Maximizing Solar Integration: Enhancing Off-Grid Rural Energy Storage in Zambia

ABSTRACT

Energy stands as an indispensable aspect of contemporary human life. This study endeavours to explore the challenges and opportunities associated with the adoption of photovoltaics (PV) for sustainable electricity supply in Africa, with a particular focus on Zambia. The primary objectives include assessing the current state of PV integration, identifying key obstacles, and highlighting potential applications in critical areas such as irrigation, rural electrification, and water heating.

Drawing upon the latest research on PV in Africa, this study synthesizes information from the top ten most cited studies, with a specific emphasis on the complexities involved in large-scale PV integration. The research design entails a comprehensive review of technical aspects such as storage and bifacial modules, providing insights into the challenges faced in optimizing PV systems.

The study primarily centres on Zambia, a country endowed with significant solar potential. Through case studies, it demonstrates the feasibility of employing PV for vital applications such as irrigation and rural electrification. The timeframe encompasses recent years, reflecting the dynamic nature of PV research and implementation.

To evaluate the advantages and obstacles of PV adoption, a multifaceted approach is employed. This includes examining the potential of PV in specific applications, analyzing electrification rates in Zambian urban and rural areas (57% and 13% respectively), and identifying barriers such as high costs, inadequate infrastructure, and a lack of training. Additionally, thermal systems are considered, emphasizing both untapped potential and the limitations of solar cookers.

The study incorporates interviews conducted in Lwangwa Village to gather firsthand perspectives on the use and necessity of energy. Furthermore, data from previous literature is utilized to compile valuable insights into the demand for clean energy in Zambia.

Key findings underscore the untapped potential of PV in Zambia, highlighting its capacity to enhance energy access and reduce emissions. However, significant challenges exist, necessitating targeted policies, financial mechanisms, and community engagement to foster widespread adoption. Addressing infrastructure limitations, maintenance needs, costs, and social factors is essential to fully realize the benefits of PV implementation.

Zambia's abundant solar resources present a promising pathway towards sustainable energy. However, strategic planning and support are imperative for successful PV integration. Future research endeavors should

focus on investigating specific challenges arising from clean energy adoption, including potential health effects and negative impacts, to further advance sustainable energy initiatives.

Keywords: Renewable energy; Energy storage system; Photovoltaic solar; Zambia.

1. INTRODUCTION

Solar energy has become a key component of the answers to Africa's urgent energy problems in recent years. Due to its year-round abundance of sunlight, Africa holds great potential for producing solar energy. In this situation, photovoltaic (PV) systems are especially well-suited because they directly convert sunlight into electricity. A large section of the population suffers from energy poverty, which can be lessened with the help of these systems, which provide a clean, renewable, and sustainable energy source. Furthermore, PV systems are potentially important in providing energy security and resilience, lessening dependence on fossil fuels, and limiting exhalations related to energy. Thus, it is crucial to comprehend the uses, advantages, and difficulties of photovoltaic systems in Africa [1, 2].

As of 2019, Africa's energy generation capacity was approximately 300 mega wards, which were mostly generated from fossil fuel-based sources such as heavy fuel oil and diesel (253 MW) 80% of the total renewable energy capacity. As illustrated in Fig.1, the capacity for solar and hydropower generating was 10%, 33 MW and 32 MW, respectively.

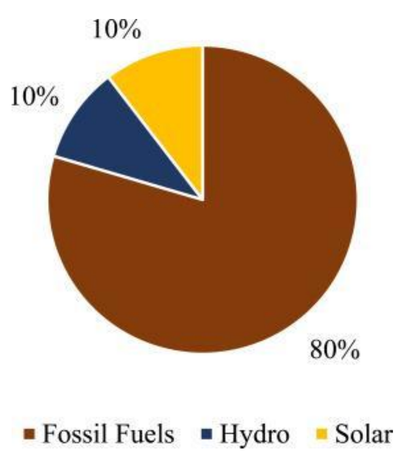

Fig. 1 Capacity of solar generation in Africa

However, it should be noted that Africa is a good source of renewable energy housing over 61% of solar sources. It is thought to possess the greatest potential for global renewable energy systems [3, 4]. Only 1% of the globe’s installed solar energy capacity is in Africa, despite its potential [5]. The biggest obstacle to African economic development, according to some, is the lack of access to energy [4]. Nonetheless, solar photovoltaics (PV) are expected to surpass all other power sources by 2030 and are currently the least expensive option in many regions of Africa. By 2030, it is anticipated that 81% of the solar power generated in Sub-Saharan Africa will come from green power which includes geothermal, hydropower, and clean energy. This suggests that renewable energy systems are establishing benchmarks for the solar power industry in Africa.

The off-grid concept completely changed rural Africa's access to renewable energy. Modular renewable energy installations are being implemented on a small scale at the village and household levels [6, 7]. Farms can be supported by solar energy systems for fertilization and irrigation, offering 791 million Africans without electricity a new means of assistance. However, installing renewable energy is more challenging in some parts of the African continent because of several issues, including those about finances, technology, humanity, and the environment [8]. To ensure sustainability in the future, it will be necessary to overcome these challenges and implement efficient renewable energy technologies to take advantage of Africa's abundant solar power.

African leaders have shown their commitment to introducing clean energy in remote areas by establishing several market developments for businesses operated from warehouses. However, installing green systems in Africa is still difficult. The lack of infrastructure is a major barrier to rural electrification initiatives. An additional barrier to the widespread utilization of solar power systems in Africa is a continued reliance on established power sources [10].However, even with such problems, the pay-as-you-go (Pay-Go) green energy model has shown to be a dependable way to get around them. East Africa now has 500,000 more users of the PayGo system than it did in 2015.

Financing clean energy is a strategy to help in improving the use of solar energy in affected areas. Several nations in Africa have managed to establish funds to help with solar energy system financing for consumers[11]. Advanced power storage has balanced micro-grid energy supplies more affordably, which opens doors for organizations in minor residential solar [12]. Africa's isolated solar power plants can help lessen the region's power outages by providing electricity to farms, safari lodges, and building sites. Solar power offers various benefits to the African continent, including accelerating electrification and reducing organic destruction from fuel-tree cutting, even though the majority of individuals in Africa are relying on the ineffective established power source.

Clean energy systems can be broadly divided into two forms: photovoltaic and solar energy [13, 14]. In contrast to solar power systems, which use a mirror to concentrate solar heat before creating steam to generate electricity, photovoltaic systems use solar panels to directly convert sunlight into electrical power. Africa is starting to lead the world in solar energy production, but more funding is needed to reach the continent's full potential. PVC systems are popular in African nations and have proved to succeed in supplying remote communities, businesses, and residences with electricity.

Africa has a lower prevalence of solar devices than photovoltaic systems. Nevertheless, they have a great deal of the ability to produce higher energy since most of these countries can produce enough steam to power turbines and produce more electricity. In nations like Morocco and Egypt that have plenty of direct sunlight and spacious, level spaces for installation, solar thermal systems are used more frequently [15]. Africa possesses 61% of the global prime solar resource, making it a promising leader in solar thermal and photovoltaic technologies. But currently, just 3% of electricity in Africa is obtained from solar power [16, 17]. Despite this, the continent is moving in the direction of the letter years, for example, Solar power sources are given priority. By 2030, it is anticipated that over 80% of South Africa's new power generation capacity will be produced from clean energy sources like solar energy. This demonstrates how Africa can contribute significantly to the global switch to clean energy sources.

1. Sources of clean energy and technology for mini-grids in Southern Africa

However, the source of energy used in an off-grid community is significantly influenced by presence of the domestic solar power in the Southern Hemisphere of Sub-Saharan Africa (SSA). Currently, the most common source of solar power in SSA for off-grid mini-grids is solar energy [18, 19, 20, 21]. Solar or solar hybrid systems made up 63% of over 8,100 mini-grids in Asia and Africa. Hydro, diesel/heavy fuel oil and biomass made up the remaining 11% and 3% of the systems, respectively [22]. To achieve energy access goals through sustainable electrification of SSA, it is essential to hybridize different energy sources in light of available resources and technological and economic constraints.

Different Renewable energy sources (RES) technologies are displayed in different categories in Fig. 2. [23] Electrical-based storage devices are not sources of energy; rather, they enable the effective and continuous use of power produced in situations where other energy sources are momentarily unavailable.

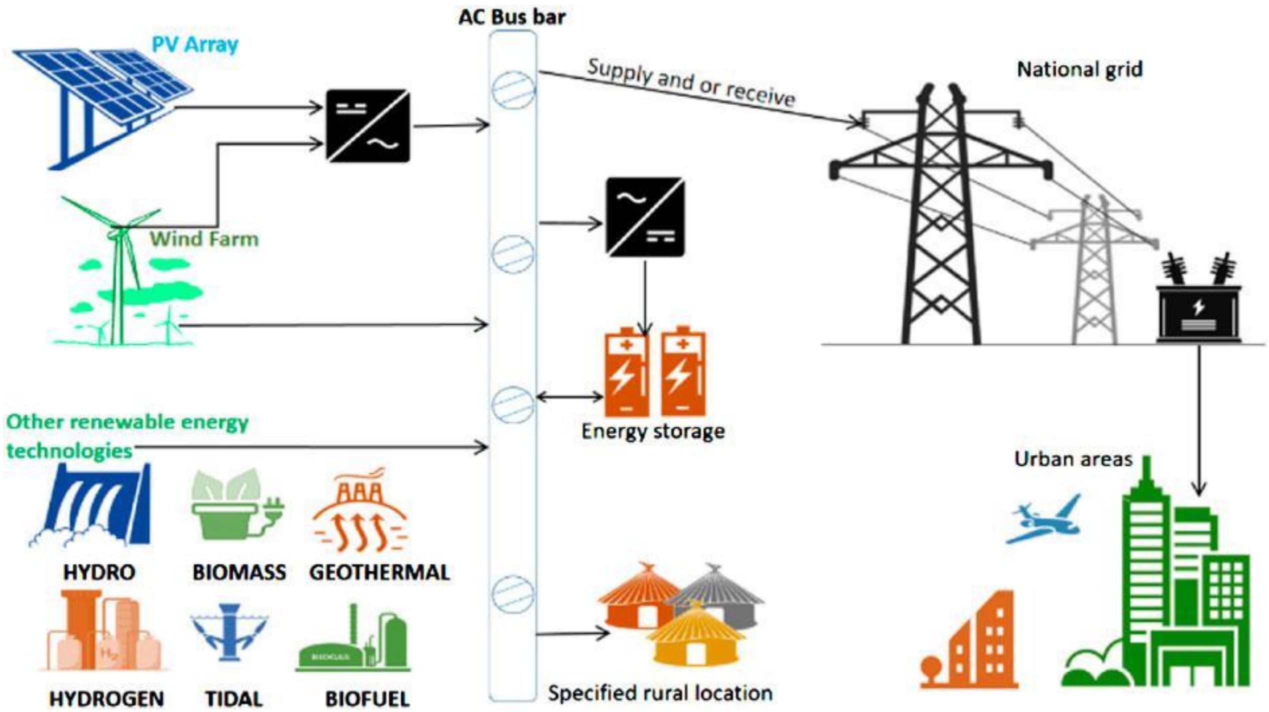

Fig. 2. Mini-grid systems with renewable energy technologies

The quantity of power required determines the mini-grid system's size. Typically, it blends several sources of energy which includes water, and gas.

In conclusion, Africa has an enormous ability to implement the growth of renewable energy, which may hold the key to resolving the issue of energy poverty. Even though there are obstacles like inadequate funds as well as infrastructure, creative means to bring a solution like models such as Pay as You Go are opening doors for the widespread growth of renewable energy in Africa.

In the previous studies presented by Santos et al, and Oliyide et al [24, 25] there was presented an innovative integrated strategy for thermal system Electronic data capture (EDC) optimizationas well as insightful observations that could be adapted and used in the African environment. In addition to building on previous concepts, this work presents an intricate model based on exact matrics mathematics and solutions. In addition, it provides techno-economic researchers with a helpful tool to handle the EDC problems about thermal systems providers.

2. Research Methods and Materials

The target area of study is Zambia but Luangwa District is the main area of focus. The area borders the Luangwa River and Zambezi River. Luangwa River is located to the east and it's the one that separates Zambia from Mozambique. On the other hand, we have the Zambezi River which is located to the south part of the district and flows eastwards to meet the Luangwa River before continuing as the Zambezi River, forming the boundary between the district and Zimbabwe.

However, the district is one of the most forested with multiple hills. Before 1964, the district which by the time was known as Feira, is believed to have been the site of the country's first European settlement. The area has a total population of about 37, 001 people.

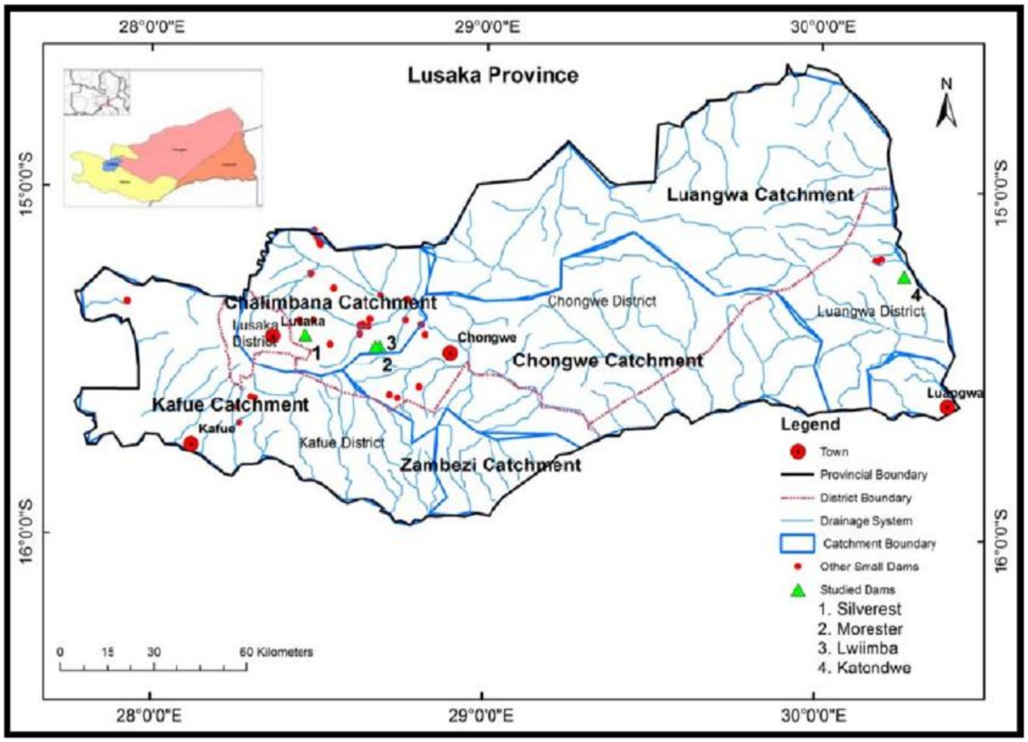

Fig.3.The topography, administrative boundaries, and location of Luangwa Village

2.1 Methods

We conducted a study visit to Luangwa District which is in Lusaka Province were conducted in July 2023 and August 2023 for two months, during which time data and information were collected. In Zambia, information gaps and data scarcity about rural conditions are widespread issues. However, in 2014, the Law on Freedom of Information was approved, which grants unrestricted access to information (freedominfo.org, 2018). Because of this, some of the data and information used in this paper may have come from official records. During the study visits, semi-formal interviews in the Luangwa District found in Lusaka Province were combined with preliminary literature reviews and in-depth analysis of documents. The results of interviews with various stakeholders, including experienced individuals in various governmental organs such as ministries and global institutions, individual heads managing domestic power firms and the locals who are potential users of power in Luangwa District in Lusaka Province, offered insightful information about Zambia's national electrification policies that was comparable to actual conditions on the ground. These observations were made utilizing document analyses and literature reviews. Prominent experts were examined and spoke with. However, the Zambia Electricity Supply Corporation Limited (ZESCO) and Zambia's energy sector are some of the organizations that provided us with information. Also, we interviewed four domestic operators of Zambia hydropower in Lusaka. Every interview involved a set of questions aimed at clarifying economic factors, environmental circumstances, and socio-cultural traits. The methodology employed to comprehend the connections between electrification and industrial goals was informed by more thorough literature reviews on sustainability, as Ritchie et al. (2013) pointed out.

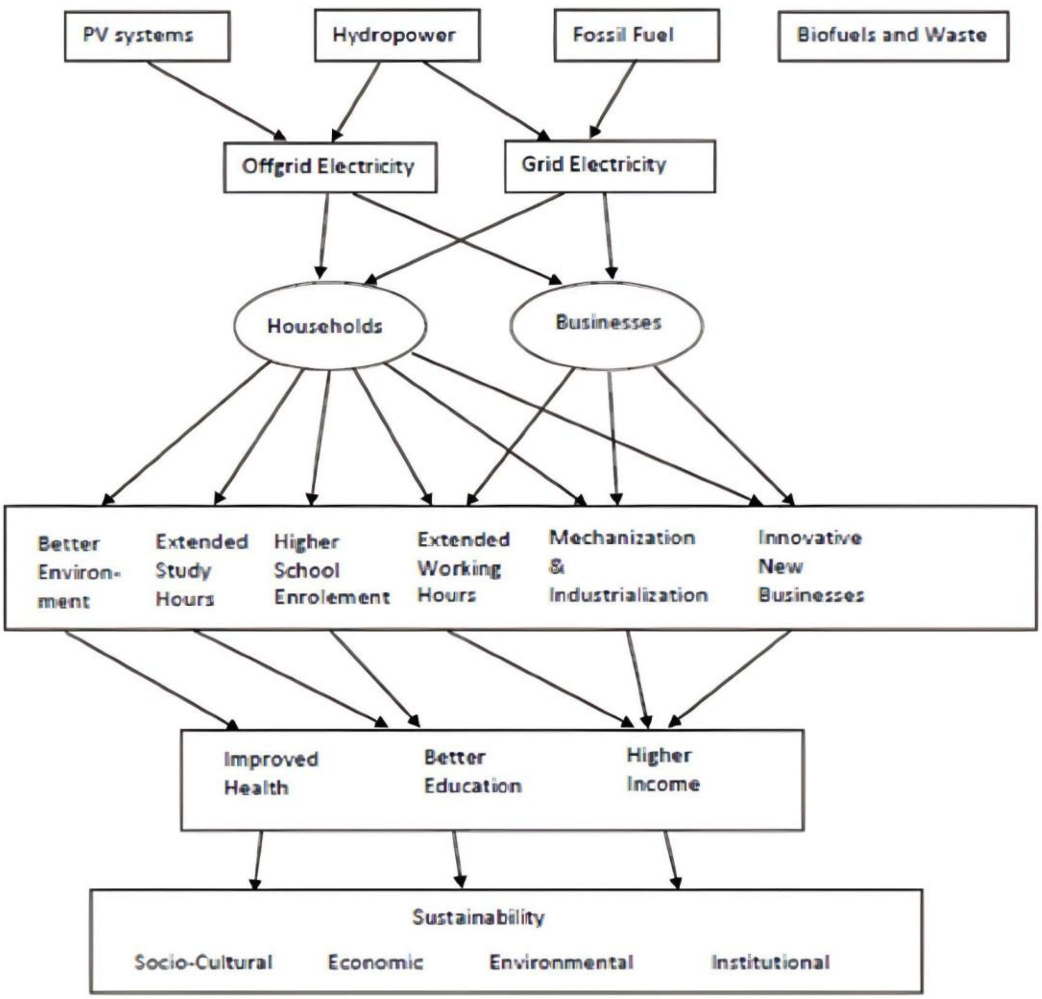

Fig. 4. Connections between Zambia's electrification and the potential for increased sustainability.

Families and companies looking to obtain free, safe electricity might be interested in connecting to the grid or an off-grid system. As shown in Fig. 4, the potential effects of electricity could simplify household chores, boost academic performance, enhance the environment, and spur the growth of industries other than traditional agriculture.

Additionally, we conducted interviews with a particular group of people in villages in the Luangwa district. However, analyzing the need for electricity by locals was the main goal as well as weighing into how the supply of electricity can equal the demand. We conducted a face-to-face interview with a total population of 50, who were differently represented based on both electrified and non-electrified homesteads so that we could develop a good understanding of the local sustainability of various options for electricity in the village. The findings provided information on the village's five main demand areas, which are households, small businesses, public infrastructure, small industries, and recreational pursuits. To obtain a general evaluation of village operations and the requirements for public electricity, we interviewed the village leader for accurate information. To record the results of the interview obtained during the survey, notes which were typically written by hand were used. To obtain information about the layout of the home, the fundamental need for electricity, including lighting, the need for a refrigerator, common use of water, cleaning and washing, use of appliances and demands for cooking, we used a checklist to attain the needed information. Additionally, questions about village administration, public lighting, the use of the nearby hospital, the state of the primary schools, and business opportunities were raised.

3. CONCLUSION

This review article provides a comprehensive analysis of the state of green energy in Africa, with a specific focus on Zambia. By synthesizing the most cited research on photovoltaics (PV) in the region, it sheds light on critical technical aspects such as grid integration for large-scale PV plants and system component optimization. Moreover, it underscores the significance of financing arrangements and incentive programs in driving the adoption of PV technology.

The examination of research on Zambia highlights the vast potential of photovoltaics in addressing key challenges such as rural electrification, irrigation, and water heating. Despite the existing hurdles, including high upfront costs and limited infrastructure, the findings indicate promising opportunities for leveraging PV technology to enhance energy access and promote sustainable development in the country.

Moving forward, further research and initiatives are warranted to capitalize on the identified potential of photovoltaics in Zambia and across Africa. By fostering collaboration between stakeholders, implementing supportive policies, and investing in infrastructure and capacity building, the region can harness the transformative power of solar energy to meet its energy needs, drive economic growth, and mitigate climate change impacts.

. [26, 27, 28, 29, 30]. It also highlights issues with high upfront costs, a lack of infrastructure, and the requirement for training and maintenance.

With only 13% of its rural areas electrified, Zambia suffers from a serious lack of access to electricity. To expand access sustainably, photovoltaics are essential [31, 32]. Reduced dependency on diesel, lower emissions, and less strain on the grid are among the benefits that have been noted [50, 51]. The potential of solar thermal systems is unrealized.

But there are obstacles, like not having enough electricity for cooking needs and not having enough money or knowledge [33, 34]. Adoption promotion requires targeted policies and funding sources [35, 36, 37]. Technical, economic, and social factors must be integrated through thorough planning and analysis [38, 39, 40].

With the help of ZESCO, Zambia is realizing this potential. In particular, PV systems are being used to improve access to electricity in difficult-to-reach rural areas [41, 42, 42]. Though SREP (Scaling-up Renewable Energy Programme) is a leader in promoting solar energy, its methodology may restrict local adaptability. Even though solar energy is very affordable, there are still issues that need to be resolved locally, through strict regulations, and with community involvement [43, 44, 45].

The enormous solar potential of Zambia is highlighted by this review. While photovoltaics can offer decentralized, clean electricity access, infrastructure, cost, and maintenance challenges need to be addressed [46, 47, 48, 49] To fully realize the potential of solar energy and advance the goal of universal energy access, policies and community involvement are essential. The systems and frameworks can be optimized for sustainable implementation with the aid of additional research.

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COMPETING INTERESTS

Declaration of competing interest should be placed here. All authors must disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work. Examples of potential conflicts of interest include employment, consultancies, honoraria, paid expert testimony, patent applications/registrations, and grants or other funding. If no such declaration has been made by the authors, SDI reserves to assume and write this sentence: "Authors have declared that no competing interests exist.".

AUTHORS' CONTRIBUTION

Authors may use the following wording for this section: " 'Author A' designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. 'Author B' and 'Author C' managed the analyses of the study. 'Author C' managed the literature searches…… All authors read and approved the final manuscript."

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DEFINATIONS, ACRONYMS, ABBREVIATIONS

PV, Photovoltaic; MW, Megawatts ; SSA, Sub-Saharan Africa; EDC ,Electronic data capture ; ZESCO, Zambia Electricity Supply Corporation Limited