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Rural Entrepreneurs and Forest Futures: Pathways to Emission Reduction and Sustainable Energy

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Abstract

Rural areas around the world are increasingly dealing with energy and environmental challenges. These challenges are particularly acute in developing countries, where persistent reliance on traditional energy sources—such as wood fuel—intersects with concerns about forest conservation and energy sustainability. While wood fuel use is often portrayed as unsustainable, it is important to acknowledge that much of it remains ecologically viable and socially embedded. This study explores the role of rural entrepreneurs in shaping low-carbon transitions at the intersection of household energy practices and environmental stewardship. Fieldwork was carried out in four rural Zambian communities in 2016 and complemented by 2024 follow-up reports. It examines the connections between household energy choices, greenhouse gas emissions, and forest resource dynamics. Findings reveal that over 60% of rural households rely on charcoal for cooking, with associated emissions estimated between 80 and 150 kg CO_2 per household per month. Although this is significantly lower than the average per capita carbon footprint in industrialized countries, such emissions are primarily biogenic in nature. While rural communities contribute minimally to global climate change, their practices have significant local environmental consequences. This study draws attention to the structural constraints as well as emerging opportunities within Zambia's rural energy economy. It positions rural entrepreneurs not merely as policy recipients but as active agents of innovation, environmental monitoring, and participatory resource governance. A model is proposed to support sustainable rural energy transitions by aligning forest management with context-sensitive emissions strategies.

Keywords: greenhouse gas emission; forest sustainability; wood fuel; clean energy; rural; rural entrepreneur; seasonal entrepreneur; Zambia

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1. Introduction

Access to clean and sustainable energy remains one of the most urgent global challenges of our time. An estimated 2.6 billion people—primarily in developing regions—continue to rely on wood and other traditional biomass fuels for household cooking and heating [1]. This reliance is deeply embedded in rural livelihoods and is closely linked to forest ecosystems, where wood is harvested from both natural and managed forests, frequently without sustainable regeneration. Nowhere is this dependency more pronounced than in rural Africa, where over 90% of harvested wood is used for fuel, underscoring the continent's enduring dependence on biomass energy [2,3]. While biomass offers energy security for off-grid households, its widespread use raises critical environmental and public health concerns. These include accelerated deforestation, degradation of ecosystems, loss of biodiversity, and indoor air pollution—issues that carry significant implications for long-term sustainability and climate mitigation strategies.

Within this broader global trend, Sub-Saharan Africa (SSA) remains one of the most wood-fuel-dependent regions, with households consuming an estimated 5 kg of wood daily for cooking [2,4]. This extensive use of biomass affects soil fertility, upsets local food systems, and holds back groundwater. However, the environmental consequences of wood fuel consumption are shaped by factors such as forest regeneration rates, logging methods, and local policy interventions. Although cleaner energy alternatives exist, widespread adoption remains hindered by economic, infrastructural, and social challenges [5–7]. Given projections indicating increased biomass use in the coming decades, addressing rural energy needs requires a holistic strategy. One that integrates sustainability principles not only in forestry but also into rural entrepreneurial activities based on natural resource extraction.

In this study, we distinguish between two primary categories of rural entrepreneurs: seasonal and permanent. Seasonal entrepreneurs engage in income-generating activities that are closely tied to environmental cycles—such as rainfall patterns, agricultural seasons, or forest product availability. For instance, smallholder farmers may cultivate crops after the rainy season and sell surplus yields or forest products during harvest windows. In contrast, permanent rural entrepreneurs operate year-round, often running micro- or small-scale enterprises that provide essential goods and services within their communities. These include general trading, food vending, or the sale of forest-based commodities. The scope and scale of their activities vary, but both groups rely heavily on natural resource flows and local ecological rhythms [8].

In this regard, rural entrepreneurs are not only economic actors, but they are also embedded stewards of place-based knowledge and resource systems. While the entrepreneurial process in rural contexts may not follow conventional models, it is nonetheless dynamic and adaptive to the context. Activities include organic honey production, basket weaving, wild fruit collection, charcoal and mushroom harvesting, artisanal fisheries, and small-scale agriculture, among others. These enterprises often emerge from necessity, but they also reflect innovation, resilience, and deep ecological familiarity. Importantly, rural entrepreneurs are uniquely positioned to contribute to sustainable resource governance, particularly in forest regeneration, biodiversity conservation, and low-carbon transitions [9].

Rural regions, both in developed and developing countries, are typically dispersed and anchored in key sectors such as agriculture, forestry, and tourism, or even mining. These regions are central to food production and the stability of supply chains [10] and are the foundation for agro-industrial systems that support urban populations. However, structural changes, particularly demographic shifts, are reshaping rural areas in global food and environmental systems. For example, many rural areas in the European Union are experiencing population decline and aging demographics, which are altering land-use patterns and putting new pressures on forest ecosystems [11]. In countries such as Finland, Italy, and Germany, the abandonment of agricultural land has led to a reorientation of forest management strategies [11–13]. While some landscapes are undergoing passive reforestation due to reduced farming activity, others face unintended ecological consequences, including biodiversity loss, increased wildfire risk, and weakened conservation efforts.

While forest protection remains vital for climate change mitigation, demographic trends complicate the rural sustainability agenda. As studies show, in developed countries, particularly across Europe, rural depopulation and the decline in agricultural activity have led to land abandonment and, in some cases, forest regeneration [13,14]. However, this demographic shift also threatens food production, livelihoods, and the long-term viability of rural communities. Nevertheless, developing countries continue to experience rural population growth, where human labor is essential to local economies and where access to clean energy remains limited. Wood fuel remains the dominant source of household energy, particularly for cooking, and presents complex challenges in terms of forest management, health, and emissions [15]. Wood's ecological impact against its role in energy access and rural development is not unsustainable, but it requires an evaluation that weighs wood's ecological impact against its role in energy access and rural development. To better understand these dynamics, we identify three categories of household fuel strategies, which are further elaborated in the analytical section.

Methane emissions present a significant challenge to rural energy systems, particularly through livestock management, agricultural residues, and organic waste. While clean energy technologies contribute to reducing greenhouse gas (GHG) emissions, effective methane mitigation requires strategies that extend beyond energy efficiency alone. However, existing research often overlooks how methane mitigation can be embedded within broader rural energy transitions, especially in ways that leverage the agency of local actors. This study addresses that gap by examining the intersection of methane emissions, rural energy sustainability, and entrepreneurial innovation, with a particular focus on Zambia. It explores how rural entrepreneurs—through practices such as biogas production, waste valorization, and decentralized energy solutions—can contribute to methane reduction while enhancing local energy resilience. This study is guided by the following research questions: (1) How do methane emissions impact rural energy sustainability? (2) What role can rural entrepreneurs and AI-driven monitoring systems play in mitigating methane emissions? (3) How can policy interventions support entrepreneurial-led transitions to cleaner energy alternatives while addressing methane-related challenges?

Using qualitative methods—including fieldwork, focus group discussions, and secondary data analysis—this study is based on data originally collected in 2016 and updated in 2024 by intensive fieldwork in rural Zambia.

Description of the Study Site in Rural Zambia

Mpulungu, situated in northern Zambia, is a rural district with a population of 153,564, as recorded in the Zambian census for the year 2022. The area is noted for its rich biodiversity, including extensive forests and the vast Lake Tanganyika. The lake is an important source of fish, while the surrounding forests provide essential wood and energy for the household (see [16]). However, the challenge of aligning forest supply with the demand for wood fuel consumption presents a significant sustainability issue and hinders efforts to reduce emissions. A study conducted by [17] found that Zambia's forest cover, which makes up 66.5 percent of the nation's total land area, is rapidly declining as of 2019. Similar to what was mentioned in [18], the country's forest cover decreased by 6.3 percent starting in the 1990s, or 3.332 million hectares. With an average annual deforestation rate of 166,600 hectares, or 0.32%, Zambia is one of the developing nations most impacted by forest loss. Africa faces challenges in balancing the sustainability of natural resources with the demands of forest material consumption. Logging, timber, and charcoal production are particularly pertinent to Mpulungu. There remains a gap in understanding the role and anticipated contribution of rural communities, particularly rural entrepreneurs, to sustainable forest initiatives, despite forests being a fundamental part of rural existence and a critical backbone of livelihoods.

2. Research Method

This study used qualitative data collection methods to study the challenges of sustainable forest management, particular forest management strategies, and emissions in rural Zambia. The survey, conducted in four rural villages, collected qualitative data through semi-structured interviews, focus group discussions, and direct observation. This approach allowed for a thorough examination of local knowledge, household wood-fuel collection activities, and forest management practices, based on previous and current studies [2,16,19].

2.1. Data Collection

In 2016, I was involved in a sustainable development project at Lake Tanganyika in Mpulungu, Zambia, which was supported by the Global Environment Facility (GEF) and the African Development Bank and was being implemented by the Ministry of Lands, Natural Resources, and Environment of the Republic of Zambia. As part of this initiative, I carried out fieldwork in four rural communities selected on the basis of accessibility, village size, and the support of local leaders in hosting focus groups. This study involved 303 individuals, supplemented by high-level interviews with representatives of the communities.

Recognizing the need for updated insights, I integrated new findings from the Tanganyika Lake Sustainability Project reports and studies with extended fieldwork in 2024 [20–22]. This ensured a longitudinal perspective, allowing for an informed assessment of evolving rural energy consumption patterns, emissions metrics, and policy developments impacting forest management. Over two weeks, I collected data across the four villages, situated in remote landscapes of dense forests and lake ecosystems. Table 1 below shows the profile of the data for the four communities.

Table 1. Demographic and economic profiles of rural communities in Mpulungu.

Age Group	Males (n-136)	Females (n-167)
19–24	28	36
25–50	98	115
50+	10	16
Educational level	*Grade 7–12*	*Grade 4–10*
Main occupations	*Farmer, livestock keeper, charcoal producer, and craft making*	
Economic/livelihood activities	*Farming, firewood collection, craft making, timber collection, and fishing (seasonal entrepreneurship)*	
Household size	*Average of 5 persons*	
Residential areas	*Rural communities*	
Total study sample size of 303		

This study conducted focus group discussions across four remote communities in the Mpulungu area, engaging 303 participants selected from registered community lists. While the number of households was not explicitly recorded in the study's data profile, an estimate based on an average household size of five members suggests approximately 60 households participated:

$$\textit{Estimated Household Size} = 303/5 \approx 60.06 \textit{ households}$$

To ensure methodological robustness, triangulation was employed by integrating datasets from multiple communities. This approach reinforced the validity and reliability of the findings, enabling a comparative analysis of diverse perspectives on emissions, forest use, and their implications for climate change.

2.1.1. Participation Selection

The community members were selected by means of a purposive selection process, ensuring the participation of key stakeholders in the forestry, agriculture, and fisheries sectors, including village field officers and representatives of the private sector in the forestry and related sectors. This strategic choice has increased the relevance and applicability of the discussions by bringing together first-hand experience from those directly involved in rural energy practices.

2.1.2. Discussion Design

The focus group discussions were structured around open-ended questions adapted to the specific circumstances of each community. These discussions examined the problems of access to and acceptance of improved stoves, together with practical recommendations, and encouraged participants to share their personal experiences and insights. Each meeting lasted two to three hours and promoted a broad dialog, followed by informal but valuable discussions on local energy practices, sustainable livelihoods, and infrastructure constraints.

2.1.3. Data Analysis

The thematic analysis strategy was used for qualitative responses and identified common patterns and themes related to the transition to rural areas and sustainable forest management. The inclusion of participatory debates ensured that rural voices were directly involved in shaping policy recommendations and strategies to improve sustainability.

2.2. Impact of Climate Change and GHG Emissions

Building on the thematic analysis, this section examines the influence of climate change and greenhouse gas (GHG) emissions on rural energy transitions, focusing on methane and carbon dioxide emission patterns and their effects on forest sustainability and local energy practices. This study proposes an institutional model that integrates bottom–up innovation with multi-level governance to support sustainable energy transitions. The model emphasizes three interlinked pillars: 1. Local Entrepreneurial Ecosystems—recognize rural entrepreneurs as embedded actors who mobilize natural resources, social capital, and indigenous knowledge to drive low-carbon solutions. ii. Enabling Policy Frameworks—advocating for decentralized energy policies, microfinance access, and capacity-building programs that legitimize and scale grassroots innovations. ii. Participatory Forest and Emissions Governance—promoting inclusive monitoring systems where entrepreneurs contribute to forest stewardship, emissions tracking, and adaptive land-use planning. This model challenges conventional top–down approaches by focusing on rural entrepreneurs not only as beneficiaries of development interventions but as co-creators of institutional change. Figure 1 aligns itself with the larger goals of climate resilience, energy justice, and rural revitalization.

The impulse for this research on rural energy use and its environmental impact stems from a limited understanding of the agency of rural communities—particularly rural entrepreneurs—in driving sustainable forest management and emissions reduction efforts. These actors are not merely passive participants but rather active agents capable of shaping resource utilization and environmental conservation practices. Human activities affecting forests—such as forest-based cultivation, wood fuel consumption, and charcoal production—are major contributors to greenhouse gas emissions [2,15,23]. However, by recognizing and strengthening the agency of rural entrepreneurs, sustainable energy solutions and responsible forest stewardship can be more effectively integrated into local economic systems.

Therefore, understanding the link between rural energy consumption and its environmental impact is essential to address the challenge of climate change. This study therefore examines the impact of traditional biomass, including coal and wood, on greenhouse gas emissions and environmental degradation. Due to the geographically dispersed nature of the settlements, the impact of limited market access and transport inefficiencies on carbon leakage is also taken into account. Using an empirical approach, this study reveals important patterns affecting energy consumption in rural areas and highlights the critical need for sustainable energy solutions. The institutional model described above was developed to help in policy development, technical progress, and community engagement, all of which are necessary to promote sustainable energy solutions in rural areas and reduce environmental damage.

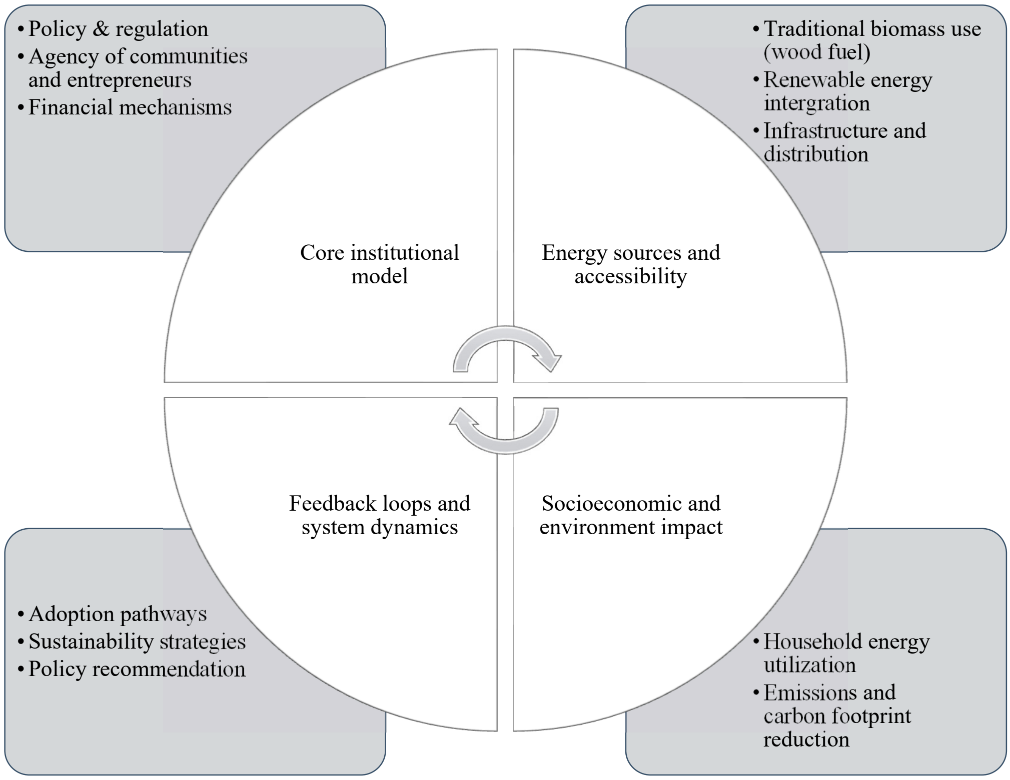

Figure 1. Institutional model for rural energy systems: key drivers and policy interventions. Created by the author.

2.2.1. Dominant Energy Sources in Rural Areas: Charcoal, Firewood, and Solar

In rural areas, energy consumption is largely driven by traditional biomass [3] and the phasing-in of renewable energy sources. Charcoal and firewood are the primary energy sources; however, while individuals can freely gather firewood, charcoal remains a priced commodity. For example, logging for the production of charcoal or firewood is often carried out in forests close to settlements. It is well documented that production of charcoal, which serves both rural and urban populations, exacerbates deforestation and greenhouse gas emissions [24]. Similarly, firewood, a staple for cooking, places additional pressure on local natural resource ecosystems. In this regard, studies show that improved stove appliances offer a viable solution to reduce the use of wood and emissions from wood energy [25,26]. Such that their widespread adoption is hampered by a number of factors, such as accessibility, lack of training, and limited access to the necessary resources. Conversely, solar energy offers a promising sustainable option but has not been widely adopted due to high upfront investment costs and infrastructure bottlenecks.

Despite better forest protection regulations, production of charcoal remains widespread, with many households still relying on it for both income and energy [2]. The charcoal production process relies on sourcing forest materials, primarily timber, for energy conversion. This often involves cutting down trees in open forests, contributing to deforestation and altering the dynamics of carbon storage. While government initiatives have been aimed at preserving some forest areas, uncontrolled combustion of coal still affects forest ecosystems, which reduces carbon sequestration capacity and affects the absorption of CO_2 from the atmosphere. Growing trees actively sequester CO_2 while standing trees store carbon in their biomass. Although tree removal reduces immediate carbon storage, in some cases the dynamics of forest regeneration can increase future carbon sequestration, depending on reforestation efforts and sustainable land management strategies.

At present, there is limited research assessing the carbon footprint of charcoal burning. Therefore, exploring sustainable energy alternatives—such as the adoption of improved stoves or the expansion of solar energy access—is crucial. The limited availability of solar power and other renewable energy sources presents a significant opportunity for further research into sustainable household energy solutions. Additionally, shifting rainfall patterns and rising temperatures, indicative of climate change, remain a pressing concern. In this context, examining the connections between these climatic changes and local greenhouse gas emissions is essential for developing long-term strategies for natural resource management. Strengthening community-based climate adaptation efforts can help reduce future emissions and enhance resilience.

2.2.2. Seasonal Entrepreneurship and Environmental Impact in Rural Resource Management

Natural resource systems, including fish, trees, soil, wildlife, and livestock, are essential to the livelihoods of rural communities. In addition to meeting daily needs, these resources also drive local economic development and shape livelihoods in many sectors. Seasonal entrepreneurs, individuals engaged in rain-fed farming and fishing during specific seasons, are key players in this ecosystem, e.g., [9,27]. Their activities generate income, improve food security, and have an impact on the sustainability of rural areas. For example, small-scale farming provides staple crops such as maize, cassava, beans, and peanuts, although yields vary widely from village to village. Similarly, fisheries are a cornerstone of both nutrition and local culinary traditions and strengthen the economic and cultural fabric of rural life.

However, while seasonal business offers economic benefits, its environmental impact remains a matter of concern. Certain farming practices, such as slash-and-burn farming, release CO_2 and methane and contribute to deforestation and air pollution. In addition, the use of fertilizers and livestock breeding are major sources of nitrous oxide and methane emissions, which exacerbate the accumulation of greenhouse gases. Climate-smart farming practices and soil protection methods have been extensively explored as strategies to mitigate environmental damage. Sustainable approaches, including agroforestry, improved irrigation, and regenerative agriculture, offer promising solutions for reconciling rural economic growth with conservation.

Therefore, by including seasonal entrepreneurs in climate adaptation plans, rural communities can maintain natural ecosystems and boost economic resilience at the same time, keeping environmental sustainability at the forefront of local growth.

3. Limitation and Challenges

This study offers important insights into rural energy transitions, yet it is essential to acknowledge several challenges and limitations encountered. The geographical constraints posed significant obstacles, as the remoteness of the study sites complicated accessibility, particularly for conducting follow-up research and maintaining prolonged engagement with participants. Additionally, logistical challenges, such as high transportation costs and inadequate infrastructure, impeded the scope and efficiency of field data collection. Sampling limitations also emerged due to the reliance on purposive participant selection. While this method ensured the inclusion of key stakeholders in forestry, agriculture, and fisheries, it may not fully reflect the varied experiences of other community members involved in informal energy-related activities. Furthermore, potential biases in participant responses should be considered, as discussions on energy use and environmental impact might be shaped by social and economic contexts or preconceived notions about policy interventions.

Due to differences in local record-keeping and the accessibility of updated reports, this study also ran into issues with data consistency. The intricacy of rural energy documentation is highlighted by disparities between official statistics and community observations, notwithstanding efforts to incorporate recent findings from the Tanganyika Lake Sustainability Project [20–22]. Future research must continue to take these data inconsistencies into account.

4. Results and Findings

In this study, we categorize household energy practices into the following three types: (1) traditional practices dominated by firewood and charcoal; (2) transitional practices where households begin integrating improved cookstoves or hybrid solutions; and (3) emerging practices that adopt alternative fuels such as LPG, solar, or electric cooking. This typology helps illuminate the varied pathways through which rural households engage with energy transitions—shaped by accessibility, affordability, and cultural preferences.

4.1. Methane Emissions and Rural Energy Systems

Based on the empirical analysis that informed the development of the institutional model for rural energy systems [28], this section presents key data on GHG emissions, methane dynamics, and the role of rural businesses in the use of forest resources. According to the MIT Climate Portal, methane (CH_4), a particularly powerful greenhouse gas, traps about 80 times more heat than carbon dioxide over a 20-year period, but its impact is reduced to about 28 times as much over a 100-year period. Although CO_2 is still the main driver of climate change [29], methane emissions are a significant contributor to global warming and require targeted mitigation strategies to reduce their impact on the environment. Recognizing and addressing the high global warming potential of methane is crucial to the development of sustainable energy solutions in rural communities.

The following tables show the main socio-economic and environmental drivers. These include household energy consumption patterns, emissions from wood burning, and methane from agricultural and waste management practices, in particular manure and organic waste management. Given the high methane emission potential, monitoring and addressing methane emissions from rural areas is important. Especially through better waste management, better farming practices, and technological interventions. While entrepreneurial activities contribute to rural economies and livelihoods, their collective decisions have a significant impact on carbon footprints and environmental sustainability. Therefore, interpretation of these data points reveals trends that highlight both the challenges and opportunities of reducing emissions while promoting sustainable business models. These findings provide a basis for assessing existing mitigation strategies and for identifying ways forward for climate-smart business and energy policy.

In rural regions, energy consumption is predominantly reliant on traditional biomass fuels, such as charcoal and firewood [24]. Charcoal production not only meets household energy demands but also provides a vital source of income for economically disadvantaged families. Firewood, commonly used for cooking, is typically sourced from nearby forests. This dependency raises significant environmental concerns, including deforestation and ecosystem degradation. Although improved cookstoves have been introduced in some communities to reduce wood consumption, their widespread adoption remains limited due to a lack of training in stove-making techniques. These cookstoves not only reduce fuel use but also lower emissions of volatile organic compounds (VOCs) and particulate matter, improving indoor air quality. Meanwhile, solar energy presents a promising sustainable alternative [30]; however, its uptake in rural areas faces significant challenges, including high initial costs, limited access to solar technologies, and insufficient awareness of its benefits. Overcoming these challenges and promoting sustainable energy use in rural areas requires a comprehensive approach. This approach should encompass financial incentives, policy interventions, localized training programs, awareness campaigns, public–private partnerships, and investment in research and development of cost-effective and culturally appropriate solar solutions tailored to rural contexts. Equally, transportation is included regarding mode of transportation and its emissions. Table 2 shows the data collected on rural energy use through community-led discussions, which focused on everyday life issues of access to wood monthly.

Table 2. Household energy use and emissions across four rural communities.

Community ID	Primary Energy Source	Average Monthly Consumption	Charcoal Production (Households Involved)	Estimated CO_2 Emission (kg/month)	Use of Improved Cookstoves (%)
CT	Firewood, charcoal, and solar	30 bundles of firewood	20 × 25 kg bag /household	150 kg	60%
IY	Firewood and charcoal	25 bundles of firewood	Few households	120 kg	55%
KB	Firewood and charcoal	20 firewood,	Few involved commercially	100 kg	50%
CH	Firewood and charcoal	15 firewood	Less than 10, involved commercially	80 kg	70%

Community codes: (CT) Chitimwa, (IY) Iyendwe, (KB) Kabyolwe, and (CH) Chinakila.

The above table shows household consumption and emissions in four rural communities in Mpulungu, Zambia. Each community is represented by a short form: CT (Chitimwa), IY (Iyendwe), KB (Kababala), and CH (Chinakila). The table above shows the primary energy sources, average monthly consumption, share of charcoal production, estimated CO_2 emissions, and the percentage of households using improved stoves. These findings help to assess the environmental impact of traditional use of biomass and the uptake of cleaner alternatives.

Barriers to Clean Energy Adoption

Despite the acknowledged benefits of clean energy technologies, rural communities face significant barriers to widespread adoption. The primary challenge remains economic constraints, as the upfront costs of solar energy systems and improved stoves often exceed the financial capacity of rural households [31]. Lack of access to funding mechanisms such as microloans or government grants further limits accessibility. In addition, technological challenges, including limited grid coverage and insufficient maintenance support, raise concerns about the reliability and durability of clean energy solutions. In regions such as Mpulungu, infrastructure constraints—such as unreliable power networks and limited access to transport—make integrating energy from biomass a more difficult task.

In addition to financial and technical barriers, cultural and social acceptance plays a key role in the uptake of clean energy. Traditional cooking methods using wood and charcoal are deeply rooted in local customs and daily practices. Many rural households prefer cooking by fire, not only out of habit but also because of the perceived superiority of the flavor of the food when prepared by traditional methods. Moreover, there may be skepticism or mistrust towards modern technologies, especially when introduced without strong community involvement. Resistance to change is compounded by the lack-of-awareness campaigns to demonstrate the long-term economic and health benefits of cleaner energy (see [32,33]).

Moreover, the geographical remoteness of many rural communities presents logistical problems for the dissemination and availability of clean energy technologies. Poor road infrastructure increases the cost and difficulty of transporting solar panels or improved stoves to remote villages. Limited market access makes it more difficult for local retailers to supply and service these technologies, which creates further barriers to their continued uptake. Moreover, rural governance and leadership play a key role in driving the transition to renewable energy. In many cases, support for policies at the local level is weak or inconsistent, and communities are given little incentive to switch to cleaner alternatives. Specifically, it is stressed that the low investment in infrastructure and community-led initiatives contributes to the low take-up of clean energy in rural areas.

4.2. Impact of Improved Cookstove Adoption

The widespread use of improved cookstoves has had a notable impact on household energy practices in these communities. One key benefit is the reduction in time spent collecting firewood, as households require less fuel due to the increased efficiency of these stoves. This shift has allowed many rural families to allocate more time to agricultural activities, enhancing food security and local economic stability.

While direct health benefits—such as reduced indoor air pollution—are difficult to quantify within the scope of this study, the positive implications for forest management are evident. By decreasing wood consumption, improved cookstoves contribute to mitigating deforestation pressures and fostering more sustainable resource use. These findings highlight the importance of continued investment in cleaner cooking technologies and complementary awareness programs to maximize both environmental and social benefits.

According to the World Population Review, Zambia has a per capita CO_2 emission of 0.4 metric tons, compared to 13.8 metric tons in the US and 7.06 metric tons in Germany (see [28]). This study quantifies household CO_2 emissions in rural Zambia, but these are relatively low compared to those in more developed countries. For context, Zambia's per capita CO_2 emissions remain significantly lower than those of industrialized countries, where fossil fuel consumption accounts for a large share of emissions. By comparison, US per capita emissions exceed 13 metric tons, underlining the stark contrast between rural energy use and large fossil fuel consumption.

This contrast underlines the need for a nuanced debate on emissions in rural communities, where the use of biomass is important but is not the predominant cause of global climate change. The findings highlight the importance of sustainable energy solutions not only in reducing local environmental impacts but also in supporting wider efforts to strengthen climate resilience.

4.3. Emission Trends and Household Energy Metrics

To deepen our understanding of CO_2 emissions as presented in Table 2, particularly those arising from the use of wood and charcoal, we utilized estimated conversion factors derived from established sources. To ensure accuracy, these estimates were validated against internationally recognized conversion factors, such as those provided by the Greenhouse Gas Protocol and the UK Government's Greenhouse Gas Reporting framework [34,35]. Based on this approach, the estimated CO_2 emissions were calculated using the following methodology, ensuring consistency with standardized practices in emissions assessment:

$$CO_2\ emissions = Wood\ fuel\ consumption \times emissions\ factor$$

where:

- *Wood fuel consumption = Number of firewood bundles or charcoal usage per household per month.*

- *Emission factor = Average CO_2 per kg of wood fuel.*

To clarify the methodology of this calculation, let us examine the firewood emission factor, which is quantified as 1.5 kg of CO_2 per kilogram of firewood. Each bundle comprises 10 kg of firewood, and the monthly consumption amounts to 30 bundles:

$$CO_2\ emissions = 30\ bundles \times 10\ kg/bundle \times 1.5\ kg\ CO_2\ per\ kg = 450\ kg\ CO_2/month$$

Similarly,

$$Percentage\ of\ households = \frac{Household\ using\ improved\ stoves}{Total\ surveyed\ households} \times 100$$

While the application of this method shows considerable diversity across various countries in the region, related research has identified comparable strategies [36–38]. For the calculations referenced above, the standard methods were obtained from Forest Research guidelines in the United Kingdom, which examine carbon emissions from different fuel types [34,39].

Another important carbon emission aspect is that access to rural markets is severely constrained by the lack of road infrastructure, which hampers the efficient movement of goods. This dependence on old and inefficient transport methods not only reduces economic productivity but also exacerbates carbon leakage. Evaluating the environmental impact of existing transport systems is essential for finding sustainable solutions. Investing in environmentally friendly transport options such as better road networks, electric vehicles, or community-based transport cooperatives could reduce the environmental impact while promoting economic growth. The focus groups were asked about their sources of income, general livelihoods, and sustainable practices that they had experienced or adopted in their community (Table 3).

Table 3. Barriers to clean energy adoption: economic, technological, and social factors.

Community ID	Main Livelihood Activities	Sustainable Practices Adopted	Challenges Faced
CT	Agriculture, charcoal production, and fish trading	Agroforestry and improved cookstoves	Limited access to market
IY	Agriculture, timber production, and fish trading	Reforestation and solar adoption	High cost of transporting products
KB	Agriculture, fish trading, and handicrafts	Crop rotation and reduced charcoal use	Lack-of-awareness programs and high cost of solar panels
CH	Agriculture, livestock, organic honey production, timber production, and fish trading	Sustainable land use and clean cook stoves	Limited financial resources

The findings indicate that farming was prevalent among most households, with a strong commitment to sustainable practices. However, the adoption of clean energy remains limited due to challenges in accessing solar and other renewable energy sources. This section examines the barriers to solar energy adoption, including high upfront costs, restricted funding opportunities, and insufficient awareness of its benefits, to inform effective policy and intervention strategies.

As shown in Table 4, many households demonstrated awareness of solar energy, with some installing small solar panels for lighting and phone charging. Despite this, the high costs associated with solar energy remain a significant obstacle, reflected in the elevated average price of solar electricity. Addressing these financial and infrastructural challenges is crucial to expanding access to renewable energy in rural communities.

Table 4. Solar energy awareness and adoption challenges in rural Zambia.

Community ID	Awareness of Renewable Energy	Interest in Solar Adoption	Barriers to Adoption
CT	40%	30%	High initial cost
IY	50%	45%	Limited technical support
KB	35%	25%	Lack of financing options
CH	60%	55%	Limited distribution channels

These findings highlight the delicate balance between forest protection initiatives and the continued dependence of rural Zambia on wood fuels as its primary energy source. While sustainable forestry seeks to preserve the integrity of the environment, the continued demand for biomass fuels exacerbates deforestation and contributes to carbon emissions and environmental degradation [39]. Rural households, limited in access to clean energy alternatives, are caught in a vicious circle of unsustainable energy consumption. Although new technologies and policy interventions offer ways to move towards cleaner energy transitions, the effectiveness of these solutions remains mixed, especially in mitigating methane and other greenhouse gases. This complex reality underlines the urgent need for innovative emission monitoring mechanisms, adaptive policy frameworks, and economic incentives to reconcile forest conservation with rural security. The interaction between environmental sustainability and socio-economic imperatives requires a holistic approach, combining community-based solutions, technological progress, and regulatory mechanisms to create viable paths to a low-carbon rural economy. These findings pave the way for a forthcoming debate on the structural and political dimensions needed to integrate sustainable energy models into rural livelihoods.

4.4. Comparative Case Studies in Rural Energy and Sustainability

The Mpulungu case study is a representative example of rural energy use and forestry problems, reflecting wider trends in similar rural contexts. Research in different rural areas highlights the interlinked issues of wood-fuel dependency, emissions reduction, and sustainable livelihoods, which reinforce the relevance of the experience of Mpulungu in the global debate on rural sustainability [40,41].

While this study provides valuable insights into these dynamics, benchmarking is crucial to improve the universality and applicability of the findings. Many rural communities, particularly in Sub-Saharan Africa, are facing a parallel challenge of balancing the transition to cleaner energy with sustainable forest management. In order to address this, we include further case studies from Zambia, which show similar patterns of resource dependence, economic structure, and environmental constraints, showing the common threads that shape rural energy use:

1. *Lake Tanganyika, Zambia*

This case examines the seasonal food insecurity affecting households in the Mpulungu community within the Lake Tanganyika basin. It highlights the critical links between natural resource dependency, rural enterprise, and environmental sustainability, reinforcing the significance of Mpulungu's challenges within the broader context of rural development.

2. *Agricultural Food Security Package Program, Zambia*

Research under this program in the Mpulungu district examines coping strategies used by vulnerable rural households. The findings show that rural communities rely on diversified livelihood strategies, including sustainable forest management, to alleviate food insecurity (see [20]).

3. *Local Rural Development Initiatives in Zambia*

The selection of successful rural development projects across the country demonstrates the effectiveness of strategies for energy access, environmental sustainability, and forest protection. These initiatives provide comparable information on rural energy use and highlight local interventions that contribute to sustainable development.

This study's applicability outside of Mpulungu is increased by incorporating these comparative cases, which show that sustainability initiatives and rural energy challenges are not distinct issues but rather a component of larger systemic issues. Similarly, examples of cases from other nations can be drawn from Nigeria, Ethiopia, and Zimbabwe, like [5,42,43]. This perspective strengthens this study's contribution to conversations about environmental management and rural energy policy.

4.5. Rethinking Poverty: Global Metrics vs. Local Realities

Poverty is often conceptualized in terms of standardized global metrics, such as the United Nations definition of extreme poverty, which refers to people living on less than USD 1.90 per day, a measure that affects more than 700 million people worldwide [44,45]. While this definition provides a broad statistical overview, it often does not capture the lived experience of rural communities such as Mpulungu, where poverty is understood beyond monetary thresholds.

The findings challenge conventional poverty metrics and show that people judge poverty not only by their financial income but also by their tangible household assets, land ownership, and economic stability in their local environment, factors that more accurately reflect their lived realities. Participants were asked the following questions: (a) What defines a wealthy household? (b) What defines a poor household? Community responses highlight a distinctly localized scale of wealth evaluation. In Mpulungu, affluence is marked by the possession of critical household items—houses with iron sheet roofing, beds, sofas, and kitchen cabinets—alongside ownership of bicycles or motorcycles and engagement in entrepreneurial ventures such as timber trade. Land ownership further signifies prosperity, with larger cultivated farms and herds of cattle serving as key indicators of wealth.

Conversely, poverty is mainly linked to food insecurity. A household struggling to provide adequate daily nutrition or able to afford only a minimum of food is considered poor, e.g., [46]. In addition, those who depend on manual labor for their survival and live in grass-paved, resource-poor dwellings are also in the category of people living in poverty. This localized understanding challenges external assumptions that link poverty to financial deprivation and highlights the need to consider livelihoods, access to resources, and economic resilience.

Recognition of these alternative poverty indicators is essential to develop policies that reflect the living reality of rural communities rather than imposing too narrow global standards. The agrarian nature of the Mpulungu communities emphasizes the intergenerational continuity, and most households live in harmony with nature. This perspective reframes the debate on poverty and calls for development initiatives to include local definitions and metrics that are in line with the social welfare of the community.

5. Discussion

5.1. Rural Energy Use and Its Environmental Impact

In rural communities, the most pressing environmental challenge is not large-scale greenhouse gas emissions but rather the inefficient and hazardous use of biomass, which directly affects air quality and public health (see [26,47]). As key players in local environmental management, these predominantly agricultural regions shape sustainability outcomes, yet their development trajectories could significantly amplify their emission footprint. If current growth patterns persist—marked by increased reliance on fossil fuels and industrial expansion—these areas may transition from low-emission zones to substantial contributors to climate change. Consequently, discussions on rural energy transition must extend beyond short-term environmental mitigation and emphasize long-term pathways that embed sustainability into future development frameworks.

In this respect, rural landscapes are characterized by different socio-economic dynamics, environmental challenges, and land-use patterns, which distinguish them from urban environments, for example [48,49]. Rural communities are heavily dependent on forests and natural resources for their livelihoods, but the gap in energy availability between developed and developing regions is still considerable. This discrepancy highlights the problem of energy poverty [45], as more than 40 percent of the world's population still rely on biomass as their primary energy source. Addressing energy poverty through cleaner technologies and improved fuel efficiency can improve both the environment and health without painting rural communities as the main contributors to climate change.

The findings of this study highlight the significant differences in access to energy in rural areas, where biomass remains the predominant fuel source for more than 40 percent of the world's rural population. While extensive charcoal production and reliance on wood contribute to deforestation and increased carbon emissions, broader land-use changes—such as agricultural conversion and urban expansion—are also major drivers of forest loss [50]. Recognizing this complexity, we analyzed rural entrepreneurial activities, including fish trading, charcoal production, agriculture, and logging; these activities influence natural resource use and methane emissions. Socioeconomic factors such as land tenure, agricultural practices, and local entrepreneurial dynamism play a crucial role in shaping sustainable energy transitions. To effectively combat energy poverty, it is essential to implement policies that not only promote cleaner energy alternatives but also address land-use pressures, provide financial incentives for rural entrepreneurs, and strengthen institutional support for smart energy management [45]. Integrating these approaches, this research therefore aims to bridge theoretical knowledge with practical solutions to enable rural communities to adopt sustainable energy practices.

Rural communities and entrepreneurs have a major impact on energy consumption patterns, which in turn influences the sustainability performance of resource-intensive regions [51]. A significant number of households, as well as small farms, fisheries, and forestry companies, continue to use traditional biomass such as wood and charcoal because of its cost-effectiveness and affordability. However, this dependency worsens deforestation and greenhouse gas emissions, exacerbating the climate challenge. Although more and more entrepreneurs in rural areas are exploring cleaner alternatives such as improved stoves, biogas, and solar energy, switching by households remains unevenly affected by financial constraints, limited technical knowledge, and barriers to infrastructure. Integrating energy efficiency into community and business activities can drive innovation while minimizing environmental impacts and ultimately support global efforts to mitigate climate change.

Moreover, empowering rural entrepreneurs to lead sustainability initiatives will increase resilience and long-term economic viability, enabling local entrepreneurs to contribute to emission reduction and resource management in a responsible way. In addition, rural economies can act as drivers of green innovation, showing that environmental protection and economic prosperity are mutually reinforcing forces for sustainable development.

5.2. Integrating Artificial Intelligence into Emission Monitoring

Building on the challenges of emissions monitoring and sustainable forestry, new technologies such as artificial intelligence (AI)-driven analytics offer promising additions to traditional approaches [52–54]. Using machine learning and remote sensing, AI can improve the accuracy of GHG monitoring, providing valuable insights for rural entrepreneurs and policymakers to make informed decisions. In the area of environmental sustainability, the integration of artificial intelligence (AI) is increasingly recognized as a transformative tool to improve the monitoring of emissions, especially in rural forest settings. Artificial intelligence technologies such as remote sensing and machine learning algorithms make it possible to monitor GHG emissions more precisely and in real time, complementing traditional monitoring techniques, e.g., [55]. These advanced systems are capable of processing huge datasets, identifying emission trends, and predicting environmental changes, providing rural entrepreneurs and policymakers with critical information for strategic decisions. In Zambia's rural areas, in particular, AI-based monitoring systems have the potential to improve the assessment of clean energy uptake and its subsequent impact on the reduction of the carbon footprint. However, the deployment of these technologies is facing obstacles, such as lack of digital infrastructure, limited data availability, and financial constraints. Overcoming these challenges by developing support policies and active cooperation between stakeholders could fully realize the potential of AI to promote sustainable forest management.

The dynamic relationship between rural enterprise, sustainable forest management, and emission reduction presents both challenges and opportunities for shaping environmental and economic outcomes. This study highlights the crucial role of rural entrepreneurs in promoting the uptake of clean energy and promoting sustainable practices. Despite their importance, these efforts are often hindered by significant obstacles, including technological limitations, political constraints, and socio-economic differences. Innovative solutions such as artificial intelligence-based emissions monitoring offer promising opportunities to improve the accuracy of GHG monitoring, thus facilitating more efficient policymaking and adaptation strategies. However, successful mainstreaming of artificial intelligence depends on factors such as the readiness of infrastructure, availability of data, and financial investment in rural areas. Overcoming these challenges requires a comprehensive approach that combines the use of innovative technologies with efforts to promote local involvement and capacity building. As policymakers, researchers, and communities work towards scalable sustainability solutions, it is essential that implementation frameworks are constantly refined and that more in-depth social and economic compromises are explored. The present study contributes to this ongoing debate by underlining the need for an integrated strategy linking business, environmental protection, and rural development to further global climate action.

6. Practical Implications

The findings of this study underscore the need for targeted strategies to reduce greenhouse gas (GHG) emissions and methane production in rural energy systems. While wood combustion contributes to emissions, the broader challenge lies in inefficient energy use, lack of access to cleaner alternatives, and limited institutional support for emission mitigation. Rural entrepreneurs and communities play a pivotal role in shaping resource management, energy innovation, and emission reduction. To facilitate a sustainable transition, this study highlights the importance of combustion efficiency improvements, such as advanced biomass boilers and decentralized renewable energy solutions like biogas. These technologies not only reduce emissions but also enhance energy accessibility and affordability for rural households. Additionally, institutional frameworks must evolve to support methane capture and carbon offset initiatives, particularly in agriculture and forestry, where unmanaged emissions exacerbate environmental degradation.

The integration of systematic monitoring, financial incentives, and policy-driven interventions can significantly bolster rural economies while advancing environmental sustainability. As rural communities transition to new energy paradigms, it is imperative to harmonize economic incentives with environmental stewardship to ensure enduring resilience and equitable access to cleaner energy solutions.

7. Conclusions

This study highlights the often-overlooked role of rural communities in global emission reduction efforts. While their carbon footprints are comparatively low, the forests they inhabit serve as vital carbon sinks, contributing to climate regulation and ecological stability. However, continued dependence on wood fuels and inefficient energy systems presents localized environmental risks that demand attention—not through blame, but through support.

Rural entrepreneurs and community leaders emerge as central actors in navigating these transitions. Chiefs, traders, and small-scale innovators hold deep knowledge of land and forest systems, positioning them as stewards of both livelihoods and landscapes. Their embedded authority and commitment to community welfare enable the alignment of economic opportunity with conservation goals, ensuring that sustainability strategies are contextually grounded and socially legitimate.

While artificial intelligence-based emissions monitoring is advancing globally, its reach into rural areas remains limited. Bridging this gap requires investment in accessible, community-driven technologies that empower local actors to track emissions, manage resources, and make informed decisions. Strengthening collaboration among researchers, policymakers, and rural stakeholders can accelerate the uptake of AI-enabled tools and decentralized clean energy solutions, enhancing both resilience and equity.

Achieving meaningful progress in rural energy transitions demands more than technological fixes—it requires inclusive, place-based strategies that center local agency. Policies must go beyond promoting clean fuels to actively support community-led entrepreneurship, forest governance, and adaptive innovation. A sustainable future depends on empowering rural communities not as passive recipients of aid, but as co-creators of climate solutions. Recognizing the leadership of rural entrepreneurs ensures that sustainability is cultivated from within, rooted in local knowledge, driven by local priorities, and resilient in the face of global change.

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