Review Article

Optimizing Energy Storage Systems for Enhanced Integration with Solar Panels in Off-Grid Rural Areas In Zambia.

ABSTRACT

This study addresses the challenges and opportunities associated with the adoption of photovoltaics (PV) for sustainable electricity supply in Africa, with a specific emphasis on Zambia. The primary aims include assessing the current state of PV integration, identifying key obstacles, and highlighting potential applications in irrigation, rural electrification, and water heating.

Drawing upon the most recent research on PV in Africa, this study synthesizes information from the top ten most cited studies, emphasizing the complexities in large-scale PV integration. The design involves a comprehensive review of technical elements such as storage and bifacial modules, offering insights into the difficulties faced in optimizing PV systems.

The study predominantly focuses on Zambia, a country with significant solar potential. Case studies demonstrate the feasibility of utilizing PV for critical applications like irrigation and rural electrification. The duration encompasses recent years, reflecting the evolving landscape of PV research and implementation.

To assess the advantages and obstacles of PV adoption, this study employs a multifaceted approach. It examines the potential for PV in specific applications, analyzes rates of electrification in Zambian cities (57% and 13% in urban and rural areas, respectively), and identifies hindrances such as high prices, inadequate infrastructure, and insufficient training. The study incorporates thermal systems, emphasizing untapped potential and the limitations of solar cookers.

Major findings underscore the untapped potential of PV in Zambia, including its capacity to enhance access to energy and decrease emissions. However, significant obstacles exist, necessitating specific policies, funding mechanisms, and community involvement to encourage widespread adoption. The study emphasizes the need for concerted efforts to address infrastructure challenges, maintenance requirements, costs, and social factors to fully realize the benefits of PV implementation.

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In conclusion, Zambia's enormous solar potential offers a promising avenue for sustainable energy, but strategic planning and assistance are imperative for successful PV integration.

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

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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, 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.

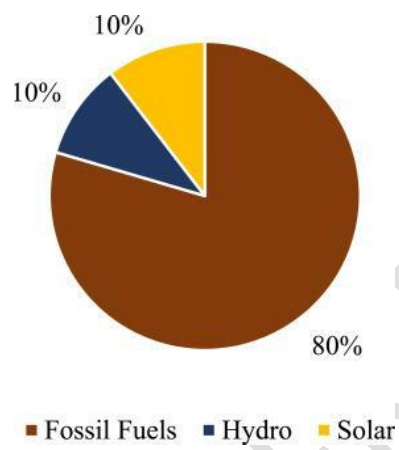

Fig. 1 Capacity of solar generation in Africa

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].

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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.

Moreover, 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

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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.

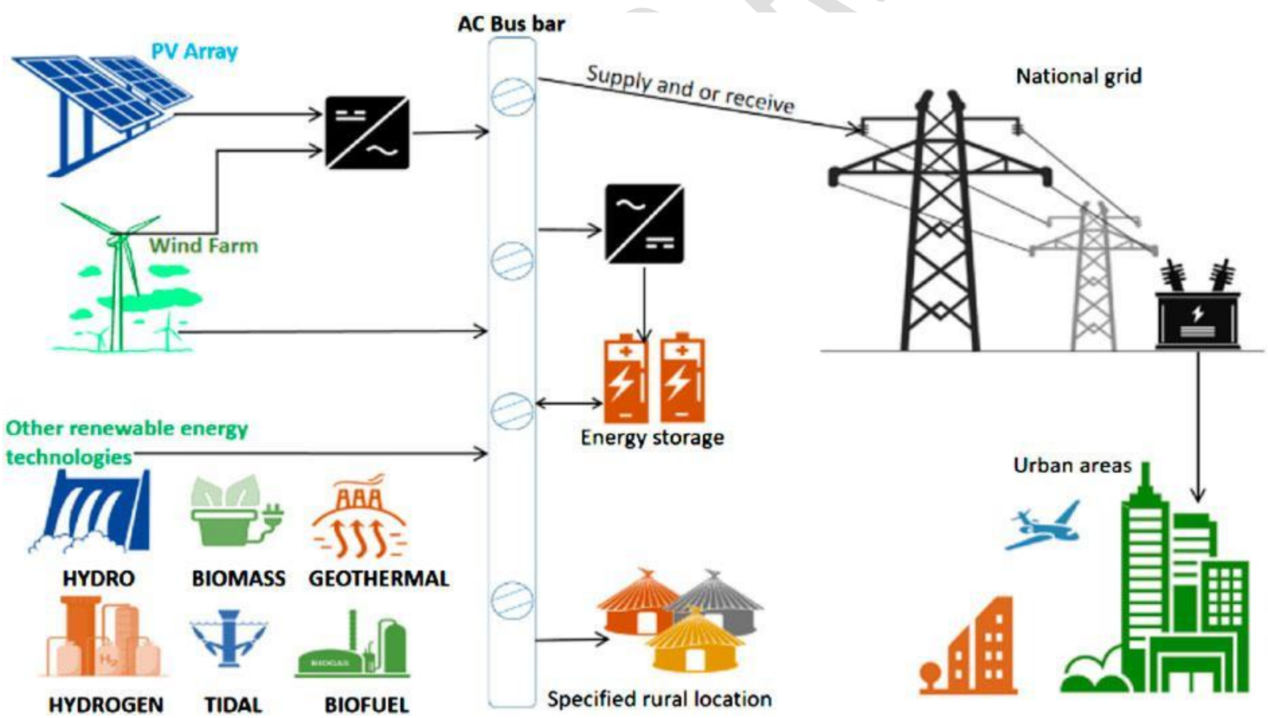

Fig. 2. Mini-grid systems with renewable energy technologies

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.

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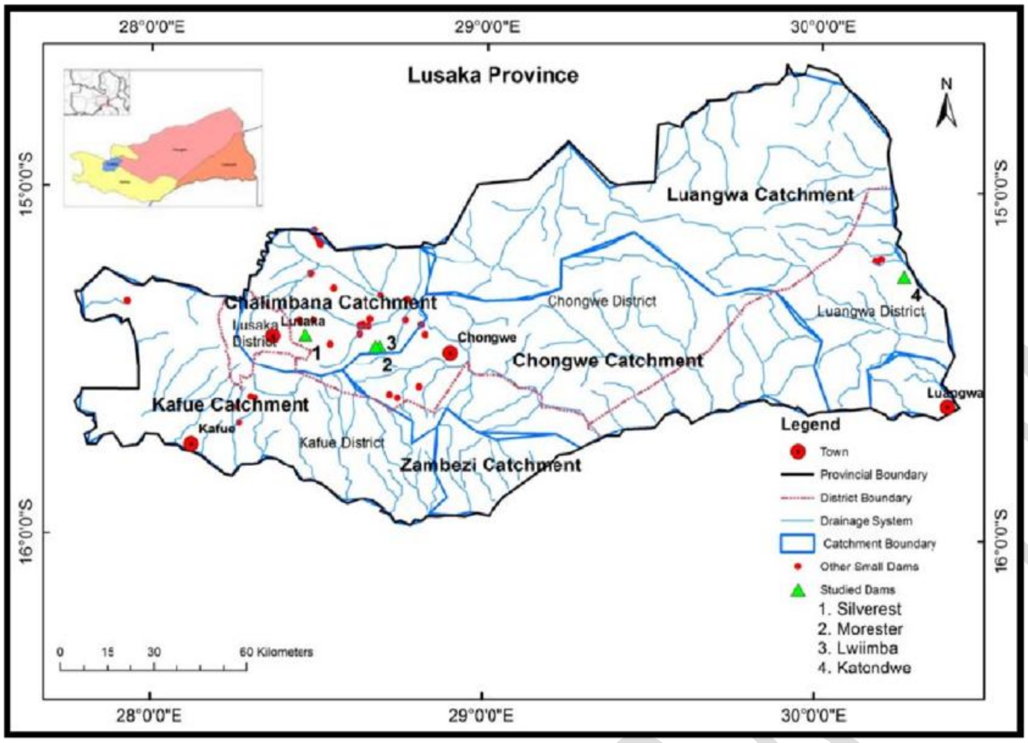

Fig.3.The topography, administrative boundaries, and location of Luangwa Village

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.

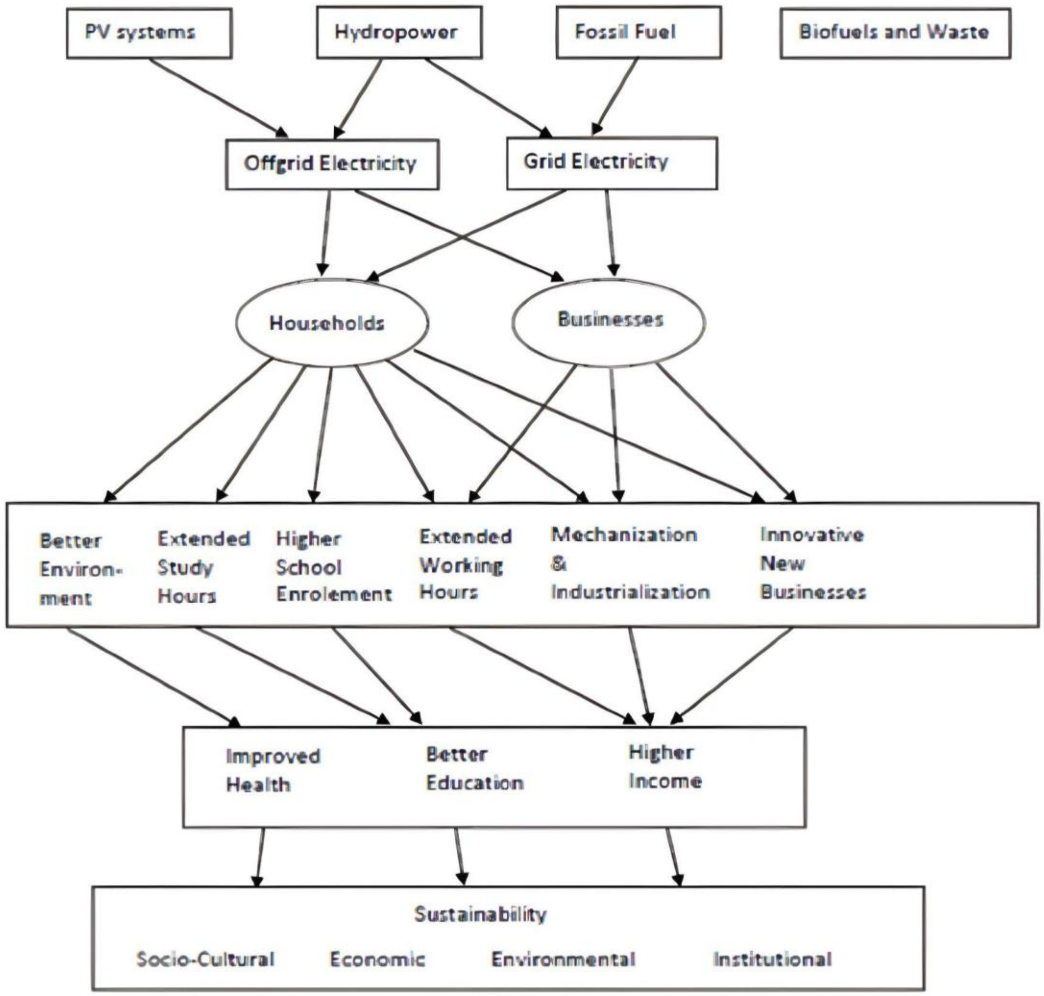

Fig. 4. Connections between Zambia's electrification and the potential for increased sustainability.

Results

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.

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3. DISCUSSION AND CONCLUSION

A thorough examination of the situation of African green energy, with a particular emphasis on Zambia, is given in this review article. The compilation of the most widely cited research on photovoltaics in Africa emphasizes important technical facets like grid integration for large-scale plants and system component optimization. It also highlights how crucial financing arrangements and incentive programs are to encourage adoption.

The examination of research on Zambia shows how photovoltaics has a great deal of potential for use in rural electrification, irrigation, and water heating. [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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CONSENT

No manuscripts will be peer-reviewed if a statement of patient consent is not presented during submission (wherever applicable).

This section is compulsory for medical journals. Other journals may require this section if found suitable. It should provide a statement to confirm that the patient has given their informed consent for the case report to be published. The Journal editorial office may ask the copies of the consent documentation at any time. Authors may use a form from their institution or SDI Patient Consent Form 1.0. Authors should send this form along with the submission. But if already not sent during submission, we may request to see a copy at any stages of pre and post-publication.

If the person described in the case report has died, then consent for publication must be collected from their next of kin. If the individual described in the case report is a minor, or unable to provide consent, then consent must be sought from their parents or legal guardians.

Authors may use the following wording for this section: "All authors declare that 'written informed consent was obtained from the patient (or other approved parties) for publication of this case report and accompanying images. A copy of the written consent is available for review by the Editorial office/Chief Editor/Editorial Board members of this journal."

DEFINATIONS, ACRONYMS, ABBREVIATIONS

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

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