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# Assessing Adoption Barriers to Solar Energy Systems for Enhancing Rural Socio-Economic Development and Climate Change Adaptation: A Case of Kaputa Boma, Zambia

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**Abstract: Access to affordable, reliable, and sustainable energy remains a major challenge in rural Zambia, limiting socio-economic development and climate resilience. This study assessed the barriers to solar energy adoption and examined the contribution of solar energy systems to rural socio-economic development and climate change adaptation in Kaputa Boma and surrounding off-grid communities in Northern Province, Zambia. A mixed-methods concurrent triangulation design was employed, involving household surveys (n = 345), enterprise surveys (n = 45), 22 key informant interviews, six focus group discussions, and field observations. Quantitative data were analyzed using SPSS Version 26, while qualitative data were analyzed thematically using NVivo 12.**

**The findings indicate that Pay-As-You-Go (PAYG) solar systems have significantly improved household access to lighting and phone charging; however, adoption of productive-use solar technologies remains limited. The major barriers identified were high upfront costs, limited financing, inadequate technical support, shortage of spare parts, weak policy implementation, and poor management of public solar infrastructure. Despite these challenges, solar energy contributed to improved household welfare, better educational and health services, increased enterprise productivity, and enhanced climate resilience through reduced dependence on traditional energy sources.**

**The study concludes that expanding the socio-economic benefits of solar energy in rural Zambia requires strengthening financing mechanisms, technical capacity, institutional support, and public-private partnerships to promote productive-use solar technologies.**

***Keywords:*** *Solar Energy; Adoption Barriers; Rural Electrification; Socio-Economic Development; Climate Change Adaptation; Productive-Use Energy; Kaputa District; Zambia.*

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## I. INTRODUCTION

*A. Background and Motivation*

Universal access to affordable, reliable, and sustainable energy is essential for achieving sustainable development and improving livelihoods. Sustainable Development Goal 7 (SDG 7) emphasizes universal energy access by 2030, yet approximately 570 million people in Sub-Saharan Africa still lack reliable electricity, with rural communities being the most affected. Zambia faces a similar challenge despite its abundant renewable energy resources. The country's heavy dependence on hydropower has increased its vulnerability to climate-induced droughts, resulting in prolonged electricity shortages and highlighting the need to diversify the national energy mix.

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Solar photovoltaic (PV) technology has emerged as a practical solution for rural electrification due to Zambia's high solar irradiation and the expansion of decentralized systems supported by government programmes and private companies such as Engie Energy Access (MYSOL), Sun King, and RDG. While Pay-As-You-Go (PAYG) financing has improved household access to basic electricity services, adoption of productive-use solar technologies remains limited.

Kaputa District provides an important case study because most surrounding communities remain off-grid and continue to rely on traditional energy sources. Although solar energy has improved household electrification, government investments in productive-use technologies, including solar-powered hammer mills, have experienced operational challenges related to inadequate maintenance, limited technical capacity, and weak institutional support. These challenges underscore the need to better understand the barriers to solar energy adoption and its contribution to rural socio-economic development and climate change adaptation.

*B. Research Problem and Significance*

Despite growing investment in decentralized solar energy in Zambia, limited empirical evidence exists on the economic, technical, and institutional barriers affecting solar energy adoption in remote rural districts such as Kaputa. While Pay-As-You-Go (PAYG) models have expanded household access to basic solar technologies, adoption of productive-use systems that support income generation, agricultural development, and climate resilience remains low. In addition, public solar investments continue to face challenges related to inadequate maintenance, limited technical capacity, and weak institutional support.

Climate variability has further increased the vulnerability of rural livelihoods in Kaputa District, underscoring the need to understand how solar energy can strengthen climate adaptation while identifying the factors limiting its wider adoption. This study addresses these gaps by examining the barriers to solar energy adoption and evaluating its contribution to rural socio-economic development and climate change adaptation, providing evidence to inform policy and investment decisions for sustainable rural electrification in Zambia.

*C. Research Objectives and Questions*

This study was guided by the following objectives:

- To assess access to and utilization of solar energy technologies among households, enterprises, schools, and health facilities in Kaputa Boma.
- To examine the contribution of solar energy systems to rural socio-economic development, including household welfare, education, healthcare, and enterprise productivity.
- To identify and rank the economic, technical, and institutional barriers influencing the adoption of solar energy systems, particularly productive-use technologies.
- To evaluate the contribution of solar energy systems to climate change adaptation and livelihood resilience within rural communities.

These objectives were addressed through the following research questions:

- What is the current level of access to and utilization of solar energy technologies in Kaputa Boma?
- How do solar energy systems contribute to rural socio-economic development among households, enterprises, schools, and health facilities?
- What economic, technical, and institutional barriers constrain the adoption and productive utilization of solar energy systems?
- How do solar energy systems contribute to climate change adaptation and resilience among rural communities in Kaputa District?

## II. LITERATURE REVIEW

*A. Solar Energy Adoption and Rural Development*

The global transition to renewable energy has accelerated as countries seek to enhance energy security, reduce greenhouse gas emissions, and achieve the Sustainable Development Goals (SDGs). Solar photovoltaic (PV) technology has become one of the fastest-growing renewable energy sources due to declining costs, technological advancements, and increased investment in decentralized energy systems (IEA, 2024; IRENA, 2024). In developing countries, off-grid solar technologies have significantly expanded electricity access in remote rural communities, improving household welfare, education, healthcare, and livelihood opportunities. However, the adoption of productive-use solar technologies remains constrained by financial, technical, and institutional barriers, limiting their broader contribution to rural socio-economic development.

*B. Renewable Energy, Sustainable Development and Climate Change Adaptation*

Renewable energy contributes to multiple Sustainable Development Goals beyond SDG 7 by promoting poverty reduction, improved healthcare, quality education, economic growth, and climate action (WCED, 1987). In rural communities, solar energy supports climate change adaptation through applications such as irrigation, refrigeration, water pumping, agro-processing, and healthcare services, thereby strengthening livelihood resilience. Furthermore, decentralized solar systems reduce reliance on biomass fuels, helping to mitigate deforestation and greenhouse gas emissions. These benefits position solar energy as an important driver of sustainable rural development across Sub-Saharan Africa.

*C. Solar Energy Development in Zambia*

Zambia possesses excellent solar energy potential, receiving average daily solar irradiation ranging between 5.5 and 7.0 kWh/m²/day. Despite these favorable conditions, electricity generation remains predominantly dependent on

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hydropower, making the national energy system vulnerable to prolonged droughts and climate variability. The severe drought experienced during 2023–2024 significantly reduced hydropower generation, resulting in widespread electricity shortages and highlighting the need to diversify the national energy mix.

The Government of Zambia has responded through several policy initiatives, including the National Energy Policy (2019), the Rural Electrification Master Plan, and the Eighth National Development Plan (2022–2026), all of which prioritize renewable energy expansion and increased private sector participation. Institutions such as the Rural Electrification Authority (REA), together with private companies including Engie Energy Access (MYSOL), Sun King, and Rural Development Group (RDG), have significantly expanded access to off-grid solar technologies through Pay-As-You-Go (PAYG) financing models.

Although household solar adoption has increased considerably, evidence suggests that productive-use solar technologies remain underutilized. Limited access to finance, inadequate technical support, weak maintenance systems, and institutional challenges continue to constrain wider adoption, particularly in remote districts such as Kaputa.

### *D. Solar Energy Adoption in Rural Africa*

Across Sub-Saharan Africa, decentralized solar technologies have transformed energy access for millions of rural households. Countries including Kenya, Rwanda, Tanzania, and Uganda have experienced significant expansion of off-grid solar systems through innovative financing mechanisms, particularly PAYG business models. These initiatives have improved household welfare by reducing expenditure on kerosene and candles, increasing study hours for schoolchildren, improving communication through mobile phone charging, and supporting small-scale enterprises.

However, empirical studies consistently report that affordability remains the principal barrier preventing households and rural enterprises from adopting larger productive-use solar systems capable of powering irrigation equipment, refrigeration, milling, and manufacturing activities. Technical constraints including inadequate maintenance services, shortage of trained technicians, and poor availability of spare parts further limit long-term sustainability. Institutional weaknesses such as limited consumer awareness, weak policy implementation, and insufficient post-installation support continue to affect renewable energy programmes across many African countries.

### *E. Research Gap*

Although renewable energy has been widely studied at global, regional, and national levels, limited empirical evidence exists on the barriers to solar energy adoption in remote rural districts such as Kaputa. In Zambia, most studies have focused on national electrification policies or utility-scale renewable energy, with little attention to household, enterprise, and institutional adoption of solar technologies. Moreover, few studies have integrated the economic, technical, institutional, and climate adaptation dimensions of solar energy using mixed-methods approaches. This study addresses these gaps by providing empirical evidence from Kaputa Boma to inform rural renewable energy policy, climate adaptation, and sustainable socio-economic development.

## III. MATERIALS AND METHODS

### *A. Research Design*

This study employed a mixed-methods concurrent triangulation research design, integrating quantitative and qualitative approaches to provide a comprehensive assessment of solar energy adoption barriers and their contribution to rural socio-economic development and climate change adaptation. The mixed-methods approach enabled the collection of complementary data from households, enterprises, public institutions, key informants, focus group discussions, and field observations, thereby enhancing the validity and reliability of the findings through methodological triangulation.

### *B. Study Area*

The study was conducted in Kaputa Boma and six surrounding rural communities Kapepula, Kalaba, Kasongole, Chocha, Katai, and Mwenda Nansapato, in Kaputa District, Northern Province, Zambia. Kaputa District is located approximately 350 km northwest of Kasama and is characterized by dispersed rural settlements, limited transport infrastructure, and low levels of electricity access. While Kaputa Boma receives intermittent electricity from the national grid supplied by ZESCO, the majority of surrounding communities remain off-grid and rely on biomass fuels and decentralized solar energy systems.

Livelihoods are predominantly based on subsistence agriculture, fishing, livestock production, and small-scale trading, all of which are increasingly affected by climate variability.

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Table 1. Profile of the Study Area

| Parameter | Description |
|---|---|
| Study Area | Kaputa Boma and six surrounding communities |
| Province | Northern Province |
| Country | Zambia |
| Communities Surveyed | Kaputa Boma, Kapepula, Kalaba, Kasongole, Chocha, Katai, Mwenda Nansapato |
| Main Livelihoods | Agriculture, fishing, livestock, petty trading |
| Electricity Access | Limited grid coverage; predominantly off-grid |
| Solar Potential | Approximately 5–6 kWh/m²/day |
| Climate | Tropical with distinct wet and dry seasons |
| Major Solar Providers | Engie (MYSOL), Sun King, RDG |

*C. Data Collection*

Primary data were collected using structured household questionnaires administered to 345 households, enterprise questionnaires administered to 45 small businesses, 22 key informant interviews, six focus group discussions involving 54 participants, and direct observations of solar installations in schools, health facilities, and solar-powered hammer mills. Key informants included officials from the Rural Electrification Authority, District Administration, District Education Board Secretary, District Health Office, Zambia Cooperative Federation, ZESCO, private solar companies, school administrators, and health facility managers.

Secondary data were obtained from government policy documents, Rural Electrification Authority reports, Zambia Statistics Agency publications, Ministry of Energy reports, peer-reviewed journal articles, and publications from the International Energy Agency and the International Renewable Energy Agency.

*D. Data Analysis*

Quantitative data were analyzed using Statistical Package for the Social Sciences (SPSS) Version 26. Descriptive statistics including frequencies, percentages, means, and cross-tabulations were used to summarize household characteristics, solar energy access, adoption patterns, and perceived barriers. Inferential statistical techniques, including Chi-square tests and independent sample t-tests, were applied to examine relationships among key study variables.

Qualitative data obtained from key informant interviews and focus group discussions were analyzed using NVivo Version 12 through thematic analysis following the framework developed by Braun and Clarke (2006). Emerging themes were categorized into economic, technical, institutional, socio-economic, and climate adaptation dimensions. Quantitative and qualitative findings were subsequently integrated to provide a comprehensive interpretation of the results.

## IV. RESULTS AND DISCUSSION

*A. Solar Energy Access, Utilization and Contribution to SDG 7*

The findings indicate that solar energy has become the primary source of modern energy for many off-grid households in Kaputa District, contributing significantly to improved energy access and supporting SDG 7 (Affordable and Clean Energy). Approximately 72% of surveyed households had adopted Solar Home Systems (SHSs) or solar lanterns, largely through Pay-As-You-Go (PAYG) financing offered by Engie Energy Access (MYSOL), Sun King, and Rural Development Group (RDG). While these systems have improved access to lighting, phone charging, and basic household appliances, adoption remains concentrated on basic energy services. Productive-use solar technologies for irrigation, agro-processing, refrigeration, and other income-generating activities remain limited, indicating that although decentralized solar systems have advanced rural electrification, their potential to drive broader rural economic transformation has yet to be fully realized.

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Table 2. Contribution of Solar Energy to SDG 7 In Kaputa District

| SDG 7 Target | Indicator | Contribution in Kaputa District |
|---|---|---|
| **7.1 Universal access to affordable, reliable and modern energy** | Household access to electricity | Approximately 72% of surveyed households accessed electricity through Solar Home Systems and solar lanterns. |
| **7.2 Increase renewable energy share** | Adoption of decentralized solar systems | Increased use of off-grid solar technologies supplied by Engie (MYSOL), Sun King and RDG. |
| **7.3 Improve energy efficiency** | Replacement of traditional lighting | Reduced dependence on candles and kerosene for household lighting. |
| **7.a International cooperation** | Public-private partnerships | Expansion of PAYG financing and donor-supported rural electrification programmes. |
| **7.b Infrastructure expansion** | Institutional electrification | Installation of solar systems in schools, health facilities and selected public infrastructure. |

*B. Socio-Economic Benefits of Solar Energy*

The study demonstrates that solar energy has generated important socio-economic benefits across households, public institutions, and rural enterprises. Survey results showed that a majority of households reported improved living standards following adoption of solar energy. Respondents indicated that access to reliable lighting reduced expenditure on candles and disposable batteries while enabling children to study during evening hours. Improved household lighting also enhanced security and increased opportunities for social and economic activities after sunset.

Educational institutions benefited through improved classroom lighting, enabling teachers to prepare lessons and learners to undertake evening study sessions where boarding facilities existed. Similarly, health facilities reported improved service delivery through reliable lighting for maternity services, emergency treatment, vaccine refrigeration, and storage of essential medicines.

Among the 45 enterprises surveyed, solar energy contributed to extended business operating hours, reduced expenditure on fuel-based generators, improved customer services, and increased business productivity. Hair salons, barbershops, grocery stores, restaurants, and small retail shops were the principal beneficiaries. Nevertheless, enterprise adoption remained concentrated on lighting and small electrical appliances because larger productive-use systems capable of supporting refrigeration, welding, milling, and manufacturing remained unaffordable for most entrepreneurs.

The study further evaluated the government's solar-powered hammer mill initiative. Although the programme was intended to enhance agricultural value addition and reduce maize milling costs, field observations revealed that most solar hammer mills were either non-operational or operating below capacity. The primary causes included inadequate maintenance, absence of battery storage systems, limited availability of spare parts, poor cooperative management, and inadequate technical support. Consequently, the anticipated socio-economic benefits of productive-use solar technologies have not yet been fully realized.

*C. Adoption Barriers to Solar Energy Systems*

The study identified three broad categories of barriers influencing solar energy adoption: economic, technical, and institutional barriers.

- *Economic Barriers*

Economic constraints emerged as the most significant determinant of adoption. Many respondents cited the high upfront cost of larger solar systems as the principal obstacle preventing investment in productive-use technologies. Although PAYG financing has improved access to basic household systems, respondents indicated that financing options for larger commercial systems remain limited. High interest rates, limited access to rural credit, low household incomes, and absence of affordable leasing arrangements further constrained adoption.

- *Technical Barriers*

Technical challenges constituted the second most important barrier. Respondents reported inadequate availability of trained technicians, poor maintenance services, limited after-sales support, and difficulty accessing replacement batteries and spare parts. Public institutions experienced additional operational challenges because maintenance budgets were insufficient to sustain installed solar systems. Observations of government-funded solar hammer mills further confirmed that inadequate technical support contributed significantly to equipment failure and prolonged downtime.

- *Institutional Barriers*

Institutional barriers included inadequate public awareness, weak implementation of renewable energy policies, insufficient community participation during project implementation, and poor coordination among implementing agencies. Respondents also highlighted the absence of local service centres for solar equipment, weak extension services, and inadequate technical training programmes. These institutional weaknesses reduced community confidence in

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solar technologies and limited long-term sustainability of installed systems.

Table 3. Adoption Barriers to Solar Energy in Kaputa District

| Barrier Category | Major Findings |
| --- | --- |
| **Economic** | High upfront costs, limited access to finance, low household incomes, lack of financing for productive-use systems. |
| **Technical** | Limited technical expertise, inadequate maintenance services, shortage of spare parts, poor after-sales support. |
| **Institutional** | Weak policy implementation, inadequate awareness, limited local technical capacity, poor management of public solar infrastructure. |

*D. Solar Energy and Climate Change Adaptation*

The findings demonstrate that solar energy contributes significantly to climate change adaptation and livelihood resilience within Kaputa District. Respondents perceived increasing temperatures, prolonged dry seasons, declining rainfall reliability, and more frequent droughts as major climate-related challenges affecting agriculture, fisheries, and household livelihoods.

Solar energy systems enhanced adaptive capacity by providing reliable electricity independent of the national grid, thereby reducing vulnerability to prolonged power outages associated with hydropower shortages. Households reported reduced dependence on candles and kerosene, while continued reliance on firewood for cooking indicated that the transition to cleaner household energy remains incomplete.

Respondents identified considerable opportunities for expanding productive-use solar technologies to strengthen climate resilience. Priority applications included solar-powered irrigation, cold storage for fisheries and agricultural produce, livestock water supply, agro-processing, and community water systems. However, realization of these opportunities will require substantial investment in financing mechanisms, technical capacity development, and institutional support.

Table 4. Contribution of Solar Energy to Climate Change Adaptation

| Climate Adaptation Dimension | Contribution of Solar Energy |
| --- | --- |
| Household resilience | Reliable lighting during grid outages; reduced expenditure on traditional fuels. |
| Agriculture | Potential for solar irrigation and climate-resilient crop production. |
| Fisheries | Opportunities for solar-powered refrigeration and reduced post-harvest losses. |
| Health | Reliable electricity for vaccine storage and emergency health services. |
| Environment | Reduced dependence on candles, kerosene, and biomass; lower greenhouse gas emissions. |

*E. Policy and Institutional Implications*

The findings indicate that rural solar energy programmes should evolve beyond household electrification toward integrated productive-use energy systems capable of supporting rural economic development. Government should strengthen implementation of the National Energy Policy through improved financing mechanisms, expanded rural technical training programmes, establishment of district-level maintenance centres, and stronger public-private partnerships.

Private solar companies should develop affordable financing models for higher-capacity productive-use systems targeting rural enterprises, farmer cooperatives, and agro-processing facilities. In addition, greater investment is required in after-sales services, technician training, and supply chains for spare parts to improve system reliability.

Local authorities, development partners, and community organizations should strengthen institutional coordination to ensure effective management and long-term sustainability of publicly funded solar infrastructure.

*F. Overall Discussion*

The study demonstrates that decentralized solar energy has substantially improved access to modern energy services in Kaputa District and contributed positively to household welfare, education, healthcare, enterprise productivity, and climate resilience. These findings support the Energy Ladder Theory, which suggests that households progressively transition from

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traditional fuels toward modern energy sources as access improves, and the Sustainable Livelihoods Framework, which emphasizes the role of energy in strengthening livelihood assets and resilience.

However, the results also reveal that current adoption remains concentrated at the lower end of the energy ladder, with limited progression toward productive-use technologies capable of generating broader socio-economic transformation. Economic affordability, technical capacity, and institutional effectiveness remain the principal constraints limiting this transition. Addressing these barriers will be essential if solar energy is to realize its full potential as a driver of sustainable rural development and climate change adaptation in Zambia.

## V. POLICY IMPLICATIONS AND RECOMMENDATIONS

The findings of this study provide practical recommendations for government institutions, private solar companies, development partners, financial institutions, local authorities, and rural communities seeking to accelerate the adoption of solar energy systems for socio-economic development and climate change adaptation. These recommendations are organized into short-, medium-, and long-term implementation horizons.

### *A. Short-Term Recommendations (1–2 Years)*

Government agencies, particularly the Ministry of Energy and the Rural Electrification Authority (REA), should strengthen rural electrification by expanding public awareness on solar energy and improving access to affordable financing for productive-use technologies. Private solar companies should enhance after-sales services through local maintenance centers, technician training, and improved availability of spare parts. Public investments, particularly solar-powered hammer mills, require regular technical audits, rehabilitation of non-functional systems, and strengthened maintenance arrangements. Furthermore, robust monitoring and evaluation frameworks should be established to assess the technical performance, socio-economic impacts, and long-term sustainability of publicly funded solar energy projects.

### *B. Medium-Term Recommendations (3–5 Years)*

Government should establish a National Rural Solar Energy Capacity Development Programme to strengthen technical skills, certification, and innovation in renewable energy. Financial institutions should expand affordable financing for productive-use solar technologies through specialized credit facilities and strengthened public-private partnerships. District Councils and cooperatives should integrate solar energy into local development planning by promoting irrigation, agro-processing, cold storage, and other productive applications. In addition, stronger coordination among government ministries, REA, private sector actors, and development partners is needed to improve the planning, implementation, and sustainability of rural renewable energy programmes.

### *C. Long-Term Recommendations (5+ Years)*

Zambia should adopt an integrated renewable energy strategy that promotes productive-use solar technologies alongside climate-smart agriculture, rural industrialization, and sustainable livelihoods. Government should support local manufacturing and assembly of solar components to reduce costs, enhance energy security, and create employment. A national framework for monitoring and evaluating renewable energy impacts should be established to guide policy and investment decisions. Additionally, decentralized solar energy should be fully integrated into national climate change adaptation strategies to strengthen resilience against droughts, energy insecurity, and climate variability.

## VI. CONCLUSION

This study examined the barriers to solar energy adoption and evaluated the contribution of solar energy systems to rural socio-economic development and climate change adaptation in Kaputa Boma and surrounding off-grid communities in Northern Province, Zambia. The findings indicate that decentralized solar energy, particularly through Pay-As-You-Go (PAYG) Solar Home Systems, has significantly improved access to modern energy services, enhancing household welfare, education, healthcare, and small enterprise productivity.

Despite these benefits, adoption remains largely limited to basic household applications. Economic barriers, including high upfront costs and limited access to finance, were identified as the primary constraints, followed by technical challenges such as inadequate maintenance services and limited technical expertise, and institutional weaknesses including poor policy implementation and inadequate post-installation support.

The study further demonstrates that solar energy contributes to climate change adaptation by reducing dependence on traditional biomass and unreliable grid electricity while enhancing community resilience. However, maximizing these benefits requires greater investment in productive-use solar technologies, strengthened financing mechanisms, improved technical capacity, and effective institutional support.

Overall, the findings highlight the potential of solar energy to contribute to multiple Sustainable Development Goals, particularly SDGs 1, 7, 8, 9, and 13. Expanding productive-use solar technologies through coordinated policy interventions and public-private partnerships will be essential for promoting sustainable rural development and strengthening climate resilience in Zambia. Future research should assess the long-term socio-economic impacts of productive-use solar systems and evaluate the effectiveness of emerging financing and policy interventions.

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