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Environmental and social impacts of self-financed solar PV adoption in rural Zambia: Insights from mopane worms, mushrooms, fishing, bushmeat and ethnomedicine

Hillary Chanda [a,*], Eugene Mohareb [a], Michael Peters [a], Chris Harty [b]

[a] University of Reading (School of the Built Environment, Department of Sustainable Energy, Environment and Engineering), UK
[b] London South Bank University (School of the Built Environment and Architecture Dean), UK

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ABSTRACT

This study, which is the first to study the relationship between Solar PV adoption in rural areas, and non-timber forest products (NTFPs), examines the environmental and social impacts of self-financed solar photovoltaic (PV) adoption in rural Zambia, with a focus on Mopane worms, mushrooms, fishing, bushmeat, and ethnomedicine - key NTFPs that rural households harvest for consumption and income generation. Qualitative research methods, including interviews and focus group discussions, were conducted across three geographically distinct and off-grid rural areas: Mkushi Rural (Central Province), Kapiri Rural (Central Province), and Chongwe Rural (Lusaka Province). These locations were selected for their relative isolation and lack of access to the national power grid.

Using the novel Rural Development Stakeholder Hybrid Adoption Model (RUDSHAM), this research explores the relationship between solar PV adoption and NTFP-based income. It highlights how NTFPs enable households to self-finance solar PV systems, reducing reliance on unsustainable biomass fuels while enhancing energy access. The paper also assesses the sustainability and scalability of NTFP-derived income.

Findings reveal a dual impact: while NTFPs are critical for financing solar PV adoption, their commercialization presents ecological risks, including overharvesting, habitat degradation, and biodiversity loss. Solar PV adoption contributes socio-economic benefits, such as reduced energy costs and improved household well-being, but exacerbates community tensions due to competition over limited NTFP resources.

To address these challenges, the study advocates for integrated strategies that combine renewable energy adoption with sustainable resource management. By emphasizing community-led governance and sustainable harvesting practices, it proposes a framework that aligns rural energy transitions with environmental conservation. The findings provide actionable insights for policymakers and development practitioners, contributing to the broader discourse on addressing energy poverty and ecological sustainability across Sub-Saharan Africa and similar rural contexts globally.

Introduction and background

Zambia, like many Sub-Saharan African (SSA) nations, faces critical energy access challenges, particularly in rural regions where only 14.5 % of households have electricity, leaving over 12 million people without access (Kapole et al., 2023). This lack of electrification perpetuates poverty and limits socio-economic development, healthcare, and education (Hafner et al., 2018; Olatomiwa et al., 2022). Zambia relies heavily on hydropower for over 85 % of its energy supply, but recurrent droughts exacerbate load-shedding, with outages lasting up to 21 h daily (ERB Report, 2023; ZESCO, 2024). By the third quarter of 2024, residential electricity in some areas was limited to three hours daily (ZESCO, 2024), highlighting the urgency of diversifying the energy mix to ensure resilience against climate variability.

Renewable energy technologies, particularly solar photovoltaic (PV) systems, provide a sustainable solution to energy poverty. With over 3000 h of annual sunlight, Zambia possesses vast solar potential (Chambalile et al., 2024). Solar PV systems can bypass grid limitations,

* Correponding author.
E-mail addresses: h.chanda@pgr.reading.ac.uk (H. Chanda), e.mohareb@reading.ac.uk (E. Mohareb), m.d.peters@reading.ac.uk (M. Peters), hartyc@lsbu.ac.uk (C. Harty).

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delivering power for lighting, irrigation, and mechanization, while reducing reliance on biomass fuels, lowering CO_2 emissions, and improving air quality (Adjei, 2024; Byaro et al., 2024). Despite declining global solar costs, adoption in Zambia remains low, contributing just 3.23 % to the energy mix (Chambalile et al., 2024). High poverty levels and a $0.83/kWh levelized solar electricity cost - the highest globally -render solar PV unaffordable for many rural households, 36 % of whom cannot transition from traditional fuels (Baurzhan and Jenkins, 2016; Szabó et al., 2021). Self-financing models offer a promising solution to address financial barriers, allowing incremental solar PV investments and reducing energy costs by up to 46 % (Mukisa et al., 2022; Tinta et al., 2023). Solar PV systems also stimulate rural economies, create jobs, and support Zambia's climate mitigation goals by curbing deforestation and biomass dependence (Ezeh et al., 2023; Makai & Daniel Chowdhury, 2017). However, socio-economic disparities and high upfront costs necessitate supportive policies to maximize adoption benefits (Agoundedemba et al., 2023; Bhattacharyya & Palit, 2021).

Non-timber forest products (NTFPs) - such as Mopane worms, mushrooms, bushmeat, and ethnomedicine - provide essential income for rural Zambians, contributing 32–35 % of household incomes (Mulenga et al., 2011; Steel et al., 2022). Approximately 100 % of rural households harvest fruits, while 86 % collect mushrooms and leafy vegetables, and 82 % rely on insects for sustenance and income (Steel et al., 2022). NTFPs bridge seasonal financial gaps, enabling households to invest in solar PV systems (C. M. Shackleton et al., 2024; Timko et al., 2010). However, unsustainable harvesting practices, including overhunting and excessive wild fruit collection, threaten biodiversity and forest ecosystems (Anyango et al., 2018). To address these challenges, conservation strategies such as scientific harvesting and community-based resource management are critical for balancing economic needs with environmental protection (Derebe & Alemu, 2023).

By integrating solar PV adoption with sustainable NTFP management, Zambia the potential to address rural energy access and environmental degradation simultaneously. This synergistic approach promotes socio-economic development while safeguarding ecosystems, providing a replicable model for SSA (Amadu & Miller, 2024; C. Shackleton & Shackleton, 2014).

Research problem

- There are currently insufficient insights into solar PV adoption in rural Zambian households:
- The immediacy of potential adverse environmental and societal effects of income from edible NTFPs:
- The need to critically assess the viability, benefits, and limitations of financing mechanisms.

Research objectives

- To analyze the link between rural household NTFP income and solar PV adoption:
- To investigate available financing mechanisms for solar PV systems in rural Zambia: and
- To assess environmental and societal impacts of current income-generating activities tied to NTFPs.

Research questions

- What financing mechanisms from edible NTFPs support (or hold the potential to support) solar PV adoption in rural Zambia?
- What are the advantages and challenges of those mechanisms?
- How do those mechanisms affect the adoption and sustainability of solar PV systems?
- What are the environmental and societal effects of income-generating activities from NTFPs?

Research gap and contribution of the study

The relationship between solar photovoltaic (PV) adoption in rural areas and income derived from NTFPs has not been extensively studied, particularly in the context of Sub-Saharan Africa. This study uniquely addresses this gap by applying the novel Rural Development Stakeholder Hybrid Adoption Model (RUDSHAM) to examine how income from NTFPs facilitates self-financed solar PV adoption in rural Zambia. It is the first research to focus on the specific role of five key NTFPs - Mopane worms, mushrooms, fishing, bushmeat, and ethnomedicine - in enabling solar PV adoption, while simultaneously exploring the environmental and socio-economic consequences of this dynamic.

As global efforts intensify to promote renewable energy adoption, it is vital to understand the financing methods rural households employ to afford solar PV systems. This paper highlights how NTFPs, while providing vital income streams for solar PV investments, can also create environmental pressures such as overharvesting, habitat degradation, and biodiversity loss, alongside potential risks to rural food security. Its findings and recommendations contribute to the broader discourse on energy access and sustainability by offering actionable insights for policymakers, aid agencies, and stakeholders. It stresses the need for integrated solutions that simultaneously promote renewable energy adoption, sustainable resource management, and rural food security. By identifying strategies that balance energy transitions with environmental conservation, this research – and indeed the paper itself - offers a replicable model for addressing energy poverty and ecological sustainability in similar rural contexts globally.

Literature review

This literature review evaluates income-generating activities linked to NTFPs in rural Zambia - specifically Mopane worms, mushrooms, fishing, bushmeat, and ethnomedicine. These activities provide significant economic and nutritional benefits but pose environmental and social challenges, particularly within the context of financing self-sustained solar photovoltaic (PV) systems.

Mopane worms

Mopane worms, a key source of nutrition and income in rural Zambia, are rich in protein and play an essential economic and societal role, particularly for women and unemployed individuals. Annual regional harvests of 9.5 billion caterpillars underline their economic importance, enabling marginalized households to meet basic needs (D'Souza & Govender, 2019; Hlongwane, Slotow and Munyai, 2021; Togarepi et al., 2020). However, unsustainable harvesting and climate change threaten their populations, with up to 70 % of their habitats projected to disappear by 2080 due to land-use changes (Shen et al., 2023). Sustainable harvesting practices and local governance are necessary to protect this income stream and maintain ecosystem stability (Ndlovu et al., 2019; Sekonya et al., 2020).

Wild mushrooms

Wild mushrooms serve as both a dietary supplement and a valuable income source, particularly for communities reliant on forest resources.

Species like Amanita loosii hold high market value, supporting rural economies (Mlambo & Maphosa, 2017; Rookmaaker, 2020). Yet, forest degradation and overharvesting, often due to weak regulations, endanger these ecosystems and exacerbate biodiversity loss (Sileshi et al., 2023; Steel et al., 2022). Foraging practices remain largely unsustainable, stressing the importance of integrating ecological preservation strategies into local governance (Anyango et al., 2018; Zulu et al., 2019).

Ethnomedicine

Ethnomedicine is central to healthcare and livelihoods in Zambia, with approximately 70 % of the population relying on traditional remedies. Ethnoveterinary practices aim further to support rural well-being, especially in areas lacking formal healthcare (Eiki et al., 2021; Muyenga et al., 2018). Medicinal plants, for example, generate up to 58 % of annual household income in some cases, highlighting their economic potential (Timmermann & Smith-Hall, 2019). However, overexploitation and supply chain inefficiencies limit sustainable commercialization. Policies incorporating traditional knowledge and sustainable harvesting training are essential for balancing economic benefits with biodiversity conservation (Fandohan et al., 2017; Meke et al., 2017).

Bushmeat

Bushmeat serves as a critical protein source and income generator for rural households. Initiatives like sport hunting provide substantial economic benefits, distributing over 129,000 kg of game meat annually (White & Belant, 2015). During periods of food scarcity, bushmeat trade acts as a financial safety net (Stone & Stone, 2022). However, unsustainable hunting near protected areas threatens wildlife populations, while increasing zoonotic disease risks, including Ebola and HIV (Gonçalves et al., 2019; Kurpiers et al., 2015). Policies promoting sustainable hunting practices and addressing poverty are crucial to mitigate ecological and health impacts (M. Sakala, 2016).

Wild fishing

Fishing provides critical sustenance and income, especially in areas like Luapula Province, where fish is a dietary staple. Almost all rural households engage in fishing-related activities, underscoring its significance for food security and economic stability (Marinda et al., 2023; Steel et al., 2022). However, overfishing, inadequate infrastructure, and destructive techniques such as water poisoning degrade aquatic ecosystems and diminish fish stocks (Tweddle et al., 2015). Enhancing women's participation in fisheries and improving access to credit and markets are vital for long-term sector sustainability (Muzari & Muzari, 2013; Temesgen et al., 2019).

Witch doctor practices

Traditional healing practices provide critical healthcare services and income in underserved areas. However, these practices also perpetuate what some observers have characterized as harmful beliefs, fostering fear and deepening social divisions (Eiki et al., 2021; Gershman, 2016). Extreme manifestations, such as ritual killings, exacerbate poverty and instability, particularly in marginalized communities (Mwiba, 2018; Steyn, 2022). Addressing these issues requires community education and governance mechanisms to curb harmful practices while preserving their income potential.

From the literature review, it is evident that while NTFPs undeniably support rural livelihoods substantially and enable solar PV financing, their unsustainable exploitation expose some considerable ecological and social risks. Addressing these challenges requires integrating sustainable management practices with inclusive policies to balance economic development, environmental conservation, and social equity.

Successful case studies of NTFP management

Non-timber forest products (NTFPs) are vital for rural livelihoods and play a critical role in forest conservation across Africa. Case studies highlight the economic and ecological benefits of NTFPs, underscoring the importance of indigenous knowledge and sustainable harvesting practices in improving forest and tree-based ecosystem management (Amusa et al., 2024). Successful examples include the commercialization of baobab fruit in South Africa and Malawi and the sustainable harvesting of golden grass in Brazil, demonstrating the potential for NTFPs to provide income while conserving biodiversity (C. Shackleton, 2015). Underutilized categories such as edible insects and mushrooms are gaining recognition for their ability to alleviate food insecurity and reduce the environmental footprint of food production. Their sustainable management within Africa's multifunctional landscapes offers promising pathways for economic and environmental resilience (Amusa et al., 2024). Additionally, the Action Against Desertification project promotes sustainable harvesting of products like gum arabic, honey, and Balanites oil, further exemplifying the potential of NTFP-based livelihoods in fostering rural development and conservation (Sacandé, 2018).

Challenges and risks associated with solar PV financing using NTFPs

The NTFP income to finance solar PV systems in rural African communities is fraught with several risks and challenges. Financially, NTFP income is highly volatile due to seasonal availability and market demand, leading to inconsistent funding for solar projects (Adelhardt & Berneiser, 2024). The high initial costs of solar PV systems further exacerbate this challenge, as they often exceed the financial capacity of rural households reliant on NTFP income (Baurzhan & Jenkins, 2016; Soboyejo, & Otiti., 2006). Regulatory barriers, including inadequate policies and dependency on international subsidies, hinder the establishment and sustainability of solar projects (Adelhardt & Berneiser, 2024; Baurzhan and Jenkins, 2016). Furthermore, rural communities often lack the technical expertise required to maintain solar systems, leading to operational failures (Utoh et al., 2024). Solar PV systems may also fail to meet the energy demands of critical activities like agro-processing, which are vital for rural economic development (Otiti & Soboyejo, 2006). Additionally, NTFP enterprises themselves face challenges such as poor marketing, transportation difficulties, and regulatory obstacles, which limit their capacity to generate stable income (Kunwar et al., 2009; Yusuff, 2014). Addressing these risks requires government investment in rural infrastructure, improved market access, and civil society involvement to influence supportive policies (Kunwar et al., 2009; Yusuff, 2014).

Solar PV financial models in rural areas

Table 1
Financing Models compiled by author.

Financing Model	Cost-Efficiency	Scalability	Community Impact	Sustainability	Environmental Impact	Advantages	Disadvantages
1. Pay-As-You-Go (PAYG)	High cost-efficiency for low-income users, as small installments reduce financial barriers.	Highly scalable due to mobile payment technology and widespread adoption of off-grid systems.	Provides affordable energy access, reduces reliance on kerosene, and improves household health.	Sustainable if default rates are low and payment mechanisms are robust.	Reduces deforestation and carbon emissions by replacing kerosene and wood fuels.	Affordable for low-income households; accessible *via* mobile technology.	May not be sustainable in areas without reliable mobile money networks or low-income regions with payment defaults.
2. Microfinance Loans	Moderately cost-efficient, as small interest rates spread costs over time.	Scalable in areas with established microfinance institutions.	Empowers women and small entrepreneurs, fostering rural development and energy access.	Sustainable if repayments are regular and institutions are well-managed.	Reduces reliance on polluting fuels, indirectly conserving natural resources.	Encourages entrepreneurship and economic development; flexible repayment terms.	Requires strong financial institutions; interest rates can vary, burdening borrowers in some cases.
3. Government Subsidy Programmes	Very cost-efficient for users, as governments bear most of the initial cost.	Limited scalability, often depending on government budgets and political will.	Expands access to energy for underserved populations, benefiting households and public facilities.	Sustainable only with well-targeted subsidies and phased-out plans for market independence.	Reduces dependency on wood fuel but risks inefficiency if poorly managed.	Reduces costs significantly for rural households; can stimulate adoption quickly.	Risk of dependency on subsidies; implementation can be delayed due to bureaucratic processes.
4. Community-Owned Cooperatives and village banking.	Long-term cost-efficiency, as profits are reinvested into local energy projects and community initiatives.	Moderately scalable; requires strong community organisation and governance structures.	Enhances community ownership, creating jobs and fostering local pride in energy solutions.	Highly sustainable if communities are empowered to manage operations effectively.	Promotes clean energy adoption and protects natural ecosystems through local stewardship.	Strengthens local decision-making and economic resilience; creates a sense of ownership.	Initial organisation can be challenging; requires effective leadership and management skills at the local level.
5. Income from Non-Timber Forest Products (NTFPs)	Moderately cost-efficient, as NTFP-derived income (*e.g.*, honey, fruits) offsets solar system costs.	Limited scalability; depends on sustainable forest management and availability of resources.	Supports rural livelihoods and self-financing of energy systems while promoting economic independence	Sustainable if NTFPs are harvested responsibly to avoid resource depletion.	Reduces deforestation when managed sustainably; integrates conservation with development.	Encourages self-reliance; aligns energy goals with forest conservation efforts.	Vulnerable to overexploitation and climate impacts on forest productivity; limited to areas with rich forests.
6. Private-Sector Mini-Grids	Moderate cost-efficiency; higher upfront costs but cost-efficient in clustered rural areas.	Highly scalable with supportive policies and private investment incentives.	Provides reliable electricity for entire villages or clusters, fostering economic and social development.	Sustainable if backed by long-term policies, financial viability, and community engagement.	Reduces greenhouse gas emissions and protects local environments.	Reliable and efficient for clustered rural areas; can support small businesses and public facilities.	Requires significant capital investment; may face challenges in regulatory and licensing frameworks.

Theoretical framework to inform the study

The current study introduces and employs the novel Rural Development Stakeholder Hybrid Adoption Model (RUDSHAM) to help explain and interpret the extent to which self-financed solar PV systems in rural areas of Africa impact rural society and the environment. (See Fig. 1) RUDSHAM integrates three main theoretical frameworks to understand the factors influencing the adoption of renewable energy technologies in rural areas. It combines the Technology Acceptance Model (TAM), Diffusion of Innovations Theory (DOI), and Theory of Planned Behaviour (TPB) to focus on internal factors affecting adoption willingness. TAM highlights performance expectancy, effort expectancy, social influence, and facilitating conditions as key drivers of technology adoption (Ajzen, 1991; Davis, 1989; Rogers Everett, 2003; Venkatesh & Davis, 2000). Diffusion of Innovations Theory explains the stages and factors influencing the spread of new technologies over time (Rogers Everett, 2003). TPB suggests that behavioural intentions are shaped by attitudes, subjective norms, and perceived behavioural control (Ajzen, 1991). Additionally, RUDSHAM incorporates Social Learning Theory (SL), which emphasizes the role of observation and imitation in shaping attitudes and adoption decisions (Bandura, 1977). Social dynamics, such as peer effects and active communication within social networks, significantly influence individuals' decisions to adopt renewable energy technologies.

By combining internal factors from TAM, DOI, and TPB with external influences from Social Learning Theory and peer effects, RUDSHAM offers a comprehensive understanding of the multifaceted factors driving renewable energy adoption in rural developing areas. This holistic approach recognizes the complex interplay between individual beliefs, social influences, and community dynamics in shaping adoption behaviours. The framework provides valuable insights for policymakers, researchers, and practitioners aiming to promote sustainable energy transitions. RUDSHAM's alignment with a mixed-methods research approach, including in-depth interviews, focus groups and observations, ensures a thorough examination of solar PV adoption in rural Zambia. This integration of theoretical and methodological rigor offers a robust foundation for investigating the complex factors impacting solar PV adoption, facilitating the development of effective strategies for sustainable energy development.

The Rural Development Stakeholder Hybrid Adoption Model (RUDSHAM) is suitable for analysing the environmental and social impacts of self-financed solar PV systems in rural Zambian rural households. By integrating perceived ease, usefulness, social norms, and behaviour control, RUDSHAM captures key factors influencing adoption. Policy support, economic cost, and community participation contextualize the socio-economic environment, while green concern and financial models highlight sustainability and financing challenges. The model's comprehensive approach aligns with assessing energy access, sustainability, and

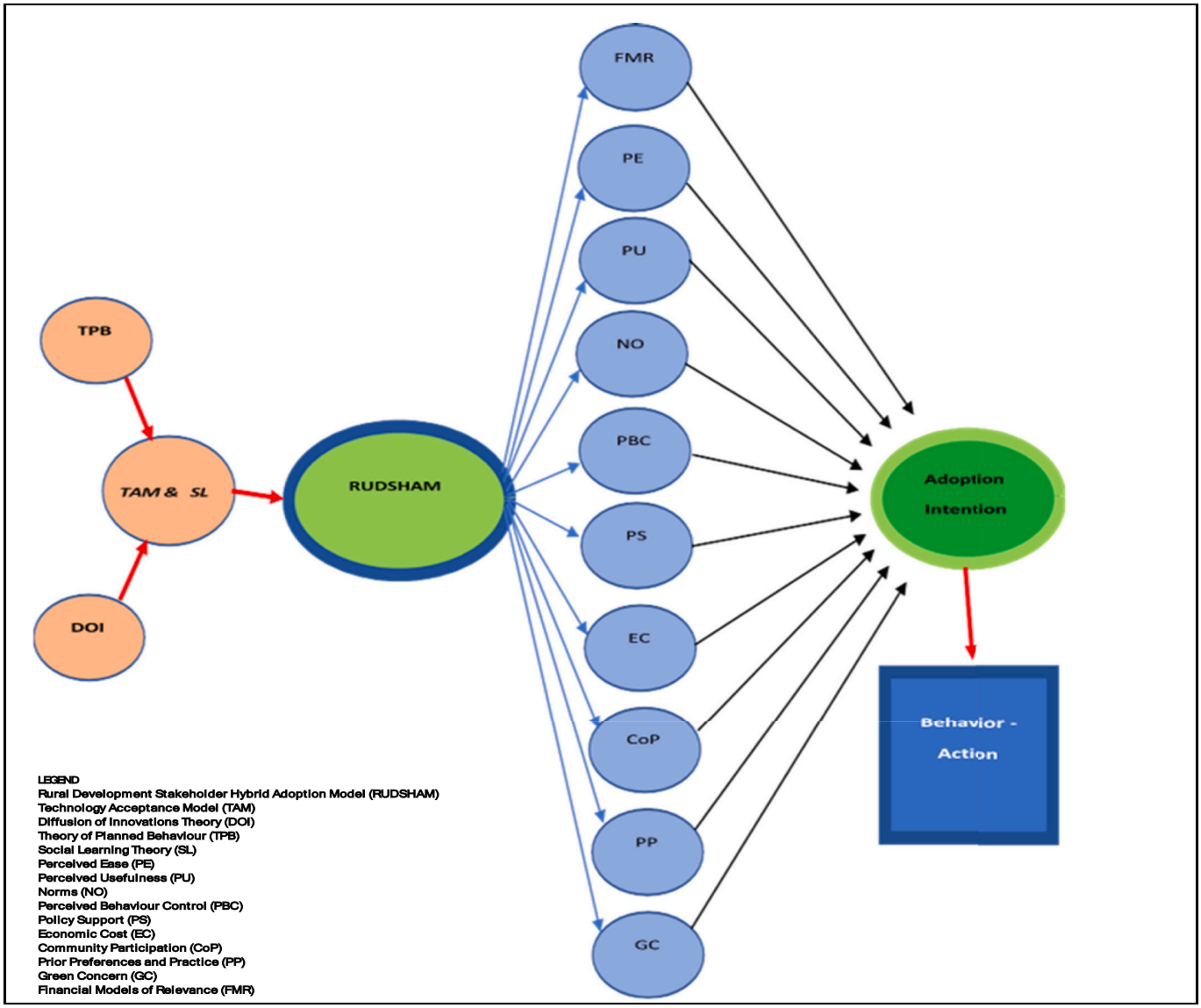

Fig. 1. RUDSHAM Hybrid Adoption Model.

rural livelihoods, offering a valuable theoretical lens to understand household decision-making in the context of solar PV systems adoption. For details on the description of how each attribute of the RUDSHAM framework assisted, refer to appendix B.

Research methodology: Research strategy and data collection methods

The study was conducted over six months, from October 2022 to March 2023, across three remote rural areas in Zambia: Mkushi Rural (Central Province), Kapiri Rural (Central Province), and Chongwe Rural (Lusaka Province) (see Fig. 2). These areas were purposively selected due to their relative isolation and lack of access to the national power grid. A multi-stage sampling approach was employed. In the first stage, Mkushi, Kapiri, and Chongwe were purposively selected for their geographical and infrastructural characteristics. In the second stage, participants for focus group discussions (FGDs) and interviews were selected using non-probability sampling techniques. Specifically, convenience sampling was used for FGDs, and purposive sampling was applied to select key informants and stakeholders. A four-week pretesting pilot study involving five participants from Luano village (Chingola Rural, Copperbelt Province) was conducted to ensure the validity and reliability of the research instruments. Data collection was facilitated by one research assistant fluent in English and multiple local languages (Bemba, Tonga, Soli, Lamba, and Nyanja), alongside the primary investigator, who is fluent in English and has working knowledge of Bemba, Nyanja, and Lamba.

The primary data collection methods included in-depth interviews and focus group discussions. A total of 40 rural farmers, 16 commercial farmers, and 3 key stakeholders from solar energy companies and government policymaking institutions were interviewed, with interview durations ranging from 30 to 60 min. Seven FGDs were conducted, including three in Kapiri, two in Mkushi, and two in Chongwe. Each group comprised 8 to 12 participants, ensuring diverse perspectives. Gender-sensitive practices were incorporated by organizing mixed and separate FGDs for men and women, facilitated by village headmen or councillors to foster trust and mitigate dominance issues. Participants received refreshments and tokens of appreciation for their involvement. Recorded interviews and photographs, taken with consent, were securely stored on the University's OneDrive cloud account with protected access to ensure data security. Data analysis employed NVIVO 14 to enable methodological integrity and systematically analyze findings derived from the RUDSHAM framework. Interview transcripts and focus group discussions were coded into themes, using both colour-coding

Fig. 2. Map of Zambia. Map sources: UN 2022. Map of the world.

techniques and NVIVO's advanced analytical tools to identify patterns and insights. NVIVO facilitated the organisation of data related to RUDSHAM attributes, including Perceived Usefulness, Policy Support, and Community Participation. This approach ensured robust thematic analysis, enhancing the study's credibility and reliability.

Research findings

The RUDSHAM framework's attributes facilitated the comprehensive gathering of findings in the study. Each attribute guided specific data collection efforts, producing a range of important insights. Perceived Ease (PE) revealed challenges in solar PV installation, maintenance, and support accessibility. Perceived Usefulness (PU) highlighted solar PV's role in improving livelihoods, reducing energy insecurity, and enhancing productivity. Norms (NO) examined societal acceptance and the influence of peer networks on adoption. Perceived Behaviour Control (PBC) assessed consumer confidence through warranties, system flexibility, and choice availability. Policy Support (PS) identified government subsidies and supplier roles in overcoming barriers. Economic Cost (EC) clarified affordability perceptions and energy expenditure impacts. Community Participation (CoP) explored local ownership, supplier engagement, and sustainability factors. Prior Preferences and Practice (PP) contextualised the transition from traditional energy sources. Green Concern (GC) connected environmental awareness to solar PV adoption motivations, while Financial Models of Relevance (FMR) compared global financing models with local practices, offering scalable pathways. Together, RUDSHAM produced holistic results, linking socio-economic, environmental, and cultural factors to solar PV adoption in Zambia.

Income sources in rural Zambia: Empirical evidence via RUDSHAM model

Mopane worms (edible caterpillars)

The narratives reveal conflicting perspectives on Mopane worm harvesting, highlighting its socio-economic benefits and environmental challenges. Rural farmers emphasize its economic importance, noting that it provides a critical income source, often surpassing agriculture *(a2.1, a2.4, a3.1)*, despite dangers and declining worm populations due to overharvesting *(a2.2, a2.6, a3.6)*. In contrast, commercial farmers express concern over deforestation and unsustainable practices, citing aggressive collectors cutting down key host trees *(a1.1, a1.2, a1.5, a3.6)*. Governance issues exacerbate tensions, with collectors bribing authorities *(a1.6)* and ignoring traditional controls once enforced by chiefs *(a3.7)*.

Illustrative direct quotations from commercial farmers (CF) interviews.
(a1.1) "Well, people come to our farm and chop down trees to collect the caterpillars (Mopane worms) ...There's one particular variety called the

Mutondo (Cordyla africana) tree which got completely wiped out from my farm…" (CF Interview 8)

(a1.2) "They also came to my farm…and cut these big trees just to get the caterpillars..." (CF Interview 14)

(a1.3) "…this would have been sustainable in the past…, it's obviously something that is a cultural thing…but now it's not sustainable." (CF Interview 6)

(a1.4) "…Mopane worm collectors are very aggressive people, and people have even been killed by them…the affected rural farmers complained to the police and to the chief to no avail…" (CF Interview 7)

(a1.5) "…stopping them was dangerous because these people were very aggressive. They would camp on farmers' lands… as they collected Mopane worms and cut down trees." (CF Interview 9)

(a1.6) "The collectors are well-connected, and they would be bribing the police, they would be bribing the local council people, and …, the police and councils don't have the resources to stop these aggressive Mopane worm collectors." (CF Interview 9)

(a1.7) "Look at this big tree that has just been cut down!... Obviously, there was something in that tree he wanted, either the Mopane worms or the honey…" (CF Interview 10)

(a1.8) "If I take you through this forest, you'll see some beautiful trees that have been cut..." (CF Interview 11)

Illustrative direct quotations from rural farmers' interviews. (a2.1) "Mopane worms are a very good source of income which has helped me supplement income from farming and sometimes even surpassing agriculture income in yester years. My house has a radio, solar charger and solar lighting… If I work hard, I might even install a solar pump to help with irrigation." (Mkushi Interview 5)

(a2.2) "There are many dangers that I face as I collect caterpillars, like snakes, wasps etc…" (Mkushi Interview 2)

(a2.3) "I collect worms from any forest except where there is a fence…but there are others who dare break fences to collect the worms especially if there is a lot." (Mkushi Interview 3)

(a2.4) "I sell the worms at $25 (K500)/20ltr container…in a good season you can raise a lot of money…I did not struggle to buy uniforms for my children... necessities, nice phone, radio and the solar lighting…" (Mkushi Interview 2)

(a2.5) "Mopane worm collectors … in groups, carrying axes, pangas and other weapons, so no one dares to stop them…, collecting a large number of worms and making substantial money as they resell them to town people…" (Mkushi Interview 4)

(a2. 6) "Mopane worm numbers have drastically reduced in the past decades because of overharvesting and cutting down of trees... In the past, it was sustainable… but now, there are many people and a very high demand…" (Mkushi Interview 1)

Illustrative direct quotations from rural farmers' FGDs. (a3.1) "Mopane worms are a tasty delicacy that has helped many families to survive and also raise some money for buying other household necessities." (Mkushi FGD 2)

(a3.2) "The worms are usually sold wholesale to urban buyers or by the roadside along main roads to passing motorists…" (Mkushi FGD 1)

(a3.3) "The roadside selling is mostly done by women and children, but wholesale selling is done by the men. It's a good alternative source of income to agriculture which is seasonal and once off." (Mkushi FGD 2)

(a3.4) "Commercial Mopane worm collectors are quite aggressive, especially towards people who try to frustrate their collection efforts…" (Mkushi FGD 2)

(a3.5) "…collectors come with machetes and are willing to use them on those opposing them if necessary. Sometimes, the best you can do is to negotiate with them so that they leave you a portion of their collection… a win-win situation…" (Mkushi FGD 1)

(a3.6) "But we don't know what the future holds because there has been overharvesting in recent decades due to increased demand. Mpasa (Julbernadia globiflora), Mutondo (Cordyla Africana) and Miombo (Brachystegia boehmii) trees are mainly the trees that host the caterpillars, and which have been cut down during Mopane worm collection…" (Mkushi FGD 1)

(a3.7) "In the past, caterpillar collection could only start after the chief had given a go ahead… The chiefs also warned against starting any fires during the caterpillar season. These days such issues are not taken seriously..." (Mkushi FGD 2)

Wild mushroom

The direct quotations illustrate the socio-economic importance of mushroom collection amid environmental and safety challenges. Rural farmers rely on mushrooms as a vital income source, especially during hardships like poor rains and high fertilizer costs *(b2.3, b3.4)*, but they face declining availability due to deforestation and land clearance *(b2.1, b3.5)*. Collectors endure significant risks, such as encounters with wild animals and potential poisoning from misidentified mushroom species *(b2.2, b3.1, b3.3)*. Despite these challenges, mushrooms provide food security and enable investments like solar lighting *(b3.6)*. Commercial farmers recognize their role in sustaining forests and allowing locals to benefit from mushroom harvesting *(b1.2, b1.3)*.

Illustrative direct quotations from CF interviews. (b1.1) "Apart from local consumption, there is increased demand for mushrooms…the demand is mainly driven by urban area…" (CF Interview 5)

(b1.2) "…many people come through my farm because we try to preserve the forest, which allows mushrooms to thrive. I don't stop them, but I do request that they don't cut down any trees." (CF Interview 9)

(b1.3) "As much as this is my land…I allow the locals to collect mushrooms, which helps them have relish and also to sell and raise some… income." (CF Interview 1)

Illustrative direct quotations from rural farmers' interviews. (b2.1) "It's not easy to find mushrooms (nearby) nowadays because there are very few trees left…also, a lot of land has been cultivated, leading to the loss of forest area..." (Mkushi Interview 3)

(b2.2) "Mushroom collection is not for novices because a lot of people have gotten lost (in the bush) while collecting mushrooms…" (Kapiri Interview 6)

(b2.3) "… there is a good market for mushrooms in urban areas. This helps bring in some income for many of us... I make between £30–£35 (K600–K700) per week during the peak mushroom season…supplementing income from agriculture… I have a decent phone, a good solar charger, and… good solar lighting." (Mkushi Interview 6)

(b2.4) "It's not always easy to preserve the mushrooms, and some of them end up going bad…" (Chongwe Interview 11)

Illustrative direct quotations from rural farmers' FGDs. (b3.1) "Consuming mushrooms is risky because entire families have been poisoned and killed from consuming … poisonous mushrooms… We ensure that we eat and sell only what we know…" (Kapiri FGD 2)

(b3.2) "…Some greedy parents…to earn more money, even take their young school-going children to collect mushrooms..." (Chongwe FGD 3)

(b3.3) "Mushroom collection is a dangerous activity because collectors venture into deep bushes and expose themselves to wild animals, especially snakes…" (Chongwe FGD 1)

(b3.4) "…with fertilizer becoming so expensive… reduction in subsidies… recent poor rains, we would have died of hunger without mushroom…" (Mkushi FGD 1)

(b3.5) "Mushroom thrives well under trees and health forest, sadly the tree numbers have reduced… Land clearance for agricultural purposes is another contributing factor." (Mkushi FDG 2)

(b3.6) "…we collect enough mushroom and other NTFPs for consumption and selling…many of us use part of income to pay back loans for solar lighting systems which the mobile companies give us..." (Kapiri FGD 2)

Wild fishing

The direct quotations highlight the critical role of fishing in rural livelihoods, despite environmental degradation and safety challenges. While fish provide both income and nutrition *(c2.1, c2.2, c3.1)*, overfishing and unsustainable practices, such as using small or mosquito nets and fish poison, deplete fish stocks and harm ecosystems *(c1.2, c3.2, c3.3)*. Commercial farmers attempt to regulate fishing on private dams to promote sustainability *(c1.1)*. However, fishing remains perilous, with risks including drowning, crocodile attacks, and snake bites *(c3.4)*. Despite these obstacles, fish sales contribute to household income, supporting basic needs and investments like solar lighting *(c2.2)*.

(c1) Illustrative Direct Quotations from CF Interviews.

(c1.1) "I allow the locals to fish from my dam, but only if they are using fishing rods and not fishing nets, so that the fish is preserved and protected. (CF Interview 17)

(c1.2) "…sometimes questionable fishing techniques are used especially in public dams and rivers." (CF Interview 5)

Illustrative direct quotations from rural farmers' interviews. (c2.1) "…I sell the bigger fish to passing motorists... We consume the smaller fish..but there aren't many fish in this area…"(Kapiri Interview 26)

(c2.2) "…1Kg cost between $6 to $8 (K150 to K200… It helps to raise some income for the home when available and even for financing our current solar lighting system…" (Mkushi Interview 3)

Illustrative direct quotations from rural farmers' FGDs. (c3.1) "Fish is good relish… but the fish numbers are depleted." (Kapiri FGD 2)

(c3.2) "People sometimes use illegal fishing methods, like using small nets or even mosquito nets…" (Kapiri FGD 2)

(c3.3) "There are others who use fish poiso (Tephrosia vogelii) … to kill the fish along with any other living organisms in the water..." (Kapiri FGD 2)

(c3.4) "Fishing… comes with many risks. Many people have drowned…, others have been attacked and/or killed by crocodiles, snakes etc or other reptiles while fishing in big streams and rivers." (Mkushi FGD 1)

Bushmeat

The direct quotations reveal the complexities of bushmeat hunting and consumption, highlighting its economic and cultural significance amidst legal and ecological challenges. Bushmeat provides income and sustenance, with profits used for essentials like solar lighting *(d2.2, d3.1)*. However, forest loss, restrictions, and the risks of poaching limit supply (d2.1, d2.3, d3.3). Hunters face dangers from wildlife, game rangers, and even supernatural beliefs *(d2.4, d3.2, d3.4)*. While private farms harbour wildlife, access is limited *(d2.3, d1.1)*. Concerns over authenticity and meat quality add to the risks of consumption *(d3.5, d3.6)*. Despite these challenges, bushmeat remains integral to rural livelihoods.

Illustrative direct quotations from CF interviews.. (d1.1) "There are many rabbits on my farm, and some workers hunt them as they use them as relish or sometimes even sell them." (CF Interview 12)

(d1.2) "Rabbits are attracted to car headlights at night, so many are hit and killed…" (CF Interview 4)

Illustrative direct quotations from rural farmers' interviews. (d2.1) "I sell smoked and dried bushmeat…and it's a profitable business despite short supply… due to the many restrictions on bushmeat hunting." (Chongwe Interview 7)

(d2.2) "The demand for bushmeat usually exceeds the supply, but when it's available, I earn enough for essentials like soap, sugar, solar charger, solar torch and solar lighting…" (Chongwe Interview 13)

(d2.3) "Rabbits are difficult to find as the forest cover is decreasing, and most of the rabbits are now found in protected private areas belonging to white commercial farmers…" (Mkushi Interview 2)

(d2.4) "…I used to go hunting with my grandfather…but I opt out, especially when I was pressured to undergo rituals to protect me from wild animals and game rangers…" (Kapiri Interview 26)

(d2.5) "When I find animals that thrive in trees while hunting, and they run up a tree, I cut down the tree." (Kapiri Interview 21)

(d2.6)"…hunting antelopes is illegal in game reserves unless you have a license. However, when antelopes come near the villages, we kill them for food and sometimes sell..." (Chongwe Interview 14)

(d2.7) "There are several rodents and small animals in this area, but they are not found near the villages…" (Luano Interview 3)

Illustrative direct quotations from rural farmers' FGDs. (d3.1) "We love bushmeat… just like urban people… It's supplied by hunters…" (Chongwe FGD 1)

(d3.2) "Many bushmeat hunters also engage in poaching and use magical powers to protect themselves from predators, game rangers…and some have even been associated with human/albino sacrifice." (Kapiri FGD 2)

(d3.3) "Some people have licenses and permits to hunt game meat…in some seasons. However, many of them are just armed poachers…" (Chongwe FGD 1)

(d3.4) "Bushmeat hunting is a risky business…because you encounter many dangers… Hence only a few engage in it, and…use charms and magical powers for protection." (Mkushi FGD 2)

(d3.5) "…we are very careful before consuming bushmeat because unscrupulous people sometimes sell dog meat as bushmeat…" (Kapiri FGD 2)

(d3.6) "Though we buy bushmeat from trusted suppliers, we are still cautious and inspect the meat to ensure it is well-preserved and not rotten; otherwise, you can get sick." (Mkushi FGD 1)

Ethnomedicine and traditional healing

The direct quotations highlight the coexistence of traditional and modern medicine in rural communities, reflecting both practical reliance and cultural beliefs. Traditional healers are vital due to limited access to clinics and their confidentiality in treating sensitive ailments like STIs (Sexually Transmitted Infections) *(e2.1, e3.1)*. Witch doctors also address spiritual and social issues, earning significant income *(e2.4, e3.3)*. However, scepticism persists, with concerns about their practices, moral implications, and risks, such as discouraging conventional treatment for serious diseases *(e3.5, e2.5)*. While some view traditional remedies as complementary to modern medicine *(e3.6)*, others reject them outright, associating them with superstition and harm *(e1.2, e2.5)*.

Illustrative direct quotations from CF interviews. (e1.1) "…certain trees, fruits, roots, and other plants have medicinal properties that locals use..." (CF Interview 6)

(e1.2) "There are many superstitions/mystical beliefs in the rural community…, but as a Christian, I encourage them to trust in God…" (CF Interview 15)

(e1.3) "I am aware of the traditional medicines used, especially by people who live far from clinics and town centres. However, I personally rely on conventional medicine." (CF Interview 12)

(e1.4) "Though the large majority of commercial farmers are white, we ensure that we respect the belief systems of the local communities and honour their chiefs..." (CF Interview 5)

Illustrative direct quotations from rural farmers' interviews. (e2.1) "A lot of us combine conventional and traditional medicine. Clinics are few and sometimes very far, so we use traditional healers who are always within reach." (Chongwe interview 3)

(e2.2) "Modern medicine is limited, so you cannot go to the clinic for spiritual problems…for such issues, you go to witch doctors." (Kapiri Interview 19)

(e2.3) "There was a powerful witch doctor in Chongwe called 'Mugwegwenu'… who was so good that people used to come from all over, and he made some good money…" (Chongwe Interview 4)

(e2.4) "We have some good witch doctors around who help heal many

illnesses, including STIs, and people come from urban areas to seek charms to help in marriage, promotion, business success, fertility…" (Chongwe Interview 4)

(e2.5) "I am a Christian and I don't believe in witch doctors; they are evil and use evil spirits. They bring enmity between neighbours and in families… I believe they are to blame for ritual killings and human sacrifice. They should just be banned." (Kapiri Interview 10)

(e2.6) "I bought this farm at a giveaway price because the previous owner was convicted of practicing witchcraft and banished from the village by the Chief…" (Kapiri Interview 7)

Illustrative direct quotations from rural farmers' FGDs. (e3.1) "Traditional healers are more confidential, so people who suffer from embarrassing diseases like STIs…prefer to visit traditional healers to avoid shame… some people recover from serious STIs even within a week…" (Chongwe FGD 3)

(e3.2) "Witch doctors make lots of money. They charge around $2 (K50) for diagnosis and about $12 (K300) for treatment and medication. For STIs, though their concoctions work, I believe conventional medicine is better except there is no confidentiality at clinics…" (Chongwe FGD 1)

(e3.3) "For spiritual purging, ghost cleansing, business boosts, etc., the charge is around $120 (K3,000) depending on the witch doctor. Some make lots of money and some have iron sheet roofs, nice bikes and huge solar panels on top." (Kapiri FGD 2)

(h3.4) "Salt and vinegar are sometimes also used for spiritual cleansing. The charge for salt is about $1 (K25), while vinegar goes for around $2.50 (K65)…" (Mkushi FGD 1)

(e3.5) "I use some local remedies to treat illnesses, but I don't trust these witch doctors. They claim to heal any disease, including cancer and HIV… stopping people from taking ARVs…they have led to a lot of deaths." (Mkushi FGD 1)

(e3.6) "The medicines found in hospitals are just purified versions of the God given medicinal plants and roots which freely surround us…" (Mkushi FGD 2)

Discussion and interpretations of findings

Mopane worms

The discussion of the environmental and social impacts of self-financed solar photovoltaic (PV) systems in rural Zambia, particularly in relation to edible NTFPs like Mopane worms, reveals a complex interaction between income generation, deforestation, and socio-cultural factors. Empirical evidence suggests that the commercialization of Mopane worms, which thrive on trees such as Mutondo (Cordyla africana), Mpasa (Julbernadia globiflora), and Miombo (Brachystegia boehmii), leads to substantial deforestation, negatively impacting both ecosystems and livelihoods (Mkushi Interview 1, *CF* 8). Commercial farmers, for instance, express concerns over the widespread felling of large trees to access these caterpillars (*CF* Interview 8,10,11,14). The rapid and often unauthorized harvesting undermines sustainable land management, resulting in a loss of critical tree species that serve as hosts for the caterpillars, exacerbating deforestation pressures (*CF* Interview 8).

This aligns with the findings of Chidumayo and Mbata (2002), who highlight that overharvesting of host trees is a critical issue in maintaining the sustainability of caterpillar harvesting. While younger miombo woodlands exhibit higher regeneration rates after disturbances such as selective cutting, older woodlands face higher mortality rates and poorer regeneration potential, thus diminishing their long-term capacity to support edible caterpillars. The destruction of key tree host species, such as Mutondo and Mpasa, further threatens this dynamic, compromising both biodiversity and the long-term availability of NFTPs.

The financial benefits derived from Mopane worm collection cannot be overlooked, as rural households often report significant income (with some earning as much as $25 per 20-l container of caterpillars) from selling the worms, which even at times surpasses agricultural returns during peak seasons (Mkushi Interview 2). This supports earlier studies that have documented the significant economic contribution of edible caterpillars to household income and food security across SSA (Hlongwane et al., 2021; Makhado et al., 2014). However, this income generation comes at a high environmental cost, with evidence of over-harvesting, reduced worm populations, and weakened forest ecosystems (Mkushi FGD 1).

Socially, the collection of Mopane worms is marked by growing tensions. Commercial collectors, often migrating across territories, pose significant challenges to both local farmers and traditional authorities (Mkushi FGD 2). In some instances, their aggressive behaviour has led to fatalities (*CF* Interview 7) and violence, illustrating the socio-economic desperation driving this trade (*CF* Interview 9,7,14). These findings resonate with broader regional challenges, where weak governance structures and limited regulatory enforcement have led to unsustainable practices in communal areas (Sekonya et al., 2020; Togarepi et al., 2020).

The introduction of solar PV systems, cited by local farmers as an important tool in improving household well-being, has helped offset some environmental pressures on local forests that would be affected by mopani worm harvest; PV reduces dependency on firewood while enhancing clean energy access (Mkushi Interview 5). Nonetheless, without stronger regulations and sustainable harvesting practices for Mopane worms, these efforts alone are unlikely to mitigate the broader environmental degradation resulting from the overexploitation of NTFPs. Sustainable management and community-based governance, as suggested in the literature (Chidumayo & Mbata, 2002), remain crucial for ensuring the continued viability of both solar energy initiatives and Mopane worm harvesting as complementary livelihood strategies in rural Zambia.

Wild mushroom

The integration of self-financed solar photovoltaic (PV) systems into rural Zambia has had notable environmental and social impacts, particularly regarding the sustainable harvesting of edible NTFPs such as wild mushrooms. Empirical evidence from commercial and rural farmers in Zambia indicates that wild mushrooms play a crucial role in both food security and income generation. During the peak season, farmers reported weekly earnings ranging from £30 to £35 (K600–K700), contributing significantly to household income (Mkushi Interview 6). This mirrors findings from previous studies, where mushroom commercialization in SSA demonstrated a similar income potential, with Amanita loosii mushrooms fetching between US$0.10 and US$1.00 per liter in Zimbabwe (Mlambo & Maphosa, 2017). The income generated from wild mushroom sales helps rural households manage financial obligations, such as repayments for solar lighting systems (Mkushi Interview 6, Kapiri FGD 2).

The growing demand for mushrooms, particularly in urban areas where they are valued for their health benefits, has encouraged increased foraging (*CF* Interview 5). However, the mushroom sector faces numerous challenges, including the depletion of forest cover, which is critical for mushroom proliferation. As noted by farmers, the loss of trees and deforestation, often driven by agricultural expansion, has adversely affected mushroom availability (Mkushi FGD 2). This is consistent with research findings from Steel et al. (2022) and Sileshi et al. (2023), both of which emphasize the detrimental impact of deforestation on the sustainability of wild mushroom resources in SSA.

Social issues also emerge from mushroom commercialization. The need for income has led some households to prioritize foraging over education, with children missing school to help collect mushrooms (Chongwe FGD 3). Furthermore, the dangers of venturing into deep forests and use of inexperienced gatherers expose collectors to risks from wild animals and consumers to poisonous mushrooms (Chongwe FGD 1,

Kapiri FDG 2). Therefore, while wild mushrooms contribute to income generation, these activities present ecological and social challenges that require careful management to ensure the long-term viability of NTFP-based livelihoods in rural Zambia.

Wild fishing

Our empirical evidence reveals that apart from fish being consumed, income generated from fishing (approximately $6 to $8 per kilogram of fish) has enabled rural households to finance the acquisition of solar PV systems, highlighting the integral role of fishing in rural income generation (Mkushi Interview 3, Kapiri Interview 26, Kapiri FGD 2). This reflects broader findings across SSA, where fishing serves as both a critical income source and food security measure (Gondwe et al., 2023; Temesgen et al., 2019). The income from fish sales contributes not only to daily sustenance but also to broader investments in sustainable energy, showing a direct link between fishing income and improved household infrastructure, such as solar PV systems.

However, despite the socio-economic benefits derived from fishing, there are significant ecological and economic challenges associated with wild fishing in Zambia. Evidence from the focus groups and interviews suggests that overfishing, depletion of fish stocks, and the use of destructive fishing methods, including fish poison (*Tephrosia vogelii*), threaten the long-term sustainability of fisheries (Kapiri FGD 2; *CF* Interview 5). This mirrors broader concerns across the region, where overfishing and environmental degradation severely impact aquatic ecosystems, undermining the viability of fishing as a reliable income source (Temesgen et al., 2019; Tweddle et al., 2015). Additionally, unsustainable practices, such as the use of small nets and fishing in ecologically sensitive areas, compound the ecological risks, leading to the gradual depletion of natural resources crucial for rural livelihoods (Kapiri FGD 2.,71).

The low productivity of small-scale fisheries, exacerbated by seasonal fishing bans and inadequate infrastructure, limits the income potential for rural households (Kapembwa, Gardiner and Pétursson, 2021). Furthermore, safety risks, such as crocodile or snake attacks and drowning incidents, present additional barriers to the sustainability of fishing as an income source (Mkushi FGD 1., 73,74).

Bushmeat

Bushmeat serves as an essential yet ecologically and socially complex source of income in rural SSA, including Zambia. Findings indicate that rural households rely on bushmeat trade to supplement livelihoods in contexts of limited economic opportunities (Chongwe Interviews 7, 13). This aligns with studies by Kouassi et al., 2023 and Lindsey et al., 2011, which highlight poverty and unemployment as drivers of rural dependence on bushmeat. Increasing urban demand has shifted hunting from subsistence to commercial trade, as similarly observed by Brown and Marks (2008).

The economic significance of bushmeat in Zambia is underscored by its role in addressing financial and food security needs. Farmers engage in bushmeat trade despite legal restrictions, using earnings to purchase essential goods (Chongwe Interview 13, *CF* Interview 12). White and Belant (2015) emphasize bushmeat's critical role in alleviating food insecurity, estimating an annual yield of 129,000 kg valued at over $600,000 in Zambia. Particularly during periods of food scarcity, hunting in game management areas helps rural households mitigate shortages.

While Zambia's Wildlife Act of 2015 (Zambia Wildlife Act, 2015) permits regulated hunting, illegal bushmeat trade remains pervasive due to urban demand, particularly in Lusaka, where annual trade volumes are estimated at 1140 t (Davies, 2017). The gap between demand and legal supply has fuelled illegal hunting, with around 6000 people involved in such activities in the Greater Kafue Ecosystem alone (Davies, 2017). This dynamic exacerbates habitat conversion for agriculture to meet growing food needs, further intensifying environmental pressures (Alexander et al., 2015). The ecological costs of the bushmeat trade are profound. Overhunting, especially in areas with limited wildlife protection, threatens biodiversity and disrupts population dynamics of species like antelopes and rabbits (Mkushi Interview 2, Luano Interview 3). These findings align with broader concerns about unregulated hunting's impact on ecosystems, as noted by Che et al. (2017) and Foya et al. (2023). Furthermore, the bushmeat trade poses zoonotic disease risks by facilitating pathogen transfer from wildlife to humans, a critical issue identified by (Kurpiers et al., 2015).

Social and cultural factors further complicate bushmeat reliance. Traditional rituals often accompany hunting, reflecting a fusion of spiritual beliefs and survival strategies. Hunters in Kapiri, for instance, rely on mystical practices for protection, paralleling practices documented in Nigeria by Paul Mmahi and Usman (2020). These rituals serve as coping mechanisms to mitigate risks, including confrontations with game rangers and dangerous wildlife (Mkushi FGD 2). The bushmeat trade in Zambia presents a persistent and challenging balance between economic necessity and environmental sustainability. While it provides critical income for rural households, its environmental and social impacts are undeniably severe. Ripple et al. (2016) and Wicander and Coad (2018) advocate for alternative livelihoods as a means to reduce illegal hunting and associated ecological degradation. This approach fits well with findings from the Wildlife Economy Hub for Africa, which suggests that well-managed, legal hunting can alleviate pressures on wildlife populations (Vigne, 2022). However, as urban demand for bushmeat continues to rise, without viable economic alternatives, illegal hunting and its environmental consequences are likely to persist.

Ethnomedicine and traditional doctors

This study highlights the critical role of income from traditional healing practices in financing solar PV systems in rural Zambia. Traditional healers and Ethnomedicine practitioners (witch doctors), who offer medicinal and spiritual services, are pivotal economic actors in these communities. Income from such practices constitutes up to 58 % of household earnings in remote areas with limited access to modern healthcare (Timmermann & Smith-Hall, 2019). Fees for services vary significantly, ranging from $2 (K50) for diagnoses to $120 (K3,000) for rituals like spiritual purging or business-boosting ceremonies (Chongwe FGD 1; Kapiri FGD 2). Many households rely on a combination of traditional and modern medicine due to affordability and accessibility challenges, with 70 % of Zambia's population using medicinal plants for healthcare (Boukandou Mounanga et al., 2015; Nyirenda & Chipuwa, 2024).

Traditional medicine not only provides essential healthcare but also generates significant household income. For instance, healers treat STIs using herbal remedies derived from plants like Strychnos cocculoides (Chongwe FGD; 89). This income enhances economic resilience and supports solar PV adoption (Kapiri FGD 2). However, overreliance on ethnomedicine poses sustainability challenges. Demand for key ingredients like lemon and papaya roots is driving overharvesting, threatening the long-term availability of these resources (Kapiri Interview 19; Mkushi FGD 1; 90). Similar concerns apply to *Cassia abbreviata* (Umunsokansoka), which effectively treats malaria and STIs but faces risks from unsustainable harvesting practices (Sidney et al., 2024). The lack of regulatory oversight on medicinal plant harvesting and commercialization not only threatens environmental sustainability but potentially also undermines the availability of vital healthcare resources (Boukandou Mounanga et al., 2015; Sher et al., 2014). Cultural factors also influence the preference for traditional medicine. Stigma surrounding STIs often discourages individuals from seeking treatment in modern clinics, as traditional healers ensure confidentiality and social acceptance (Chongwe FGD 3). This is corroborated by findings in Monze, where more than 80 % of respondents identified stigma as a primary barrier to STI treatment (Simbeye et al., 2024). Traditional

medicine thus serves as a culturally sensitive alternative, addressing both medical and social needs. This aligns with (Gausset's (2001) argument that Western (Modern) healthcare programs in SSA often fail to accommodate culturally acceptable practices, alienating local populations and reducing program effectiveness. By offering a socially acceptable means of treatment, ethnomedicine not only addresses healthcare gaps but also fosters trust within local communities (Chinsembu et al., 2019; Gausset, 2001).

However, Ethnomedicine practitioners, while economically significant for some households, introduce substantial social challenges. Ethnomedicine practitioners in Chongwe and Kapiri provide various treatments and rituals, reflecting the strong belief in spiritual services, including juju rituals, even among individuals adhering to orthodox religions (Aborisade & Adedayo, 2021). Yet, these practices frequently exacerbate social tensions. Witchcraft accusations, social exclusion, and ritual killings, particularly targeting vulnerable groups like individuals with albinism, are some of the adverse consequences documented (Kapiri Interview 10).

The destabilizing effects of witchcraft beliefs are well-established in both the study's findings and broader literature. Such beliefs undermine social cohesion, hinder economic development, and foster mistrust within communities (Gershman, 2016). In Zambia, ritual killings linked to witchcraft practices have heightened fear and social instability, eroding community trust (Aquaron et al., 2009; Mwiba, 2018). These harms emphasize the need for robust legal and social frameworks to regulate witchcraft practices and mitigate their negative impacts on community cohesion (Sanou, 2020). Traditional healing plays a dual role in rural Zambia by addressing healthcare needs and generating critical income, which can support investments in solar PV systems. However, the overexploitation of medicinal plants and the social challenges associated with witchcraft practices necessitate stronger regulation and sustainable management. Balancing economic benefits with environmental sustainability and community well-being is essential for ensuring the long-term viability of these practices.

Recommendations for policymakers and practitioners

To advance the adoption of self-financed solar photovoltaic (PV) systems in rural Zambia while promoting the sustainable management of NTFPs such as Mopane worms, mushrooms, bushmeat, fishing, and ethnomedicine, policymakers and practitioners must adopt comprehensive and pragmatic strategies. These recommendations address financing models, stakeholder collaboration, integration of income generation, barriers to adoption, and regulatory frameworks.

Improving financing models

Adaptive financing mechanisms aligned with rural income patterns are essential. The Ministry of Energy and the Rural Electrification Authority (REA) should implement flexible repayment models tied to seasonal incomes from NTFPs, such as Mopane worms and fish. Income-linked repayment schemes will enable rural households to invest in solar PV systems without jeopardizing economic stability, ensuring long-term adoption and operational sustainability. Income from NTFPs serves as an effective complementary mechanism to other financing models, particularly for rural, forest-dependent communities. Integrating NTFPs with PAYG systems or microfinance loans can enhance energy access while supporting forest conservation and rural development. Adapting financing approaches to specific regional contexts is critical to achieving optimal community benefits and ensuring long-term sustainability.

Promoting multi-stakeholder collaboration

Effective solar PV implementation requires cohesive action among stakeholders. Ministries overseeing energy, agriculture, and health must collaborate with local councils, traditional leaders, and global development organizations to create inclusive policies. Incorporating local priorities ensures tailored energy solutions while encouraging sustainable NTFP use. Conservation-focused organizations, such as the Zambia Wildlife Authority (ZAWA), are crucial partners in aligning energy initiatives with resource preservation, safeguarding mushrooms and bushmeat ecosystems.

Integrating NTFPs with renewable energy initiatives

Income generation from NTFPs should be strategically linked to solar PV adoption. Promoting sustainable harvesting and community-based processing facilities for products like mushrooms, fish, and medicinal plants can enhance household revenues while reducing environmental impacts. Initiatives such as eco-tourism centred on NTFPs offer alternative income streams, with the ability to incentivize conservation while at the same time fostering renewable energy investments.

Addressing barriers to solar PV adoption

Solar PV adoption faces obstacles such as financial constraints, low awareness, and technical challenges. Public education campaigns should, we argue, highlight solar PV benefits alongside sustainable NTFP harvesting practices. Microfinance institutions and NGOs must provide targeted loans and technical support to enhance accessibility and system maintenance. Capacity-building initiatives are critical to equipping communities with knowledge about solar PV usage and sustainable resource management, particularly for bushmeat and fish.

Strengthening regulatory frameworks

Robust regulation is vital to sustaining solar PV systems and conserving natural resources. The Ministry of Lands and Natural Resources should enforce sustainable practices for Mopane worms, mushrooms, and bushmeat harvesting. Community-led governance systems can ensure local accountability, while conflict resolution frameworks address disputes over resource access. Social protection policies should offer alternative livelihoods to ease transitions from unsustainable practices, promoting energy equity and ecological preservation.

Conclusion

This study provides a detailed exploration of the environmental and social effects of self-financed solar photovoltaic (PV) systems in rural Sub-Saharan Africa, focusing on Zambia's edible NTFPs such as Mopane worms, mushrooms, fishing, bushmeat, and ethnomedicine. By examining the interplay between solar PV adoption and rural livelihoods, it highlights the dual potential of these resources as critical income sources and ecological assets. The findings underscore the importance of sustainable practices, integrated policy interventions, and community-led initiatives to balance energy access with environmental conservation and socio-economic development.

Key findings

The study reveals that income derived from Mopane worms, mushrooms, fish, bushmeat, and medicinal plants plays a pivotal role in financing solar PV systems in rural Zambia. These NTFPs often serve as primary or supplementary income sources, sometimes exceeding the returns from agriculture. This financial capacity facilitates solar PV adoption, enhancing household energy access and reducing dependence on unsustainable biomass energy, such as firewood. By doing so, solar PV systems contribute to mitigating deforestation and associated carbon emissions. However, the commercialization of the NTFPs also raises significant environmental concerns, particularly overharvesting, habitat destruction, and biodiversity loss, which threaten long-term sustainability.

Environmental impacts

While solar PV systems offer environmental benefits by reducing reliance on firewood and mitigating carbon emissions, the income activities enabling their financing often pose ecological risks. The overharvesting of Mopane worms and wild mushrooms depletes natural stocks, undermining ecosystem stability and species diversity. Similarly, unsustainable fishing practices erode aquatic biodiversity, while bushmeat extraction jeopardizes wildlife populations. These environmental challenges necessitate effective resource management strategies that prioritize sustainable harvesting and ecological preservation. Without such measures, the dual pressures of resource depletion and increasing energy needs could undermine both environmental and energy sustainability objectives.

Social impacts

Socially, the integration of solar PV systems into rural communities has transformative potential, improving energy access and household well-being. The income from NTFPs empowers households financially, enhancing their ability to invest in modern energy technologies. However, commercialization of resources like bushmeat and fish can exacerbate social tensions, particularly where competition for finite resources fuels conflicts between traditional harvesters and commercial operators. Such dynamics risk deepening socio-economic disparities and destabilizing community cohesion. Solar PV systems, while beneficial, cannot independently address the challenges; robust regulatory frameworks and community-driven governance structures are essential to promote equitable access and collective resilience.

Implications for energy access and sustainable livelihoods

This research underscores the interconnected nature of energy access, poverty alleviation, and environmental sustainability in rural Zambia. Integrating solar PV systems with sustainable NTFP management presents a unique opportunity to enhance rural livelihoods while safeguarding natural ecosystems. For instance, promoting sustainable harvesting practices for Mopane worms and mushrooms, alongside eco-friendly fishing techniques, could balance income generation with conservation efforts. Educational campaigns and capacity-building initiatives are critical for equipping communities with the knowledge to manage resources responsibly. Furthermore, investing in alternative livelihoods, such as value-added processing of NTFPs or eco-tourism linked to ethnomedicine, can diversify income sources and reduce overdependence on vulnerable resources.

Contribution to knowledge

This study contributes important insights and depth of understanding to the discourse on rural development by elucidating the complex interplay between income generation, energy access, and environmental conservation. It highlights the dual role of NTFPs as economic enablers of solar PV adoption and as ecological assets requiring protection. By advocating for sustainable harvesting and integrated energy policies, the findings emphasize the importance of aligning renewable energy initiatives with natural resource management. This dual-focus approach is crucial for achieving long-term rural development goals, balancing socio-economic resilience with environmental integrity. Income from NTFPs serves as an effective complementary mechanism to other financing models, particularly for rural, forest-dependent communities. Integrating NTFPs with PAYG systems or microfinance loans can enhance energy access while supporting forest conservation and rural development. Adapting financing approaches to specific regional contexts is critical to achieving optimal community benefits and ensuring long-term sustainability.

We have introduced the novel Rural Development Stakeholder Hybrid Adoption Model (RUDSHAM), which integrates three key theoretical frameworks to provide a comprehensive understanding of the factors influencing renewable energy adoption in rural areas. This holistic approach accounts for the interplay between individual beliefs, social influences, and community dynamics in shaping adoption behaviours. By offering valuable insights into the complexities of solar PV adoption, RUDSHAM serves as a crucial tool for policymakers, researchers, and practitioners seeking to develop effective strategies for sustainable energy transitions in rural communities.

Future directions and recommendations

While this study advances understanding of the relationship between solar PV systems and NTFPs, its limitations suggest avenues for future research. A longitudinal approach would provide deeper insights into the long-term impacts of solar PV adoption on rural households and ecosystems. Expanding the geographical scope to include other Sub-Saharan African countries could uncover regional variations and commonalities in adoption dynamics. Quantitative methodologies, such as large-scale surveys, would enhance the generalizability of findings, while a broader examination of economic activities beyond NTFPs could provide a more holistic understanding of rural energy transitions.

In conclusion, solar PV systems, when combined with the sustainable management of NTFPs, provide a viable pathway to alleviating energy poverty and promoting environmental conservation in rural Zambia. Using the RUDSHAM framework, we have presented detailed findings and empirical evidence that demonstrate tangible improvements in local communities through solar PV adoption. For example, the provision of lighting has directly benefited schoolchildren by enabling nighttime study, reduced the risks posed by snakes in the dark, extended shop operating hours, and minimized health hazards associated with candle smoke inhalation and fire risks. Additionally, households with larger solar PV systems have been able to irrigate gardens using solar-powered water pumps, operate salons, and raise chickens, thereby increasing their income. These findings highlight both economic and quality-of-life improvements.

Achieving this balance requires collaborative efforts among policymakers, communities, and development practitioners to design policies and interventions that integrate energy access with sustainable livelihoods. By addressing the confluence of challenges embracing resource depletion, social inequity, and energy poverty, rural communities will potentially be able – effectively and efficiently – to transition toward a more sustainable and equitable future. This research thus serves as both a knowledge contribution and a call to action for advancing sustainable rural development in Zambia.

CRediT authorship contribution statement

Hillary Chanda: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Eugene Mohareb:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Michael Peters:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Chris Harty:** Supervision, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supportive statements from interviews and FGDs (detailed)

A.1. Income sources in rural zambia: Empirical evidence via RUDSHAM model

The Rural Development Stakeholder Hybrid Adoption Model (RUDSHAM), through interviews and focus group discussions (FGDs), has identified a range of income-generating activities prevalent in rural Zambia. These activities form the backbone of subsistence and local economies but also have varied environmental and social implications.

A.1.1. Mopane worms (edible caterpillars)

Edible Insect Harvesting (Mopane Worms and Others): The collection of Mopane worms and other edible insects provides a crucial seasonal income stream for many rural households, but it raises concerns regarding overharvesting and habitat disruption.

Illustrative Direct Quotations from Commercial Farmers (CF) Interviews.

(a1.1) "Well, people come to our farm and chop down trees to collect the caterpillars (Mopane worms). Chopping down the trees! Yeah, yeah, we lost a lot of trees. There's one particular variety called the Mutondo (Cordyla africana) tree which got completely wiped out from my farm. They cut them all down, big, big trees, just to get the caterpillar. It was like a tsunami hit my farm!" (CF Interview 8)

(a1.2) "They also came to my farm…it happened so quickly and without my knowledge or permission. They just came and cut these big trees just to get the caterpillars. And then of course, you cut the trees down. Now there's no trees. There's no capital. Then they move on again to some other land. They are so destructive." (CF Interview 14)

(a1.3) "You see, this would have been sustainable in the past because they would have moved through the area and the trees would have regrown. But they were doing this on my farm, you know, it's a limited area. It's a restricted area. So, it's a serious issue. It's obviously something that is a cultural thing, something that's happened in the past, but now it's not sustainable." (CF Interview 6)

(a1.4) "These guys (Mopane worm collectors) are very aggressive people, and people have even been killed by them. There's a chief near Serenje town, because he was standing up to them, they killed him. And, you know…the affected rural farmers complained to the police and complained to the chief. And because the chief now was standing in their way, they literally killed him." (CF Interview 7)

(a1.5) "And I mean, I came to the conclusion that stopping them was dangerous because these people were very aggressive. They would camp on farmers' lands, in Mkushi and Serenje, and they would build a village on someone's farm as they collected Mopane worms and cut down trees." (CF Interview 9)

(a1.6) "The collectors are well-connected, and they would be bribing the police, they would be bribing the local council people, and they probably supply them with whatever they produce… and you know, the police and councils don't have the resources to stop these aggressive Mopane worm collectors." (CF Interview 9)

(a1.7) "Look at this big tree that has just been cut down! This is exactly what I was telling you about. Imagine! It drives you mad! Obviously, there was something in that tree he wanted, either the Mopane worms or the honey. If you hear the sound kok, kok, kok in the distance, just know a tree is being cut down. If you don't send someone to stop them, they will cut it." (CF Interview 10)

(a1.8) "If I take you through this forest, you'll see some beautiful trees that have been cut. Though the situation is improving due to increased awareness, there are still many villagers who have the wrong attitude and don't take care." (CF Interview 11)

(a2) Illustrative Direct Quotations from Rural Farmers' Interviews.

(a2.1) "I can't lie, ifishimu (Mopane worms) are a very good source of income which has helped me supplement income from farming and sometimes even surpassing agriculture income in yester years. My house has a radio, solar charger and solar lighting so my children no longer sleep in the dark or depend on candles. If I work hard, I might even install a solar pump to help with irrigation (smiling)." (Mkushi Interview 5)

(a2.2) "There are many dangers that I face as I collect caterpillars, like snakes, wasps etc. Not to mention the job of processing the caterpillars to dry and preserve them from going bad." (Mkushi Interview 2)

(a2.3) "I collect worms from any forest except where there is a fence because you might get shot at by white commercial farm owners…Lol…but there are others who dare break fences to collect the worms especially if there is a lot." (Mkushi Interview 3)

(a2.4) "I sell the worms at $25 (K500)/20ltr container so it is quite profitable because in a good season you can raise a lot of money daily as we sell in wholesale in urban areas and also along the main roads. Consequently, I had disposable income and I did not struggle to buy uniforms for my children, buy home necessities and get a nice phone, radio and the solar lighting which has become a fashion." (Mkushi Interview 2)

(a2.5) "Mopane worm collectors (Abafishimu) move from forest to forest and from farm to farm to collect Mopane worms. They usually move in groups, carrying axes, pangas and other weapons, so no one dares to stop them. They believe it's their land, and they are entitled to benefit from it just like their forefathers. They are quite brutal, collecting a large number of worms and making substantial money as they resell them to town people, who love the worms as a healthy natural delicacy." (Mkushi Interview 4)

(a2. 6) "Mopane worm numbers have drastically reduced in the past decades because of overharvesting and cutting down of trees. In the past, it was sustainable because there were only a few people involved. But now, there are many people and a very high demand for the Mopane worms. Many times, the worms 'fipona' (fall) in private areas like 'ama famu yabasungu' (White commercial farmers land) who have managed to preserve their forests." (Mkushi Interview 1)

(a3) Illustrative Direct Quotations from Rural Farmers' FGDs.

(a3.1) "'Ifishimu munani uusuma sana' (Mopane worms are a tasty delicacy) that has helped many families to survive and also raise some money for buying other household necessities." (Mkushi FGD 2)

(a3.2) "The worms are usually sold wholesale to urban buyers or by the roadside along main roads to passing motorists. A busy road in a rural area is a source of livelihood because of the motorists who stop to buy various items." (Mkushi FGD 1)

(a3.3) "The roadside selling is mostly done by women and children, but wholesale selling is done by the men. It's a good alternative source of income to agriculture which is seasonal and once off." (Mkushi FGD 2)

(a3.4) "Commercial Mopane worm collectors are quite aggressive, especially towards people who try to frustrate their collection efforts, because it's a matter of survival for them—life and death. If they don't collect, they won't eat, and they won't be able to raise income. So they are willing to go to extreme lengths to protect and guard their trade." (Mkushi FGD 2)

(a3.5) "These commercial collectors come with machetes and are willing to use them on those opposing them if necessary. Sometimes, the best you can do is to negotiate with them so that they leave you a portion of their collection, which more or less becomes a win-win situation because you are also helping them to survive." (Mkushi FGD 1)

(a3.6) "But we don't know what the future holds because there has been overharvesting in recent decades due to increased demand. Mpasa (Julbernadia globiflora), Mutondo (Cordyla Africana) and Miombo (Brachystegia boehmii) trees are mainly the trees that host the caterpillars and which have been cut down during Mopane worm collection. We are afraid our children might not even enjoy this delicacy in the future, as it is in danger of extinction." (Mkushi FGD 1)

(a3.7) "In the past, caterpillar collection could only start after the chief had given a go ahead after they consulted local mystical spirits to ensure safe and bumper harvesting. Whoever was caught collecting before the chiefs permission was punished as they were guilty of provoking the spirits whose rath would prevent subsequent caterpillar presence in the area. The chiefs also warned against starting any fires during the caterpillar season. These days such issues are not taken seriously. Maybe that's why we are having fewer caterpillars." (Mkushi FGD 2)

A.1.2. Wild mushroom

Wild mushroom and Leafy Vegetables Foraging: Seasonal mushroom collection offers both nutritional and economic benefits. Nevertheless, overexploitation and deforestation risk undermining the sustainability of this resource.

(b1) Illustrative Direct Quotations from CF Interviews.

(b1.1) "Apart from local consumption, there is increased demand for mushrooms so you will find many women selling it along the road for motorists to buy. The demand is mainly driven by urban areas where mushroom is considered to be healthier than meat and chicken to prevent non-communicable diseases and control weight." (CF Interview 5)

(b1.2) "I have seen many people come through my farm because we try to preserve the forest, which allows mushrooms to thrive. I don't stop them, but I do request that they don't cut down any trees." (CF Interview 9)

(b1.3) "As much as this is my land, I understand that the locals depend on the land for their livelihoods. To ensure a symbiotic and peaceful relationship, I allow them to collect mushrooms, which helps them have relish and also to sell and raise some much-needed income." (CF Interview 1)

(b2) Illustrative Direct Quotations from Rural Farmers' Interviews.

(b2.1) "It's not easy to find mushrooms nowadays because there are very few trees left, and some good mushrooms thrive under trees. Additionally, a lot of land has been cultivated, leading to the loss of forest area. This forces me to go deep into the bush to find mushrooms, which takes a lot of time." (Mkushi Interview 3)

(b2.2) "Mushroom collection is not for novices because a lot of people have gotten lost while collecting mushrooms… Lol... They focus so much on looking down to find mushrooms that they lose their way, ending up sleeping in the bush… Lol. So some people avoid venturing in to mushroom collection." (Kapiri Interview 6)

(b2.3) "There are different varieties of mushrooms, and different people like different types, so there is a good market for mushrooms in urban areas. This helps bring in some income for many of us... I make between £30–£35 (K600–K700) per week during the peak mushroom season, and this helps supplement income from agriculture. My children have food and the necessary household items. I have a decent phone, a good solar charger, and as you can see, my house is well lit with good solar lighting (proudly smiling)." (Mkushi Interview 6)

(b2.4) "It's not always easy to preserve the mushrooms, and some of them end up going bad. But I try my best to either cook, add salt or dry them to preserve them if necessary." (Chongwe Interview 11)

(b3) Illustrative Direct Quotations from Rural Farmers' FGDs.

(b3.1) "Consuming mushrooms is risky because entire families have been poisoned and killed from consuming 'ichana chabene' (poisonous mushrooms). We ensure that we eat and sell only what we know, and we leave the collection to experienced and knowledgeable people so that people's lives are not endangered." (Kapiri FGD 2)

(b3.2) "…Some greedy parents, in an attempt to collect more mushrooms and earn more money, even take their young school-going children to collect mushrooms. This is not only dangerous but also causes some children to miss school." (Chongwe FGD 3)

(b3.3) "Mushroom collection is a dangerous activity because collectors venture into deep bushes and expose themselves to wild animals, especially snakes, which coil themselves under big mushrooms for shade and to eat flies, insects, and other living organisms that thrive around mushrooms." (Chongwe FGD 1)

(b3.4) "Mushrooms… are a gift to us by God, with fertilizer becoming so expensive after government reduction in subsidies, compounded by recent poor rains, we would have died of hunger without mushroom…" (Mkushi FGD 1)

(b3.5) "Mushroom thrives well under trees and health forest, sadly the tree numbers have reduced affecting the mushroom availability. Land clearance for agricultural purposes is another contributing factor." (Mkushi FDG 2)

(b3.6) "Agriculture is becoming too expensive due to expensive farming inputs and recurrent droughts. So, we work hard to collect enough mushroom and other NTFPs for consumption and for selling…many of us use part of income to pay back loans for solar lighting systems which the mobile companies give us. Because if you miss a payment, the power is disconnected." (Kapiri FGD 2)

A.1.3. Wild fishing

Wild fishing in rivers and lakes is a key food and income source but is frequently unsustainable, contributing to the depletion of fish stocks and disruption of aquatic ecosystems.

(c1) Illustrative Direct Quotations from CF Interviews.

(c1.1) "I allow the locals to fish from my dam, but only if they are using fishing rods and not fishing nets, so that the fish is preserved and protected. (CF Interview 17)

(c1.2) "Fishing is also done from some other man-made dams and big rivers within Central Province but sometimes questionable fishing techniques are used especially in public dams and rivers." (CF Interview 5)

(c2) Illustrative Direct Quotations from Rural Farmers' Interviews.

(c2.1) "When I go fishing, and if I have a good catch, I quickly sell the bigger fish to passing motorists before it goes bad. We consume the smaller fish. Fish is like hot cake, but there aren't many fish in this area…"(Kapiri Interview 26)

(c2.2) "Five big fish (1Kg) cost between $6 to $8 (K150 to K200) depending on the size. It helps to raise some income for the home when available. Even the solar lighting system that we are currently enjoying was partly financed through selling fresh fish." (Mkushi Interview 3)

(c3) Illustrative Direct Quotations from Rural Farmers' FGDs.

(c3.1) "Fish is very good relish and is considered special, especially big fish. The problem is that fish numbers are depleted, so it's difficult to catch fish." (Kapiri FGD 2)

(c3.2) "People sometimes use illegal fishing methods, like using small nets or even mosquito nets, which is quite sad." (Kapiri FGD 2)

(c3.3) "There are others who use fish poison locally known as 'buba' (Tephrosia vogelii) to kill the fish and any other living organisms in the water… It's wasteful and frowned upon even by the community." (Kapiri FGD 2)

(c3.4) "Fishing is good, but it requires courage, as it comes with many risks. Many people have drowned in the past years while trying to fish from deep waters. Others have been attacked, injured, or killed by crocodiles or other reptiles while fishing in big streams and rivers." (Mkushi FGD 1)

A.1.4. Bushmeat

Hunting for bush meat remain significant but controversial income sources, with severe negative implications for wildlife conservation and ecosystem stability.

(d1) Illustrative Direct Quotations from CF Interviews.

(d1.1) "There are many rabbits on my farm, and some workers hunt them as they use them as relish or sometimes even sell them." (CF Interview 12)

(d1.2) "Rabbits are attracted to car headlights at night, so many are hit and killed. I have also hit some, unfortunately. Bad news for me, but good news for those who eat them… ha ha." (CF Interview 4)

(d2) Illustrative Direct Quotations from Rural Farmers' Interviews.

(d2.1) "I sell smoked and dried bushmeat, but I don't hunt myself. It's a profitable business, though the dried meat is not always available due to the many restrictions on bushmeat hunting." (Chongwe Interview 7)

(d2.2) "The demand for bushmeat usually exceeds the supply, but when it's available, I earn enough for essentials like soap, sugar, and even bought a solar charger and solar torch, with some left over for a beer... you know... ha ha ha." (Chongwe Interview 13)

(d2.3) "Rabbits are difficult to find as the forest cover is decreasing, and most of the rabbits are now found in protected private areas belonging to white commercial farmers. It's not always easy to get access. Some have vicious dogs, others are fenced, and some have workers who patrol." (Mkushi Interview 2)

(d2.4) "Boss, I used to go hunting with my grandfather and his friends, who are very experienced hunters. Some of the mystical things I observed, especially during night hunts, were quite frightening. They would leave me deep in the bush, disappearing into the darkness in total silence, only to return with game meat after one or two hours. It was as though they transformed into stealth predators. At some point, I decided to opt out, especially when I was pressured to undergo rituals to protect me from wild animals and game rangers so I could join them for bigger kills." (Kapiri Interview 26)

(d2.5) "When I find animals that thrive in trees while hunting, and they run up a tree, I am left with no option but to cut down the tree." (Kapiri Interview 21)

(d2.6)"We are not allowed to hunt antelopes and other animals in game reserves unless we have a license. However, when antelopes come near the villages, especially during floods, we kill them for food and sometimes sell the meat to raise income. We are cautious, though, because if caught, it can lead to imprisonment." (Chongwe Interview 14)

(d2.7) "There are several rodents and small animals in this area, but they are not found near the villages as they were in the past. Now, you have to go a bit farther and set up traps." (Luano Interview 3)

(d3) Illustrative Direct Quotations from Rural Farmers' FGDs.

(d3.1) "We love bushmeat. It's pure meat. The urban areas also love bushmeat. It's supplied by people who go to deep bushes and game reserves to hunt antelopes, buffaloes, porcupines, wild pigs at night, etc." (Chongwe FGD 1)

(d3.2) "Many bushmeat hunters also engage in poaching and use magical powers to protect themselves from predators, game rangers, and to make themselves invisible. Many consult witch doctors, and some have even been associated with human sacrifice and albino sacrifice." (Kapiri FGD 2))

(d3.3) "Some people have licenses to hunt game meat with shotguns, which is permitted in certain seasons. However, many of them are just poachers who carry heavy weapons and even kill game rangers when confronted. It's a risky business." (Chongwe FGD 1)

(d3.4) "Bushmeat hunting is a risky business, whether you have a license or not, because you encounter predators, dangerous reptiles, and wild animals in the process. That's why only a few engage in it, and those who do—whether legally or illegally—often believe in using charms and magical powers for protection." (Mkushi FGD 2)

(d3.5) "Ha ha, we are very careful before consuming bushmeat because unscrupulous people sometimes sell dog meat as bushmeat… 'Umuselu!' (so sickening). Many people have eaten dog meat without realizing it… lol… so we always insist that the bushmeat seller presents a leg of the antelope or another part as evidence that it's genuine bushmeat." (Kapiri FGD 2)

(d3.6) "Though we buy bushmeat from trusted suppliers, we are still cautious and inspect the meat to ensure it is well-preserved and not rotten; otherwise, you can get sick." (Mkushi FGD 1)

A.1.5. Ethnomedicine and traditional healing

Income generated through traditional healing practices, spiritism, and faith-based services plays a vital role in rural economies. However, the overharvesting of medicinal plants and reliance on certain unsustainable practices challenge both environmental conservation and public health systems.

(e1) Illustrative Direct Quotations from CF Interviews.

(e1.1) "I don't believe in black magic, but I do know that certain trees, fruits, roots, and other plants have medicinal properties that locals use. After all, how do you think people survived before the introduction of Western medicine?" (CF Interview 6)

(e1.2) "There are many superstitions and mystical beliefs strongly held within the rural community and among my farm workers, but as a Christian, I encourage them to trust in God. Several churches have even been built by commercial farmers to support the local population." (CF Interview 15)

(e1.3) "I am aware of the traditional medicines used, especially by people who live far from clinics and town centers. However, I personally rely on conventional medicine." (CF Interview 12)

(e1.4) "Though the large majority of commercial farmers are white, we ensure that we respect the belief systems of the local communities and honor their chiefs. Once, the chief invited the farmers' association to a function, and we brought trees as donations. This upset the chief, who had expected financial assistance. In response, the chairman of the farmers' association in Mkushi, along with a few others, had to kneel and formally apologize according to local traditions before forgiveness was granted. Approaching the chief empty-handed is considered disrespectful, and we understand and respect these strong cultural beliefs." (CF Interview 5)

(e2) Illustrative Direct Quotations from Rural Farmers' Interviews.

(e2.1) "A lot of us combine conventional and traditional medicine. Clinics are few and sometimes very far, so we make use of traditional healers who are always within reach." (Chongwe interview 3)

(e2.2) "Modern medicine is limited, so you cannot go to the clinic for spiritual problems and cleansing from evil spirits or ghosts; for such issues, you go to traditional or witch doctors (ng'anga)." (Kapiri Interview 19)

(e2.3) "There was a powerful witch doctor in Chongwe called "Mugwegwenu" who died recently. He was so good that he could help people recover stolen items, including cars. People used to come from all over, and he made some good money. Now his children have taken over the "business."" (Chongwe Interview 4)

(e2.4) "We have some good witch doctors around who help heal many illnesses, including STIs (Sexually Transmitted Infections) , and people come from urban areas to seek charms to help with getting married, getting promoted, restoration of broken marriages, business boosts, fertility boosts, etc." (Chongwe Interview 4)

(e2.5) "I am a Christian and I don't believe in witch doctors; they are evil and use evil spirits. They bring enmity between neighbours and in families by always accusing others of being witches or wizards whenever there is sickness or death. According to them, no one dies naturally. I believe they are to blame for ritual killings and human sacrifice. They should just be banned." (Kapiri Interview 10)

(e2.6) "I bought this farm at a giveaway price because the previous owner was convicted of practicing witchcraft. He had some charms and was banished from the village by the Chief, so in fear, he sold the land to me cheaply. I paid in installments because I knew he was desperate." (Kapiri Interview 7)

(e3) Illustrative Direct Quotations from Rural Farmers' FGDs.

(e3.1) "Traditional healers are more confidential, so people who suffer from embarrassing diseases like STIs (Syphilis (akaswende)) prefer to visit traditional healers to avoid shame and being found out by spouses, parents, church members, etc. Even within a week, some people recover from serious STIs and have their reproductive systems cleansed." (Chongwe FGD 3)

(e3.2) "Witch doctors make lots of money. They charge around $2 (K50) for diagnosis and about $12 (K300) for treatment and medication. For STIs such as 'Utuswende' (Syphilis), 'Bolabola' (Lymphogranuloma venereum (LGV)), and 'Akasele' (Gonorrhea), the medicine used involves a concoction of lemon roots, banana roots, papaya roots, and barks of Jatropha prunifolia (Abrus precatorius) etc. It works, but I believe clinic medicine is better; the only problem is the whole world will know you had an STI… ha ha ha… it's embarrassing." (Chongwe FGD 1)

(e3.3) "For spiritual purging, ghost cleansing, business boosts, etc., the charge is around $120 (K3,000) depending on the witch doctor. Some make lots of money and some have iron sheet roofs, nice bikes and huge solar panels on top." (Kapiri FGD 2)

(h3.4) "Salt (for body wash) and vinegar (for drinking) are sometimes also used for spiritual cleansing. The charge for salt is about $1 (K25), while vinegar goes for around $2.50 (K65), but these can only be sourced from the witch doctor and not from shops." (Mkushi FGD 1)

(e3.5) "I use some local remedies to treat illnesses, but I don't trust these witch doctors. They are just tricksters and thieves who prey on desperate people and have caused many to die. They claim to heal any disease, including cancer and HIV... in some cases some people have even stopped taking ARVs…they have led to a lot of deaths." (Mkushi FGD 1)

(e3.6) "The medicines found in hospitals are just purified versions of the God given medicinal plants and roots which freely surround us. There are several trees that have medicinal properties, such as the 'Chibangalume' (Zanha africana) tree bark used to treat headaches and colds, 'Umunsokansoka' (Cassia abbreviata) used to treat stomach pains and malaria, guava leaves used to treat diarrhoea, and avocado roots used to boost blood levels, etc." (Mkushi FGD 2)

Appendix B. RUDSHAM framework attributes description

Below is a description of how each attribute of the RUDSHAM framework helped to inform the study:

B.1. Perceived ease (PE)

Encompasses the ease of installation, use, maintenance, and access to experts for support. PE helped assess the ease of installing, maintaining, and accessing technical support for solar PV systems in Zambia. Data on rural households' experiences with technical challenges, usability, and maintenance frequencies was gathered to evaluate the systems' practicality in remote settings.

B.2. Perceived usefulness (PU)

Factors include the technology's dependability, reliability, energy security, improvement over existing power sources, and productive use. PU guided data collection on solar PV's reliability, energy security, and economic productivity. For rural Zambian households, data on how solar PV systems improve livelihoods - such as supporting small businesses, agriculture, or reducing dependency on unreliable grid power - provided insight into its overall usefulness.

B.3. Norms (NO)

Compatibility with social norms, household norms, social acceptability, and the influence of people's opinions and experiences. NO assisted in capturing data on social and household energy use norms and the influence of peer networks on solar PV adoption. Surveys assessed how societal acceptance and household attitudes toward solar PV align with cultural expectations and neighbour experiences, influencing adoption decisions.

B.4. Perceived behaviour control (PBC)

The availability of return warranties, choice in configuration, guarantees, and the freedom and ability to choose to buy. PBC directed data extraction on consumer confidence in purchasing solar PV systems. Information on the availability of warranties, flexibility in system configurations, and rural households' freedom to choose specific systems helped assess how these factors influence adoption rates and behaviour.

B.5. Policy support (PS)

Includes incentives, subsidies, government support, alignment with UNSDGs, support from solar PV suppliers, and effective communication. PS aided in collecting data on government policies, subsidies, and solar suppliers' roles. In Zambia, insights into policy alignment with SDGs, the presence of subsidies, and communication efforts by suppliers revealed barriers and facilitators to widespread solar PV adoption in rural areas.

B.6. Economic cost (EC)

The price of solar PV systems and its impact on the decision to buy (adopt solar PV) and overall energy expenditure. EC focused on gathering data regarding the costs associated with solar PV systems and their influence on energy expenditure. Surveying rural households' affordability perceptions, financing options, income generating activities and energy savings after adoption provided a clear picture of economic viability in Zambia.

B.7. Community participation (CoP)

The extent of community ownership and involvement in designing, financing, and maintaining solar PV systems, as well as supplier engagement. CoP emphasized collecting data on community involvement in solar PV projects. Information on community-led design, financing, and system maintenance, as well as the role of local suppliers, was essential to understanding the sustainability and long-term success of solar PV systems.

B.8. Prior preferences and practice (PP)

Current energy practices, preferences, key uses of energy, reasons for these preferences, and expectations. PP guided data on previous energy practices, like using biomass or kerosene, and the motivations behind these preferences. The related challenges were also explored. Understanding these historical patterns was vital in identifying the hurdles to transitioning to solar PV, as well as households' energy expectations.

B.9. Green concern (GC)

Environmental concern and awareness of the impact at individual, household, and community levels. Deals with sustainability aspects connected to various practices and income generating activities. GC facilitated data collection on environmental awareness at both the household and community levels. The surveys gauged the degree of environmental concern and impact among rural Zambian households, particularly regarding deforestation and carbon emissions, motivating a shift toward solar PV.

B.10. Financial models of relevance (FMR)

Comparison of current finance practices with other relevant solar PV financial models globally and their applicability in the developing world context. Sources of finance for adopting/upgrading solar PV systems. FMR assisted in extracting data on financing methods for solar PV adoption, comparing global models to local practices. Gathering information on microfinance, community savings schemes, or pay-as-you-go systems helped assess their suitability for expanding solar PV in rural Zambia.

Appendix C. Detailed literature review

C.1. Mopane worms (imbresia belina)

Mopane worms (Imbresia belina) represent a crucial income and nutritional resource for rural communities across sub-Saharan Africa, significantly enhancing household livelihoods and food security (Makhado et al., 2014; Sekonya et al., 2020). These edible caterpillars, rich in protein (up to 65 %), are increasingly traded in local and regional markets, driven by rising urban demand and limited alternative income sources in rural areas (Hlongwane, Slotow and Munyai, 2021; Nemadodzi et al., 2023). Particularly, women and unemployed individuals play essential roles in the harvesting and commercialization of mopane worms, which serve as a vital source of financial support and employment (Hlongwane, Slotow and Munyai, 2021; Togarepi et al., 2020). In rural Zambia and other southern African nations, mopane worms are not only a dietary staple but also a significant economic driver, with an estimated annual harvest of 9.5 billion caterpillars from mopane forests (D'Souza & Govender, 2019).

Despite their economic advantages, the commercialization of mopane worms poses serious threats to environmental sustainability and

food security. Climate change, coupled with human-induced factors such as overharvesting and land clearing, has led to significant declines in mopane worm populations (Sekonya et al., 2020). In areas with weak governance, particularly in communally managed lands, unsustainable harvesting practices further exacerbate this issue (Sekonya et al., 2020; Togarepi et al., 2020). Projections indicate that up to 70 % of mopane worm habitats may vanish by the 2080s, particularly in Botswana and Zimbabwe (Shen et al., 2023). This decline not only threatens food security but also amplifies socio-economic disparities in rural communities reliant on mopane worms for their livelihoods (Ndlovu et al., 2019; Shen et al., 2023). Thus, while mopane worm trading remains an essential income source, it underscores the urgent need for sustainable management practices to ensure long-term viability and community resilience.

C.2. Wild mushroom

In rural sub-Saharan Africa, wild mushroom harvesting serves as an important livelihood activity, contributing to both income generation and food security. With approximately 25 % of global mushroom biodiversity, the region holds significant potential for economic development, offering 480 edible species, including those with high commercial value like Amanita loosii (Sileshi et al., 2023). For example, in Zimbabwe, the price of Amanita loosii ranges between US$0.10 to US $1.00 per liter, illustrating its economic relevance (Mlambo & Maphosa, 2017).

In Zambia, wild mushroom collection plays a particularly crucial role in supporting rural livelihoods. Mushrooms are widely foraged, providing a key dietary supplement and enhancing food security (Steel et al., 2022). Zambia's abundant forest cover, which accounts for about 60 % of its land area, creates a favourable environment for wild mushroom foraging (Rookmaaker, 2020). However, despite this abundance, forest degradation poses a significant threat to sustainable mushroom harvesting (Steel et al., 2022).

The commercialization of wild mushrooms in sub-Saharan Africa, including Zambia, comes with ecological and socioeconomic challenges. Unsustainable harvesting practices threaten biodiversity and forest ecosystems (Sileshi et al., 2023). High collection volumes, like the 800 l of Amanita loosii gathered in Zimbabwe, underscore the risk of overexploitation (Mlambo & Maphosa, 2017). In Zambia, the sale of wild mushrooms is largely unregulated, with inadequate institutional support exacerbating the risk of environmental degradation (Anyango et al., 2018). This commercialization mirrors challenges faced with other foraged foods, such as the overharvesting of lusala (Zulu et al., 2019). Furthermore, increased demand for wild mushrooms can disrupt ecosystem services essential for maintaining soil health and biodiversity (Xu & Sakai, 2024), while contributing to land tenure conflicts in rural communities (Mwamba, 2024).

C.3. Ethnomedicine

The integration of ethnomedicine and Non-Timber Forest Products (NTFPs) plays a pivotal role in the socio-economic fabric of rural sub-Saharan Africa, particularly in Zambia. These traditional practices provide essential healthcare services and contribute significantly to local economies. Ethnomedicine is especially critical in areas with limited access to formal healthcare, where traditional remedies serve as a primary health resource (Boukandou Mounanga et al., 2015; Eiki et al., 2021). The practice is comprehensive, extending to ethnoveterinary applications for livestock management (Eiki et al., 2021). In the context of HIV/AIDS care, over 74 plant species have been identified for the treatment of related conditions, emphasizing the broad therapeutic scope of traditional medicine (Maroyi, 2014).

In Zambia, about 70 % of the population relies on traditional medicinal practices, utilizing diverse plant species for various ailments (Akapelwa Muyenga et al., 2018; Nyirenda & Chipuwa, 2024). This reliance extends beyond healthcare to economic activities, such as mushroom farming, which offers both medicinal and culinary benefits (Mweemba, 2020). NTFPs, including wild plants like lusala (Dioscorea hirtiflora), are vital for household incomes and food security, yet these practices face challenges of overexploitation and improper harvesting, threatening resource sustainability (Eiki et al., 2021; Zulu et al., 2019).

The commercialization of ethnomedicinal products and NTFPs can significantly enhance rural incomes, with some households deriving up to 58 % of their annual income from these activities (Timmermann & Smith-Hall, 2019). However, this income generation is often marred by sustainability issues. Unregulated harvesting practices can deplete wild populations, leading to environmental degradation and loss of biodiversity (Meke et al., 2017; Sher et al., 2014). This is particularly concerning for Zambia, where traditional practices like the collection of wild edibles are crucial for livelihoods but are threatened by resource depletion (Zulu et al., 2019).

The complex commercialization process involves multiple stakeholders, such as middlemen and exporters, which can hinder equitable income distribution (Sher et al., 2014). Additionally, collectors often lack training in sustainable practices, resulting in poor quality control and diminished market opportunities (Mofokeng et al., 2022; Sher et al., 2014). Moreover, the environmental impact of these practices is substantial, with unsustainable harvesting contributing to ecosystem degradation (Murye & Pelser, 2018). While the economic benefits of NTFPs and ethnomedicine are evident, their long-term viability depends on improved management practices, sustainable harvesting methods, and the integration of traditional knowledge into conservation policies (Eiki et al., 2021; Fandohan et al., 2017). Addressing these challenges is critical for balancing income generation with environmental stewardship, ensuring that rural communities in Zambia and across sub-Saharan Africa can continue to benefit from these valuable resources.

C.4. Witch doctor practice

The practice of witchcraft and traditional healing in rural Sub-Saharan Africa, including Zambia, plays a significant socio-economic role by filling critical gaps in healthcare services and providing an income source for practitioners. In regions where modern medical facilities are scarce, healers leverage indigenous knowledge to address various ailments, often receiving payment in cash or kind for their services (Boukandou Mounanga et al., 2015; Eiki et al., 2021; Nyirenda & Chipuwa, 2024). This traditional form of medicine is culturally significant and is considered a vital element of community life (Boukandou Mounanga et al., 2015; Quiroz, 2015).

However, the economic activities associated with witch doctor practices also bring about negative social and political consequences. The belief in witchcraft can disrupt social cohesion and community cooperation, contributing to economic stagnation by fostering a perception of wealth as a finite resource, which can stifle innovation (Gershman, 2016; Leistner, 2014). These beliefs have been shown to undermine trust in democratic institutions, as some communities view governance through a mystical lens, which further impedes social development (Adolfsson et al., 2024).

In Zambia, the harmful effects of these practices are highlighted by extreme manifestations, such as the ritual killings of individuals with albinism. Superstitions surrounding albinism create demand for body parts, which are believed to hold magical properties, thus leading to violence and fear in affected communities (Aquaron et al., 2009; Mwiba, 2018). The consequences of such practices extend beyond immediate violence, damaging community cohesion and eroding trust in local authorities (Cruz-Inigo et al., 2011). These cycles of violence exacerbate social exclusion and deepen poverty in already vulnerable communities (De Jong, 2015; Steyn, 2022). Therefore, while witch doctor practices provide income opportunities, they also perpetuate social instability, impeding broader economic development and well-being in rural Sub-Saharan Africa.

C.5. Wild fishing

Wild fishing is a vital source of income and food security for rural communities in sub-Saharan Africa, playing an indispensable role in economic sustenance and nutrition (Gondwe et al., 2023; Temesgen et al., 2019). In Zambia, the reliance on small-scale fisheries is pronounced, particularly in regions like Luapula province, where fish constitutes a dietary staple (Marinda et al., 2023). Despite its importance, challenges such as low fish catches and seasonally enforced fishing bans significantly limit the sector's contribution to sustainable livelihoods (Kapembwa, Gardiner and Pétursson, 2021). Furthermore, nearly all rural households engage in the collection of wild foods including fish, highlighting their dependence on natural resources (Steel et al., 2022).

While wild fishing contributes to poverty alleviation and food security, it faces considerable sustainability issues. Overfishing, inadequate infrastructure, and limited access to credit undermine long-term viability, exacerbated by climate change (Muzari & Muzari, 2013; Temesgen et al., 2019). Additionally, the role of women in fisheries remains largely unrecognized in national statistics, impeding their access to necessary resources and markets (Muzari & Muzari, 2013).

In Zambia, commercialization of wild fishing brings adverse environmental and social consequences. Overfishing in ecosystems like the Zambezi River has led to a decline in fish stocks and the use of ecologically damaging methods (Tweddle et al., 2015) such water poisoning, use of explosives and mosquito nets. The unequal distribution of economic benefits further marginalizes poorer households, while poaching exacerbates biodiversity loss and ecosystem disruption (W. D. Sakala & Moyo, 2017). Unfortunately, dietary diversity remains low among children in fishing communities, with only 23 % meeting minimum dietary requirements (Marinda et al., 2023).

C.6. Bushmeat

Bushmeat is integral to the livelihoods of rural communities in sub-Saharan Africa, providing both a vital source of protein and an important income-generating commodity. In countries like Ghana, the demand for bushmeat correlates strongly with income levels, with a trade network that includes subsistence hunters and commercial operators supplying local markets (Kouassi et al., 2019; McNamara et al., 2019). This trade becomes crucial during food scarcity, offering a fallback for communities with limited access to alternative resources (Stone & Stone, 2022). In Zambia, bushmeat serves a dual purpose as a food resource and significant income generator, with sport hunting operations distributing over 129,000 kg of game meat annually, valued at US$600,000, thus supporting local populations during critical periods (White & Belant, 2015).

Despite its economic significance, the bushmeat trade has profound ecological and health implications. The exploitation of bushmeat, particularly in areas near protected habitats, threatens wildlife populations, contributing to species depletion and diminished biodiversity (Che et al., 2017; Gonçalves et al., 2019; Manyama et al., 2019). Additionally, the bushmeat market has been associated with the spread of zoonotic diseases, including Ebola and HIV (Kurpiers et al., 2015). In Zambia, economic dependence on bushmeat commercialization exacerbates pressures on local ecosystems, driven by poverty and the lack of alternative livelihoods (M. Sakala, 2016). Therefore, while bushmeat trade bolsters rural economies, it raises critical concerns regarding sustainability and public health, necessitating comprehensive policy interventions to mitigate its adverse impacts.

Appendix D. Operationalization steps of RUDSHAM (policy makers and implementors guide)

Below is a structured RUDSHAM WHEEL framework for practical implementation with the points rearranged in a logical sequence for solar PV implementation projects in rural Zambia. This rearrangement starts with foundational elements like policy support and economic considerations, followed by financial models and community participation. It then addresses social norms and perceived behavior control, ensuring that technological and practical aspects are thoroughly understood and simplified. Finally, it considers prior preferences and environmental concerns, ensuring a comprehensive approach to implementing solar PV projects. Only a score of 100 % and total interconstruct interaction analysis at each stage would be desirable to increase chances of project acceptance, social influence and success. It is termed wheel because the process needs to be ongoing.

1. Policy Support (PS)

   - o Review government incentives.
   - o Assess subsidy impacts.
   - o Evaluate supplier support.
   - o Communicate policy benefits.
   - o Facilitate external support.

2. Economic Cost (EC)

   - o Analyze upfront costs.
   - o Assess household budget impact.
   - o Compare traditional energy costs.
   - o Identify financial barriers.
   - o Propose cost-effective solutions.

3. Financial Models of Relevance (FMR)

   - o Compare local finance practices.
   - o Analyze global solar PV models.
   - o Assess financial model impacts.
   - o Identify applicable approaches.
   - o Propose sustainable finance options.

4. Community Participation (CoP)

   - o Encourage design involvement.
   - o Promote community financing.
   - o Facilitate maintenance roles.
   - o Foster collective ownership.
   - o Assess participation levels.

5. Norms (NO)

   - o Identify influential community members.
   - o Observe social learning patterns.
   - o Assess peer influence on adoption.
   - o Promote key opinion leaders.
   - o Leverage household norms.

6. Perceived Behavior Control (PBC)

   - o Survey purchase decision control.
   - o Evaluate warranty availability.
   - o Analyze configuration options.
   - o Measure autonomy perceptions.
   - o Address control-related barriers.

7. Perceived Ease (PE)

   - o Survey ease of installation.
   - o Collect feedback on usability.
   - o Identify maintenance challenges.
   - o Analyze responses for complexity barriers.

- o Simplify technological aspects.

8. Perceived Usefulness (PU)

- o Gather community feedback on benefits.
- o Assess reliability perceptions.
- o Evaluate energy security benefits.
- o Measure practical advantages.
- o Link benefits to community trust.

9. Prior Preferences and Practice (PP)

- o Survey existing energy practices.
- o Identify key energy uses.
- o Measure potential shift.
- o Compare with solar PV options.
- o Understand historical preferences.

10. Green Concern (GC)

- o Assess individual environmental awareness.
- o Evaluate household green practices.
- o Measure community concern levels.
- o Link motivations to solar PV.
- o Promote environmental benefits.

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