in homes away from the grid and is cheaper than other renewable energy sources, and

most sub-Saharan African countries have implemented photovoltaic technology.

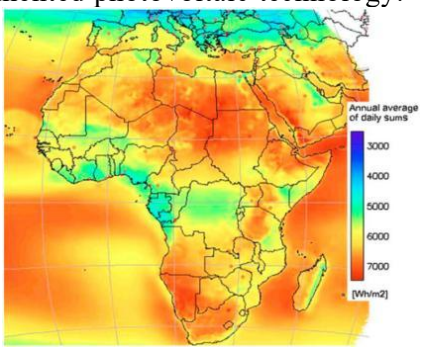

Figure 1. Africa Solar Map [3]

Country	Algeria	Egypt	Libya	Morocco	South Africa
•PVOUT:	•4.19- 5.50	•4.76- 5.74	•4.76- 5.57	•4.33- 5.54	•4.00- 5.66
•DNI:	•4.41- 6.97	•5.25- 7.85	•5.31- 6.82	•4.52- 7.20	•4.19- 8.50

- Specific photovoltaic power output (PVOUT) in kWh/kWp
- Direct normal irradiation (DNI) in kWh/m²

Figure 2. Daily Specific Photovoltaic Power and Direct Normal Exposure for 5 African Countries [4]

There are two vital active solar technologies by which solar energy is harnessed; Photovoltaics (PV), which directly convert light to electricity, and Concentrating Solar Power (CSP), which uses heat reflected from mirrors that are directed to the sun (thermal energy) to drive heat engines [5].

Solar energy comes from solar radiation and is harnessed to generate electricity through specialized equipment such as photovoltaic panels. The high level of solar radiation in Africa, The total amount of solar energy produced in Africa by PV and CST is shown in Figure 3, exceeds the daily electricity demand and provides applications such as water pumping, home lighting, traffic signaling, community lighting and limited urban street lighting in various communities in Africa.Solar PV – already the cheapest source of power in many parts of Africa – outcompetes all sources continent-wide by 2030 [5].

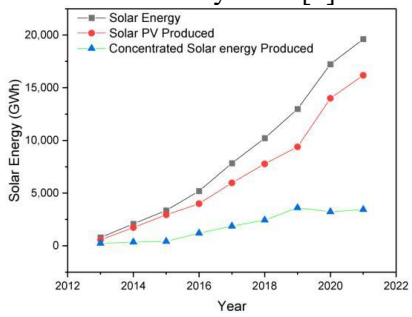

Figure 3. African Production of Solar, Photovoltaic and Solar Thermal Power Generation [3]

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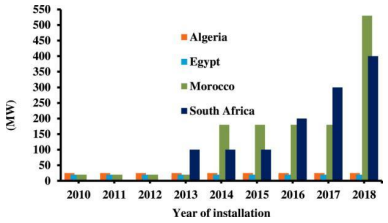

Figure 4. Total Installed Concentrated Solar Power Capacity (MW) in Africa [6]

Solar energy is virtually inexhaustible, and sub-Saharan Africa holds 90% of the world's potential solar energy resources. According to a study by McKinsey, even under the most conservative estimate that only 0.02% to 0.05% of the land area can be used for solar power generation, it is projected that sub-Saharan Africa has at least 11 million MW of solar power generation capacity [7].The continent has the highest average annual solar radiation values (over 220 kcal/cm), and much of the Cartwright Riordan and Bourges continents are located in equatorial regions where the intensity and strength of the sun's rays are always high. The region is characterised by arid and semi-arid forests in the north and less so in the south and east. The combination of all these geographic and climatic factors is the reason for the enormous solar energy potential of sub-Saharan Africa. This allows solar energy to power virtually all of Africa without the need for expensive, large-scale grid-level infrastructure development. Figure 5 shows solar panels powering newly renovated local administration buildings in Liberia.

Figure 5. Solar Panels Generate Electricity in Liberia

2. Solar Light Technology and Its Applicability in Africa

With the increasing global focus on renewable energy, solar light technology is emerging as a green, environmentally friendly lighting solution. Solar street lights are outdoor lighting fixtures powered by solar panels that convert sunlight into electricity. It consists of photovoltaic panels, batteries, controllers and LED light sources [8]. The photovoltaic panel is responsible for capturing the solar energy and converting it into direct current, while the control circuit manages and regulates the electrical energy, which ultimately emits light through the LED light fixture. Its conversion of solar energy into electrical energy is stored in the battery during the daytime and used to power the LED lamps at night. Compared with traditional road lighting, solar street lights have advantages in terms of energy efficiency, cost-effectiveness, installation conditions, safety performance and reliability.

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As one of the sunniest continents in the world, the African region is rich in solar energy resources, providing unique conditions for the development of solar lamp technology. In Africa, many areas are seriously affected by the lack of a stable power supply and the lives of residents. Solar lamps, as a kind of independently powered lighting equipment, are very suitable for application in these areas. In addition, to support clean energy development, many African countries have formulated clean energy strategies, actively promoting power market reforms, loosening government regulations, improving the business environment, and attracting external investment [10]. As shown in Table 1.

On the economic front, solar light technology has brought significant economic benefits to the African region. On the one hand, the acquisition cost of solar lamps is gradually decreasing as the technology matures, making them affordable for more households and businesses. On the other hand, since solar lights do not need to be connected to the grid, they can save a lot of electricity costs, bringing direct economic benefits to users. In addition, the lower installation and maintenance costs of solar lights further reduce the economic burden on users.

In terms of technical feasibility, solar lamp technology is already very mature and has been widely used worldwide. In the African region, many countries and organisations have begun the promotion and application of solar lights, providing residents with clean and reliable lighting solutions. At the same time, with the continuous progress and innovation of technology, the performance and efficiency of solar lamps are also improving, providing strong support for the sustainable development of the African region.

Table 1. Togo, Ghana, Kenya, Nigeria and South Africa Have Targets and Incentives in the Energy Sector through Development and Power Generation Processes

Region	Main objective	Incentives provided to promote the development of renewable energy sources
Togo	Renewable energy consumption increases from10% in 2013:15% in 2020 and 20% in 2022	C120 project with personal solar kit and Pay-As-You-Go payment
Ghana	Increase renewable energy from 2% to 10% by2020	A massive upgrade with the help of government initiatives. NGO Fund, ECOWAS and ECREE programme
Kenya	By 2024,strengthen the domestic market and benzine production, The use of home solar systems is estimated to generate 20 gigawatts of electricity per year	The government's policy framework: Further generating the ppp model, solar energy became mandatory for every new home, and WAT on solar panels was abolished in 2007

Nigeria	By 2030, 20% of our production will be powered by renewable energy. The goal is to reduce the use of renewable energy to 7 percent by2025	Funded by non governmental organizations. Feed-in tariffs to promote off-grid generation. Economic community of Western States (ECOWS), ECREE program
South Africa	By 2050, 14% of energy will be generated using solar photovoltaic systems. By 2030,8,400 MW will be achieved with photovoltaic systems	Government initiatives such as tax credits, feed-in tariffs and capital subsidies, various renewable energy schemes

3. Current Status of Solar Lamps in Africa

The application of solar lights on the African continent has made remarkable progress in recent years. The penetration of solar lights has gradually increased in several regions, especially in remote areas far from the power grid. These areas have long relied on traditional lighting methods, such as candles and oil lamps, which not only have limited lighting effects but also pose safety risks. The introduction of solar lights has brought residents a safe, convenient and environmentally friendly lighting solution.

In Africa, solar streetlights have been widely used. In many countries in Africa, solar lights are mainly used for outdoor lighting, such as streets, schools, hospitals and other public places. In addition, with the advancement of technology and the reduction of cost, more and more households are using solar lights for indoor lighting. SSA experiences solar radiation intensity ranging from 4.0 to 7.0 kWh/m, which can satisfy household electricity demand.

The main drivers for the diffusion of solar lamps in Africa include supportive government policies on renewable energy, demand due to insufficient electricity supply and increased environmental awareness. However, there are several challenges to the diffusion of solar lights. Firstly, although the price of solar lamps has fallen, they are still a significant expense for some economically disadvantaged regions. Second, residents in some areas have a wait-and-see attitude toward the new technology, and more education and publicity are needed to drive acceptance. In addition, the maintenance and repair of solar lights is also a concern, especially in remote areas where there is a lack of professional maintenance personnel and service networks.

4. Evaluation of the Effectiveness of Solar Lamps in Africa

To comprehensively assess the effectiveness of solar lights in real-world applications, we used a range of data collection and analysis methods. These methods not only helped us to understand the economic benefits of solar lights but also provided insights into their social and environmental impacts.

4.1 Economic Benefit

In terms of economic benefits, we collected data related to electricity prices in areas where solar lights are used (Figure 6). By comparing and analysing electricity expenditure, we found that solar lights reduced energy costs for households and brought positive improvements to their economic conditions. At the same time, the promotion of solar lamps has also created local employment opportunities and contributed to the economic development of the community.

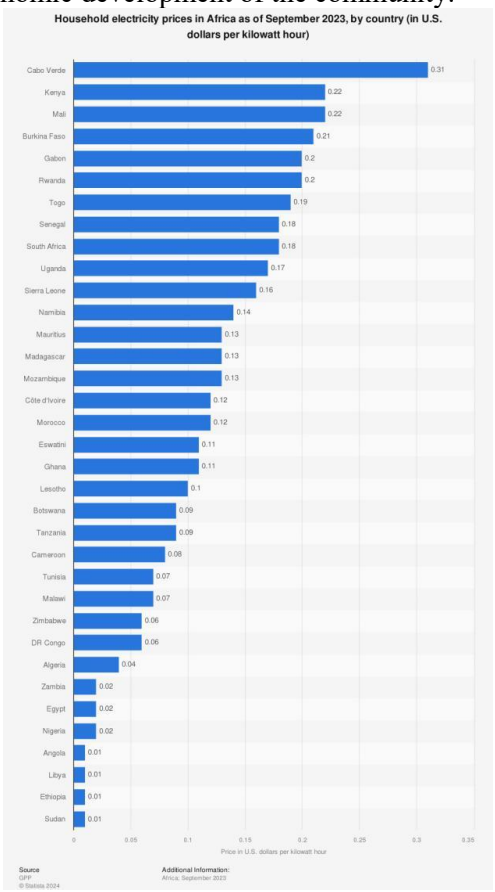

Figure 6. Household Electricity Prices in Africa as of September 2023, by Country [11]

4.2 Social Impact

In terms of social impact, we focused on the role of solar lights in improving quality of life and healthcare. We collected 210 questionnaires to investigate the use and popularity of solar lamps in Africa and the impact of solar lamps on the lives of African residents, Figure 7-10 shows the partial results. Through the survey through interviews and questionnaires, we learnt that solar lamps have a high penetration rate in the African region and provide stable lighting conditions for homes, schools and businesses. In addition, solar lights provide nighttime illumination for healthcare facilities, allowing healthcare services to be extended into the night and improving the quality of healthcare services. It is worth noting that the spread of solar lights has also helped to reduce safety risks for women travelling at night, thus promoting gender equality. However, we also found that although the penetration rate of solar lights in Africa is high, there are regional differences. In some remote areas, the penetration rate of solar lights is still low due to poor accessibility and economic backwardness. Overall, the application of solar lamps in the African region has achieved certain results, but there is still much room for improvement in terms of publicity and promotion.

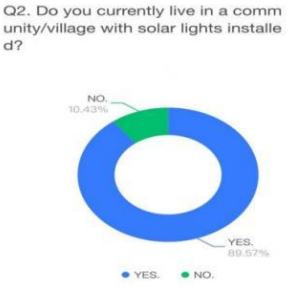

Figure 7. Questionnaire Survey - Whether the Town Where You Live Now Uses Solar Lights

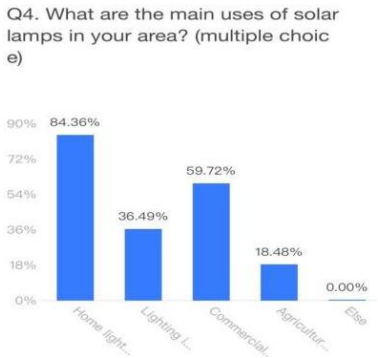

Figure 8. Questionnaire Survey - the Main Use of Solar Lamps

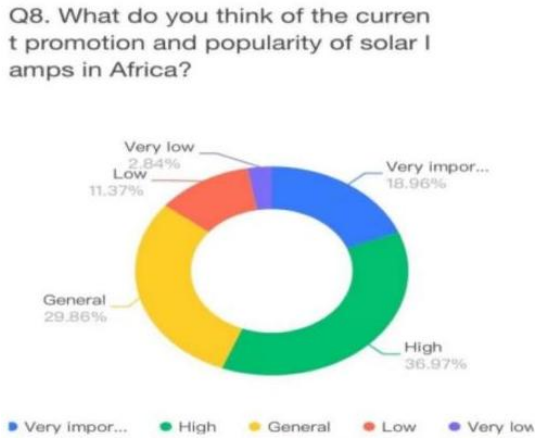

Figure 9. Questionnaire Survey - How to View the Popularization and Promotion of Solar Lamps in Africa

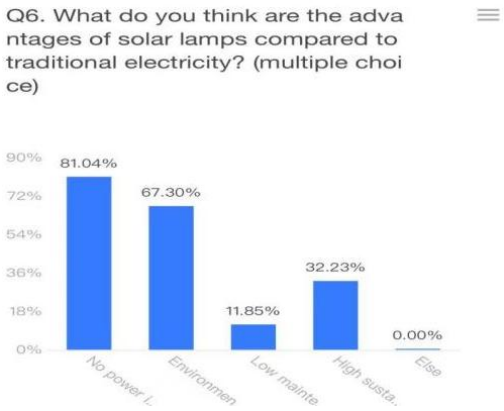

Figure 10. Questionnaire Survey - What Are the Advantages of Solar Lamps Compared with Traditional Lamps

4.3 Environmental Benefit

Africa is the continent with the highest concentration of developing countries in the world, and it has significant potential for greenhouse gas emissions. [12] According to the World Health Organisation, about 600,000 people die prematurely each year in Africa due to household air pollution caused by the use of traditional fuels, and the use of solar lamps can effectively improve the air pollution situation. In terms of environmental benefits, we have analysed the contribution of solar lamps in reducing carbon emissions and promoting environmental sustainability.

According to the National Development and Reform Commission of the coal consumption of thermal power plants to generate data: the average per kilowatt-hour (i.e., per degree) power supply coal consumption of 360g standard coal (theoretical value); however, every tonne of standard coal combustion of industrial boilers, the production of carbon

dioxide 2620Kg and sulphur dioxide 0.06Kg, carbon monoxide 0.0227 Kg, nitrogen oxides 0.0360Kg, HC 0.0050Kg, soot 0.0110 Kg, etc. (Therefore, coal-fired boiler emissions exhaust become one of the main sources of atmospheric pollution) 1.2MW photovoltaic grid-connected power station, the annual power generation of about 1.8 million degrees, that is, the system's annual energy savings of 1.8 million KWh [13].

Therefore, the amount of energy saving and emission reduction is as follows: Energy saving per unit area = 1.8 million KWh ÷ 30,900 m2 = 58.25 KWh/ m2 Annual coal saving approx:

360×1800000×10-3=648000(Kg)

The annual emission reduction of standard coal is approx:

CO2 content: 2620×648000×10-3=1697760(Kg)

SO2 content: 0.0600×648000=38880(Kg)

CO content: 0.0227×648000=14709.6(Kg)

NOx content: 0.0360×648000=23328(Kg)

HC content: 0.0050×648000=3240(Kg)

Soot: 0.0110×648000=7128(Kg)

By calculating the reduction in carbon emissions from the replacement of conventional electricity by solar lamps, we found that the use of solar lamps can reduce the use of conventional energy sources such as coal or oil in Africa and that by reducing reliance on fossil fuels, significant reductions in carbon emissions can be made, which can help to combat climate change in Africa.

5. Exploring the Sustainability of Solar Lights in Africa

The establishment of a sustainable energy supply and service system is key to ensuring the long-term, stable functioning of solar lights. Such a system needs to be technically feasible and economically viable, taking into account cultural, social and environmental factors.

Policy guidance and financial support are crucial in promoting the spread of solar lights in Africa. Policy guidance can provide clear guidelines and necessary support for the development of solar lights, while the injection of funds can directly promote the implementation of related projects and technological innovation and progress. African governments can encourage investment through tax incentives, subsidies and special funds to strengthen policy guidance and financial support to promote the popularity of solar lights in Africa and the application of the key. For example, Kenya set up a "green energy fund" to reduce the purchase cost of solar lights, attracting more investors.

In Africa, the promotion and application of solar lights is not only related to energy transformation and environmental protection but also closely linked to the improvement of the industrial chain and technological innovation. Each link of technological progress and innovation has a direct impact on the performance and market competitiveness of solar lights. Taking the supply of raw materials as an example, Africa has abundant silicon resources but needs technological breakthroughs and innovation to transform the resources into high-quality silicon materials. Through the introduction of advanced technology, African countries can improve the purity and yield of silicon materials, providing stable and high-quality raw materials for solar lamp production. In terms of product research and development, technological innovation promotes the improvement of solar lamp performance. Improved panel design and materials can improve conversion efficiency, while intelligent control technology can realise functions such as remote monitoring and automatic brightness adjustment to enhance user experience. Technological innovation in manufacturing includes the introduction of automated production lines and intelligent manufacturing technology, which improves production efficiency and quality stability, reduces production costs and enhances market competitiveness. Meanwhile, innovation in the marketing segment involves modern marketing tools such as the Internet and social media, and the development of marketing strategies that take into account local culture and customs to increase acceptance.

Financial mechanisms are also an important factor affecting the sustainable development of solar lights. Due to the long payback period of the solar lamp project and the high initial investment cost, it is necessary to establish a corresponding financial mechanism to support the sustainable development of the project. For example,

venture capital, green finance and other financial tools can be introduced to provide financial support for solar light projects; at the same time, you can also establish solar light leasing, instalment payment and other financial service modes to reduce the economic burden of users and improve the popularity of solar lights.

In addition, technological innovation is also an important force to promote the sustainable development of solar lights. Through continuous technological innovation, the conversion efficiency of solar lamps can be improved, reduce costs, extend the service life and so on, to enhance its market competitiveness. For example, researchers can improve the conversion efficiency of solar energy by improving the material and structure of solar panels; at the same time, they can also reduce the energy consumption and cost of solar lights by optimising the circuit design and improving the energy efficiency of lamps and lanterns. With continuous technological advancements, the conversion efficiency of solar photovoltaic (PV) technology has been steadily improving, enabling more effective conversion of solar energy into electricity. Additionally, the application of new materials and design methods further contributes to enhancing the efficiency of PV systems [14].

In addition to the above factors, strategies to improve the sustainability of solar light projects include enhancing community participation and establishing local maintenance and service networks. Enhancing community participation can stimulate the enthusiasm and support of residents for the solar lamp project and facilitate its smooth implementation; at the same time, establishing a local maintenance and service network can ensure that the solar lamps are maintained and serviced in a timely and effective manner during their use, thus improving their efficiency and lifespan.

The prospect of integrating solar lamps with other renewable energy technologies (such as microgrids and solar water pumps) is also worth exploring. By combining solar lamps with microgrids, it is possible to achieve complementary and optimal allocation of electric energy and improve the stability and reliability of the entire energy system; at the same time, combining solar lamps with other renewable energy technologies, such as solar water pumps, can lead to a diversified mode of energy utilisation and satisfy the diversified energy needs of residents. These integrated applications will help improve the sustainable development of solar lights in Africa.

6. Case Studies

The African continent is rich in solar energy resources due to its unique geographical location and climatic conditions. In recent years, several African countries and regions have successfully implemented solar light projects, and solar lighting products have been sold well locally, as shown in Figure 11, which not only improves the quality of life of residents but also promotes the development of renewable energy. In 2021, the sales of off-grid solar products in Africa amounted to 7.4 million sets, making it the largest market in the world. Among them, Eastern Africa has the highest sales volume of 4 million units. Kenya is the largest country in the region with 1.7 million units sold, while Ethiopia ranks second with 439,000 units sold. In 2015, East Africa accounted for more than half of the global investment in off-grid solar systems. Kenya and Tanzania have nurtured the majority of the largest off-grid solar companies operating on the African continent (such as M-KOPA, Azuri, etc.), and continue to provide the most favorable opportunities for companies looking to enter this sector [15].

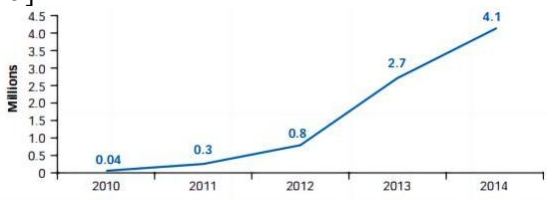

Figure 11. Unit Sales of Quality Certified Solar Lighting Products Increased in Sub-Saharan Africa from 2010 to 2014 [15]

Looking at the solar light project in Kenya, Kenya, as an East African country, has plenty of sunshine, which is ideal for solar energy, and it has one of the best economic bases in sub-Saharan Africa, as well as one of the largest trade markets in Africa. Compared to other countries in Sub-Saharan Africa, Kenya's off-grid solar industry is more advanced in terms of market activity, quality standards, and business model innovation

[15].Kenya has introduced solar light projects through cooperation with international organisations. At the same time, the Kenyan government ensured the viability of the project by working with the community to understand their needs and expectations. Training and technical support were provided at the start of the solar light programme to help local people install and maintain the solar lights. Through government subsidies and partner funding, the cost of solar lights is reduced to make them more accessible. The programme provides a clean, reliable lighting solution for people living in remote areas. After it entered Kenya, it significantly improved the quality of life of residents, while reducing the dependence on traditional energy sources, reducing environmental pollution, creating employment opportunities for people in the Kenyan region and promoting the development of the local economy.

The striking trajectory of solar lamp sales in Kenya is illustrated in Figure 12. In 2010, sales of solar lamps were equivalent to only 12 per cent of grid-connected households, but by 2014 they far outpaced grid-connected households, with a 37-fold increase in sales in four years.

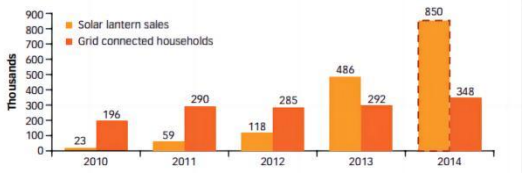

Figure 12. 2010-2014 Kenya Solar Lamp Sales [16]

At the same time, Ethiopia, Ethiopia is a power-scarce country, with rich hydropower resources development and a utilisation rate of only 5%, resulting in a significant shortage of electricity in the dry season, nearly half of the population lives in conditions of no electricity and lack of electricity. Against this background, solar lights are widely used in the country. In Ethiopia, the government supports household solar providers through access to the World Bank's Power Grid Credit and provides micro-financing for households to purchase solar lights and solar home systems. Meanwhile, the project team worked closely with the local community to ensure that the solar lights were installed, maintained and used with the active participation and support of the community. Similar to Kenya, Ethiopia provided training to residents on the installation and maintenance of solar lights, but unlike Kenya, Ethiopia adopted a step-by-step approach, piloting the programme in selected communities and then gradually expanding the scope of implementation based on the effectiveness of the pilot.

The application of solar energy in both countries shows the same effect, both promote economic development, improve the energy structure, and improve the quality of life. However, the two countries have their innovations in the popular application of solar energy. Kenya has adopted mobile payment methods to facilitate residents to buy solar lights in instalments. It has also set up a solar lamp leasing system so that residents can gradually own solar lamps under affordable circumstances. Ethiopia, on the other hand, has improved the efficiency of energy use by cooperating with local enterprises to jointly develop and produce solar lamp products suitable for the Ethiopian market, while in some areas the project team has adopted microgrid technology to connect solar lamps with other renewable energy equipment (such as wind turbines).

The above two cases illustrate successful experiences and innovative practices in the implementation of solar light projects in African countries. These experiences and practices also provide useful lessons and references for other regions, such as.

(1) The government cooperates with the community, enterprises and other parties to form a win-win situation.

(2) Step-by-step implementation: by piloting and gradually expanding the project, the feasibility and sustainability of the project can be ensured, and at the same time, it helps to reduce project risks.

(3) Make full use of local resources and innovative thinking to solve financial and technical problems.

7. Conclusions and Recommendations

Through the in-depth study of solar light projects in Africa, we can see that solar energy, as a clean and renewable energy source, has great potential for application in Africa. Through technological innovation and strategy optimisation, solar lights not only provide a stable and reliable lighting solution

in Africa but also play an important role in promoting local economic development, improving the energy structure and enhancing the quality of life. The cases of Kenya and Ethiopia have also fully proved the feasibility and sustainability of solar light projects in Africa, providing a useful reference for other regions.

The African region is rich in photovoltaic resources, which makes solar energy development great potential. During the development process, Chinese enterprises need to pay attention to the co-existence of risks and opportunities. To ensure the success of the project, it is recommended that Chinese enterprises interested in participating in the development of solar energy in Africa focus on the following three aspects:

First of all, it is necessary to conduct in-depth research on the political, economic, cultural and social environment of African countries to understand the local market demand and policy environment, to provide a basic guarantee for the smooth implementation of the project. At the same time, it is necessary to establish a good relationship with the local government and community, and jointly promote the development of solar lights and other clean energy projects to achieve mutual benefit and a win-win situation.

Secondly, we should pay attention to technological innovation and industrial upgrading, improve the quality and performance of solar lamps, reduce costs and increase user acceptance. We should focus on environmental adaptability, and optimise the design for high temperature, sand and dust and other environmental conditions in Africa to ensure product stability and durability. In addition, should also focus on cultural adaptability, combined with the local culture and traditions in Africa, designed to meet the local aesthetics and demand for solar lamp products, and improve market acceptance.

Finally, we must deepen international cooperation and join hands to promote the development of solar energy and other clean energy in Africa. Chinese enterprises can cooperate with local enterprises and international organisations to jointly research and develop new technologies and products, and promote technology transfer and industrial upgrading.At the same time, they can also make use of international markets and resources to improve the competitiveness and market share of their products and contribute to the sustainable development of the African region.

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