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Published Version

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Chanda, H., Mohareb, E. ORCID: <https://orcid.org/0000-0003-0344-2253>, Peters, M. ORCID: <https://orcid.org/0000-0002-4324-6559>, Harty, C., Green, M., Shibata, N. and Kasanda, E. B. (2025) The African clean energy-deforestation paradox: examining the sustainability trade-offs of rural solar energy expansion in Zambia. *Energy Research & Social Science*, 129. 104389. ISSN 2214-6326 doi: [10.1016/j.erss.2025.104389](https://doi.org/10.1016/j.erss.2025.104389) Available at <https://centaur.reading.ac.uk/125271/>

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To link to this article DOI: <http://dx.doi.org/10.1016/j.erss.2025.104389>

Publisher: Elsevier

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Original research article

“The African clean energy-deforestation paradox: Examining the sustainability trade-offs of rural solar energy expansion in Zambia”

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ARTICLE INFO

Keywords:

Solar PV adoption
Clean energy-deforestation paradox
Sustainability trade-offs
Rural environmental sustainability
Renewable energy financing
SSA rural energy access

ABSTRACT

Clean energy programmes increasingly promote solar in rural Africa to expand electricity access and reduce emissions. However, little is known about how off-grid households finance these systems or whether their financing pathways create new environmental challenges. This article examines the clean energy deforestation paradox in Zambia, where the adoption of solar photovoltaic technologies is partly financed through forest-based income. Over a 28-months period, a multi-sited qualitative study was conducted in four rural districts involving 80 interviews and several focus group discussions. Findings were analysed thematically and complemented by geospatial analysis of forest loss from 2001 to 2023 to estimate associated carbon stock reductions and foregone sequestration. Interviewees identified key drivers of forest loss such as charcoal production, timber extraction, firewood collection and agricultural expansion, alongside more subtle activities including firewood for funerals, hunting access, bark and medicinal harvests, honey collection and mopani worm gathering. Many households reported using income from these activities to purchase solar-lighting kits and phone-charging systems in the absence of affordable credit or subsidies. The policy review revealed fragmented governance, where solar programmes seldom consider financing mechanisms while forest initiatives overlook rural energy needs. The study makes two main contributions. First, it provides empirical evidence that clean energy adoption can be linked to environmentally damaging financing strategies. Second, it offers a combined social and biophysical assessment that connects household behaviour to carbon outcomes. The study concludes by proposing integrated policies, forest-sensitive solar subsidies, sustainable livelihood options, stronger local enforcement and targeted education to align energy access with environmental conservation.

1. Introduction

1.1. Background

Sub-Saharan Africa (SSA) remains one of the most energy-deprived regions globally, with over 600 million people lacking access to electricity [1,2]. This persistent energy poverty has spurred growing international and domestic interest in clean, decentralised solutions such as solar photovoltaic (PV) systems. Solar PV technology is increasingly seen as a viable tool for achieving the twin goals of expanding energy access and reducing carbon emissions [3,4]. Across SSA, innovations

such as pay-as-you-go (PAYG) systems and mobile-enabled smart metering have supported the uptake of pico and small-scale PV solutions, particularly in rural areas where extending the national grid is economically and logistically challenging [3]. This decentralised model holds particular promise in countries like Zambia, where only 25 % of the population, and less than 6 % of rural households have electricity access [5–8]. However, this optimistic narrative is often accompanied by significant challenges. High upfront costs, inadequate infrastructure, technical skill shortages, and system maintenance issues have slowed progress and limited solar PV's full potential [1]. While the clean energy transition is vital, its success hinges on deeper understanding of the

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<https://doi.org/10.1016/j.erss.2025.104389>

Received 15 June 2025; Received in revised form 5 October 2025; Accepted 8 October 2025

Available online 16 October 2025

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social, economic, and environmental dynamics at play - particularly in rural contexts.

1.2. The deforestation - solar Nexus in Zambia

Globally, deforestation has reached alarming levels, with an estimated 1.5 billion hectares of forest cover lost over the past 300 years [9]. In particular, SSA remains vulnerable, recording deforestation rates higher than the global average [10,11]. According to the Food and Agriculture Organization, the world loses about 13 million hectares of forest annually, with Africa accounting for a significant portion of this decline [11]. Despite this urgency, the drivers of deforestation in SSA remain contested, as factors such as population density, rural poverty, and industrial logging do not consistently explain forest loss across the region [10]. Zambia provides a particularly complex and instructive case within SSA. The country experienced a 10 % reduction in forest area and a 25 % increase in cropland between 2000 and 2018, reflecting ongoing tension between environmental conservation and rural livelihoods [12]. Charcoal production is a primary deforestation driver, constituting a key income source for many rural households [13,14]. Likewise, subsistence agriculture - especially shifting cultivation - continues to cause widespread forest clearance [15,16]. Less visible yet ecologically consequential practices also contribute to forest degradation, though they often remain unaccounted for in official assessments [17–19]. While many of these practices have historically sustained rural economies, their role in enabling access to modern energy introduces a complex sustainability dilemma. Crucially, many of these forest-based economic activities seem to be linked to the funding of solar PV installations [7,20–23]. In the absence of accessible credit or subsidies, rural households often resort to charcoal sales, timber extraction, or non-timber forest product (NTFP) collection to raise the funds needed to purchase solar lighting systems or mobile charging kits. Thus, in a paradoxical twist, clean energy adoption is inadvertently accelerating environmental degradation, a phenomenon this study refers to as the “Clean Energy - Deforestation Paradox.”

1.3. Policy gaps and missed synergies

Zambia's national policy frameworks have not adequately addressed this paradox. Energy and environmental policies are developed in silos, leading to fragmented implementation [24–26]. Energy policies typically focus on expanding solar PV access without considering how rural communities finance such technologies [27,28]. Likewise, forest conservation programmes, such as REDD+, rarely factor in the energy demands of rural households, despite their heavy dependence on forests for both income and domestic energy [29]. This disconnection results in missed synergies. For instance, rural electrification policies in Zambia lack integrated financing models tailored to low-income, forest-dependent communities [6]. Public-private partnerships and donor-funded interventions have made some progress but often fail to reach the poorest, who remain excluded from sustainable energy access while continuing to rely on unsustainable income strategies. In effect, Zambia and by extension much of SSA, is facing a sustainability paradox. Renewable energy adoption is promoted as a climate solution, yet its uptake, in the absence of inclusive financing and integrated policy, is contributing to forest loss and environmental degradation.

1.4. Research problem and aim

This study seeks to critically examine the sustainability trade-offs of rural solar PV expansion in Zambia. While solar PV is globally recognised as a clean technology, its financing mechanisms in rural Zambia have yet to be scrutinised for their potential environmental costs. The central research problem focuses on the possibility that some rural households finance solar PV systems through income derived from deforestation related activities. The primary aim is to examine how such

income contributes to solar adoption and to reflect on the broader sustainability implications of this financing model.

1.5. Research objectives

To achieve this aim, the study sets out the following objectives:

- To identify both major and minor drivers of deforestation in rural Zambia, including under-researched practices.
- To examine the financing strategies employed by rural households to acquire solar PV systems, with a focus on forest-based income streams.
- To examine the socio-environmental trade-offs of solar adoption, particularly where renewable energy transitions may inadvertently rely on harmful environmental practices.
- To propose policy recommendations that support clean energy transitions in a manner that is both environmentally sustainable and socially just.

1.6. Research questions

This study seeks to address the following research questions:

- What are the main, and often overlooked, drivers of deforestation within rural Zambia?
- What financing mechanisms are respondents using to adopt solar PV systems?
- To what extent, and in what ways, might this financing depend on forest exploitation?
- What policy interventions are required to mitigate potential tensions between clean energy access and environmental sustainability?

1.7. Study gaps and contribution

Most existing literature on deforestation in Zambia has focused on large-scale drivers, such as commercial agriculture and logging [13,15,16]. Similarly, studies on solar PV tend to highlight its climate mitigation benefits, without examining the financial behaviours enabling uptake among rural users [3,30]. This study contributes to bridging these gaps by offering a multi-dimensional perspective that links rural energy transitions with forest exploitation at the household level. It is among the first to interrogate the social and environmental costs of grassroots clean energy adoption, focusing specifically on the micro-economies that underpin solar PV expansion in off-grid communities. In doing so, it builds on but also critiques the current sustainability discourse, arguing that focusing solely on end-use outcomes (i.e., cleaner energy) risks overlooking the damaging processes through which those outcomes are achieved.

1.8. Why a holistic approach is necessary

Sustainability cannot be judged solely by outcomes. It must consider the entire lifecycle and context of technological adoption. A solar lantern that displaces kerosene is undoubtedly a cleaner alternative - but if it is financed through charcoal production or unsustainable harvesting of forest bark, its net sustainability becomes questionable. Forest degradation contributes to biodiversity loss, microclimate changes, and diminished ecosystem services - all of which negatively affect the very rural communities these technologies aim to serve [31,32]. Moreover, the decline in forest cover undermines agricultural productivity, increases fire risks, and diminishes rainfall - thus compounding the vulnerabilities of already marginalised populations [33]. By drawing attention to these interconnected challenges, this study promotes a holistic and integrated framework for evaluating sustainable energy transitions. It highlights the urgent need to reconcile the goals of energy access and environmental conservation. It reveals a largely overlooked

trade-off in rural Zambia's clean energy story.

2. Literature review

2.1. Deforestation and ecological stability

Environmental degradation continues to threaten ecosystem stability across SSA, with Zambia's Miombo woodlands standing out as particularly vulnerable [34]. As climate variability intensifies, trophic interactions within ecosystems are increasingly destabilized, triggering cascading effects such as biodiversity loss and habitat fragmentation [35]. These ecological disturbances signal the need for integrative development strategies that consider long-term sustainability and resilience rather than short-term economic gains. Deforestation in Zambia exemplifies such anthropogenic pressure. The country is losing an estimated 250,000 to 300,000 ha of forest annually [36]. Between 2001 and 2023, Zambia lost 2.44 million hectares of tree cover, resulting in over 911 Mt. of CO₂ emissions [37]. These changes are not only detrimental to biodiversity but also compromise soil structure, water cycles, and climate stability.

2.2. Fertiliser use and agricultural practices

A critical but often overlooked environmental pressure in Zambia is the widespread use of chemical fertilizers. While these inputs have been vital in addressing food security by boosting crop yields [38], their adverse effects on soil and water systems are well-documented [39,40]. Excessive nitrogen application contributes to greenhouse gas emissions, acidification, and the loss of soil organic matter [41,42]. Moreover, smallholder farmers in Zambia frequently prioritise immediate returns over environmental sustainability, continuing to rely on synthetic fertilizers even when aware of the risks [43]. This illustrates a broader trend where short-term adaptation strategies are adopted at the expense of long-term ecosystem resilience.

2.3. Forest loss and underlying drivers

Deforestation in Zambia is shaped by both direct and structural factors. Agricultural expansion, especially shifting cultivation, remains the dominant driver [13]. Smallholder farmers alone account for approximately 60 % of forest loss [15]. Notably, the Jevons Paradox appears more applicable than the Borlaug hypothesis in this context, as yield-enhancing technologies are correlated with further land conversion rather than conservation [44]. Charcoal production and timber harvesting are also substantial contributors to forest degradation [45,46]. The extraction of valuable tree species, such as Mukula and Zambezi Teak, for international trade is often facilitated by weak legal enforcement and institutional corruption [47]. Compounding these pressures are subtle yet significant drivers like bark stripping for medicinal use, artisanal wood harvesting, and small-scale clearing for fencing or firewood - all of which contribute to forest degradation but are largely invisible in conventional land-use data [17,18].

2.4. Biomass energy contradictions and dependency

Despite advancements in solar energy technologies, Zambia remains overwhelmingly dependent on biomass for household energy. In rural areas, 81.9 % of households use firewood, and 13.2 % use charcoal; in urban settings, 73 % of households rely on charcoal [48]. Traditional earth kilns, widely used in charcoal production, consume around eight tonnes of wood to produce just 1.3 t of charcoal. In contrast, steel kilns can achieve conversion efficiencies of approximately 2.4:1 [49], more than double that of earth kilns. This highlights the significant inefficiency and severe ecological costs associated with traditional methods [45]. Paradoxically, income generated from the sale of charcoal and other forest products is often used to finance solar PV systems -

technologies promoted precisely to mitigate the environmental damage these income streams exacerbate. This contradiction highlights a complex interplay between clean energy adoption and environmental harm, reinforcing the notion of a clean energy - deforestation paradox [50].

2.5. Ecological and public health effects

Deforestation's impacts go beyond carbon emissions and biodiversity loss. In Zambia's Kamfinsa sub-catchment, forest area declined from 13,430.5 ha in 1990 to just 2904.7 ha in 2010, leading to soil erosion and carbon emissions valued at over US\$300 per hectare annually [51]. Disruptions to ecosystem services such as pollination, seed dispersal, and water retention further threaten agricultural and ecological stability [52]. Moreover, forest degradation is increasingly linked to public health crises. In Sub-Saharan Africa, deforestation has been correlated with elevated malaria prevalence, especially among children in poorer households [53]. The disruption of forest habitats influences the breeding conditions for malaria vectors, exacerbating health inequalities and creating additional socio-economic burdens.

2.6. Governance failures and policy fragmentation

Zambia's deforestation crisis is intensified by weak governance and disjointed policy frameworks. Despite legal reforms such as the Forest Act No. 4 of 2015, enforcement remains sporadic and under resourced [54,55]. REDD+ initiatives, although promising, often operate within private tenure systems that exclude community voices and fail to address local needs [56]. These shortcomings are compounded by corruption, which undermines transparency and accountability in forest resource management [57]. Sectoral silos further weaken efforts to address deforestation. Energy policies seldom integrate forest conservation priorities, while forestry policies neglect the energy demands of rural populations [29]. As a result, clean energy interventions risk reproducing environmental injustices if not embedded within cross-sectoral sustainability frameworks.

2.7. Broader socioeconomic trade-offs beyond forests

Forest loss in Zambia is closely intertwined with poverty, inequality, and livelihood insecurity. Forests provide critical resources such as honey, mushrooms, caterpillars, and construction materials [7,23,51,58]. Their degradation, therefore, has cascading effects on nutrition, health, and income stability [59]. At a macro level, deforestation contributes to shifts in microclimates, reduced rainfall, and declining agricultural productivity, all of which jeopardise sectors like hydroelectricity and tourism [15,60]. Moreover, education, gender, and tenure status significantly influence forest dependency, with poorer and less educated households being more vulnerable to the consequences of forest degradation [61].

2.8. Integrated and equitable transition pathways

The reviewed literature converges on a clear conclusion: addressing Zambia's deforestation crisis requires more than technological fixes or conservation rhetoric. A truly sustainable energy transition must incorporate integrated policies that align forest conservation with rural development and clean energy access [61,62]. The clean energy - deforestation paradox serves as a cautionary tale for SSA's broader sustainability trajectory. Without targeted interventions that address both immediate livelihood needs and long-term ecological goals, the promise of solar PV and other clean technologies risks being undermined by the very environmental degradation they are intended to avert.

3. Theoretical framework

To investigate the sustainability trade-offs of rural solar photovoltaic

(PV) expansion in Zambia, this study adopts the Rural Development Stakeholder Hybrid Adoption Model (RUDSHAM) [2,7,23,63] (see Fig. 1). RUDSHAM provides an integrated, multi-theoretical lens to explore how rural communities navigate the competing imperatives of environmental conservation, energy access, and economic survival, especially within the paradox of unsustainably using forest resources to finance clean energy adoption.

RUDSHAM blends individual behavioural theories with structural and environmental insights, making it particularly suited for examining the Clean Energy - Deforestation Paradox. Central to the model are three foundational theories: the Technology Acceptance Model (TAM) [64,65], Diffusion of Innovations (DOI) [66,67], and the Theory of Planned Behaviour (TPB) [68]. Through TAM, it can be demonstrated how rural households weigh the perceived usefulness and affordability of solar PV systems, often prioritising short-term economic gains, such as lighting and phone charging, over long-term sustainability. Using DOI offers insight into how solar technologies spread within communities,

highlighting the role of early adopters and local innovation networks. Meanwhile TPB, captures the behavioural intentions behind fuel choice and technology uptake, focusing on attitudes, social pressures, and perceived constraints.

Crucially, RUDSHAM incorporates Social Learning Theory (SLT) [69] to contextualise energy decisions within communal norms and peer influence. In rural Zambia, where resource scarcity and poverty dominate, energy choices are not made in isolation but are informed by the visible practices of neighbours and kin. For instance, a household that adopts a basic PV system using income from charcoal sales may inspire others to do the same - thus perpetuating deforestation while simultaneously advancing electrification.

Moreover, RUDSHAM is unique in embedding policy, economic, and environmental variables into its framework. This allows the model to go beyond household decision-making to assess broader governance and market structures that shape energy transitions. In the Zambian context, where institutional capacity is weak and energy-financing mechanisms

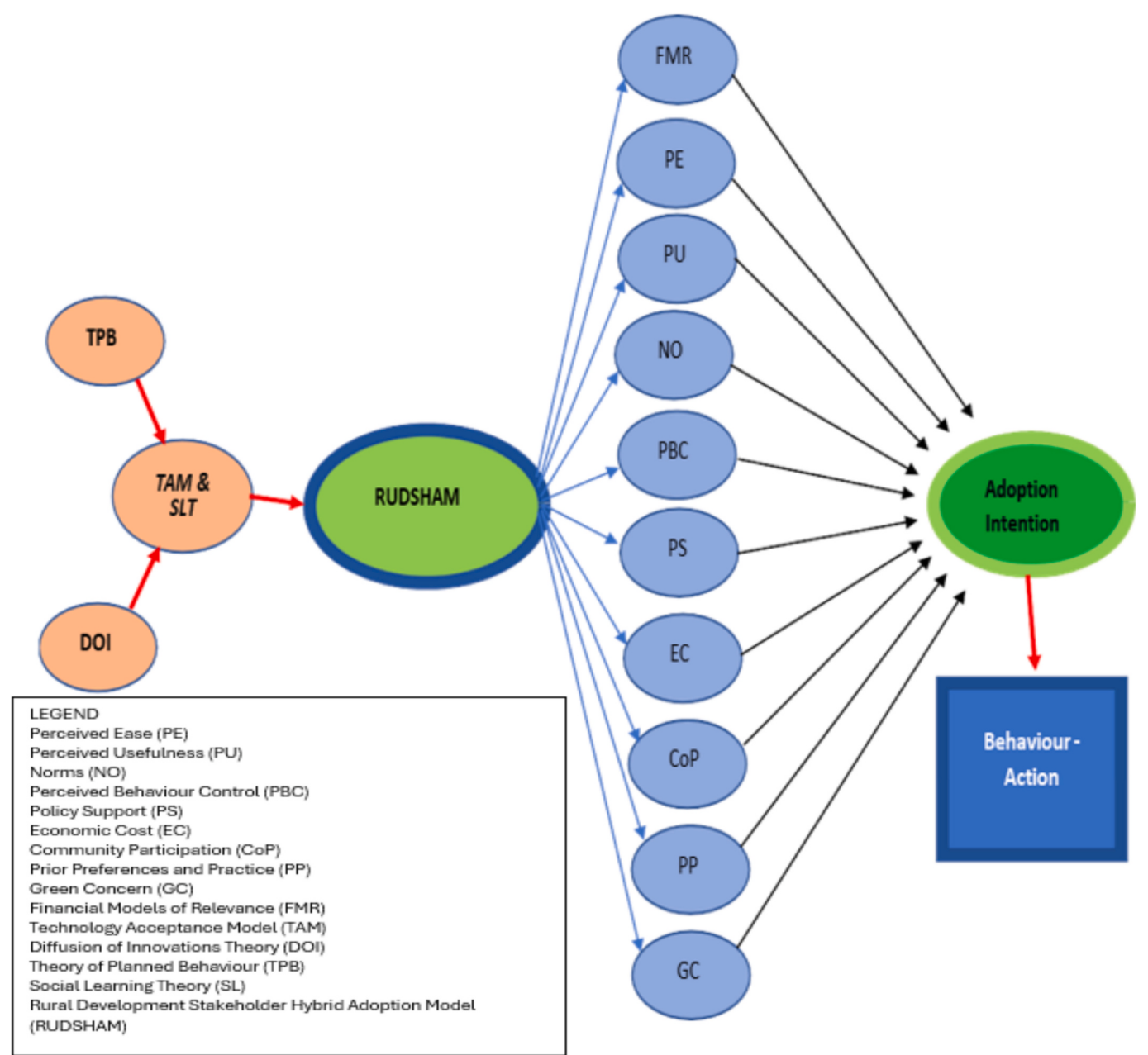


Fig. 1. RUDSHAM Hybrid Adoption Model.

are scarce, RUDSHAM helps reveal how policy gaps intersect with grassroots behaviours, fuelling unintended consequences such as forest degradation to fund clean energy purchases.

By embedding household-level solar PV adoption within broader socio-economic and environmental systems, the RUDSHAM model enables a comprehensive analysis of the clean energy - deforestation paradox. While solar technologies offer environmental gains, their uptake, when financed through forest exploitation, may inadvertently compromise sustainability goals. Applied to Zambia, RUDSHAM integrates technological, behavioural, and policy dimensions, offering valuable insights into rural energy transitions. This study employs a mixed-methods approach, including in-depth interviews, focus groups, and observational data, complemented by carbon loss analysis based on remote sensing data. Based on this, the study estimates both carbon stock loss and foregone carbon sequestration linked to distinct categories of forest loss. This research contributes to a more nuanced understanding of rural energy transitions, equipping policymakers with actionable strategies to facilitate a just, sustainable, and economically viable energy transition in the Zambian and Sub-Saharan African contexts. For a detailed breakdown of RUDSHAM's attributes and applications refer to Appendices A and B. These appendices serve as the practical and analytical foundation of this paper. Appendix A outlines the implementation logic through the RUDSHAM Policy Implementation Wheel, offering a sequential guide for policymakers and practitioners. Appendix B provides in-depth descriptions of each attribute, illustrating how they informed data collection, analysis, and interpretation within rural solar PV contexts in Zambia. Together, they bridge theory and application, enabling a comprehensive understanding of social, economic, and behavioural dimensions of energy transitions.

4. Research methodology

This study employs a mixed-methods approach grounded in the RUDSHAM framework [2,7,23,63], to examine the sustainability trade-offs of rural solar PV expansion in Zambia. The research investigates how rural households finance solar PV systems through both major and

subtle forms of forest exploitation, focusing on the implications for environmental sustainability.

4.1. Study design and fieldwork sites

Fieldwork was conducted over a 28-month period (October 2022–February 2025) in four purposively selected rural districts (see Fig. 2): Mkushi Rural and Kapiri Rural (Central Province), Chongwe Rural (Lusaka Province), and Chingola Rural - Luano (Copperbelt Province). These regions were selected for their isolation, lack of grid electricity, and prevalence of charcoal production. A multi-stage, non-probability sampling strategy guided participant selection for focus group discussions (FGDs) and interviews, with charcoal burners, smallholder farmers, commercial farmers, and key stakeholders from the energy and policy sectors forming the primary respondent base.

4.2. Data collection methods

Primary data collection comprised 21 in-depth interviews with full-time charcoal burners, 40 interviews with smallholder farmers, 16 with commercial farmers, and 3 with stakeholders from solar companies and policy institutions. Ten FGDs were conducted across the sites, each with 7–12 participants. Three FGDs were exclusively for charcoal producers. Gender-sensitive strategies - such as separate sessions for men and women - were employed to foster inclusive and balanced dialogue. Facilitators included local leaders and a research assistant fluent in English and several local languages (Bemba, Tonga, Soli, Lamba, and Nyanja), which enhanced participant engagement and data quality (see Appendix C).

4.3. Data analysis framework

Qualitative data from interviews and FGDs were recorded, transcribed, and analysed using NVIVO 14 software. A systematic thematic analysis, structured by RUDSHAM, was conducted to explore linkages between perceived usefulness of solar PV, policy support, community



Fig. 2. Map of Zambia [70].

influence, and the economic drivers behind forest exploitation. Colour coded nodes and NVIVO's advanced querying tools allowed for nuanced identification of behavioural patterns, trade-offs, and socio-environmental dynamics in the clean energy - deforestation paradox. A four-week pilot in Luano refined the instruments, ensuring the validity and reliability of the tools.

4.4. Ethical considerations and data security

Ethical research standards were upheld throughout, with ethical approval provided by the University of Reading's ethics committee prior to data collection. Participants gave informed consent prior to interviews and recordings. All data, including transcripts, photographs, and videos, were securely stored on the University of Reading's One-Drive cloud server with restricted access. Tokens of appreciation and refreshments were provided in recognition of participants' contributions.

4.5. Carbon stock analysis using remote sensing data

To quantify environmental impact, geospatial analysis was conducted using Hansen et al.'s [71] global forest cover dataset (2001–2023), processed in Quantum Geographic Information System (QGIS 3.34). The dataset has a 30-m (900m²/pixel) spatial resolution, which enables precise measurement of forest loss in the four regions. A 10 % canopy threshold was applied to classify forest cover, aligning with standard global forest definitions [72]. Total forest loss areas were further categorized into three carbon-relevant drivers: (i) forest fires, (ii) charcoal and fuelwood, and (iii) timber harvesting.

Forest fire related losses were directly extracted from the Global Forest Loss Due to Fire dataset [73]. The remaining categories were estimated based on established national trends: charcoal and fuelwood are responsible for approximately 90 % of forest loss, while timber harvesting contributes around 3 % [37,47,74–76]. Losses attributable to other minor drivers, such as bark stripping, honey harvesting, or mopane worm collection, were excluded from this analysis due to a lack of reliable quantitative data in the existing literature. This study calculates both immediate carbon emissions and the foregone carbon sequestration potential, depending on the end-use of forest biomass - whether it is combusted through forest fires, converted into fuel sources such as charcoal and firewood, or retained in long-lived wood products like sawn timber.

Based on these assumptions, this study estimates both carbon stock loss and foregone carbon sequestration associated with each category of forest loss (eqs. 1 to 4).

Carbon stock loss (tCO₂) was calculated based on the loss of above-ground biomass (AGB), using the following equations:

- Carbon Stock Loss (tC) = Forest Loss (ha) × AGB × Emission Factor × Carbon Fraction (Eq. 1)
- Carbon Stock Loss (tCO₂) = Carbon Stock Loss (tC) × 3.67 (Eq. 2)

The emission factor varies by category: a combustion factor of 0.50 is applied for forest fire [77]; 1.00 is applied for charcoal and fuelwood, and 0.00 for timber harvesting, assuming that the biomass is retained in long-lived wood products.

AGB is assumed to be 69.6 t/ha, representing the value for tropical dry forests over 20 years old [78]. A carbon fraction of 0.47 is applied to convert biomass to carbon content [78]. Belowground biomass (BGB) is excluded as it does not contribute to immediate emissions and is not combusted or removed during most forest clearance processes.

Future carbon sequestration loss (tCO₂/year) was estimated as the annual amount of carbon that would have been sequestered by the forest if it had not been cleared, using the following equation:

- Future Carbon Sequestration loss (tC/yr) = Forest Loss (ha) × AGB Growth Rate (t/ha/yr) × Carbon Fraction (Eq. 3)
- Future Carbon Sequestration loss (tCO₂/yr) = Future Carbon Sequestration (tC/yr) × 3.67 (Eq. 4)

This calculation was applied consistently across all three categories, assuming a growth rate of 1.6 t/ha/year [77] and a carbon fraction of 0.47.

5. Findings

The findings reveal a complex relationship between solar photovoltaic (PV) adoption and deforestation in rural Zambia, where low-income households frequently rely on forest-based activities to finance clean energy technologies. Charcoal production, forest clearing for agriculture, and unsustainable harvesting of non-timber forest products are common income-generating practices that directly contribute to environmental degradation. While harmful to ecosystems, these practices serve as fallback income streams amid a lack of inclusive energy financing pathways. As such, deforestation is not merely an energy source issue but becomes a financing mechanism for accessing modern energy. This paradox illustrates the unintended ecological consequences embedded within grassroots clean energy transitions in Sub-Saharan Africa. Most households interviewed used small-scale solar home systems (SHSs) ranging from 10 W to 100 W, primarily for basic lighting, phone charging, and powering radios [2]. Many of these systems were acquired through Pay-As-You-Go (PAYG) models facilitated by mobile network operators and solar vendors, while a smaller proportion were purchased outright using lump-sum payments.

5.1. Charcoal production and forest resource depletion

The data in Table 1 suggest that charcoal production is widely perceived by participants as a major contributor to forest depletion in the surveyed area, with harvesters reportedly shifting to small, fruit, and medicinal trees due to dwindling availability of larger species. Economic necessity appears to override sustainable practices, with potential implications for woodland ecosystems.

5.2. Forest degradation and local experiences

The findings in Table 2 reflect a widespread perception of visible environmental degradation in the study areas, particularly in rural zones where deforestation is reported to be more pronounced than in better-managed commercial farming zones. Participants identified multiple actors such as farmers, timber processors, and charcoal burners, as

Table 1
Participant Responses Related to Charcoal Production and Deforestation.

a	Participant	Illustrative Direct Quotation
1	Charcoal Burner FGD 2	"In the past, only mature, good trees that produced the best charcoal were used for charcoal production. But with the shrinkage of forests, we are now forced to use even small trees and sometimes fruit trees."
2	Charcoal Burner FGD 1	"Times are hard, and there is so much demand for charcoal with fewer right trees. Hence, we have been forced to start cutting even useful trees like fruit trees and medicinal trees."
3	Charcoal Burner FGD 1	"Some of the best trees used for charcoal burning are also host trees for mopane worms..."
4	Charcoal Burner FGD 2	"For a 25m ³ kiln, we use a minimum of about 10 trees ranging from around 7 m in height and above. For very big trees, it might take just a few to make a kiln, but they tend to be more expensive if you are buying them."
5	Charcoal Burner FGD 1	"The cost of buying about 10 trees for one kiln of 25m ³ is around K500 (\$20), and the cost of a single tree averages around K100 (\$4 US), which is used for various purposes, including traditional timber processing."

Table 2
Forest Degradation and Local Observations.

b	Participant	Illustrative Direct Quotation
1	Commercial Farmer Interview 3	"I own some planes, and I have been flying between Lusaka and Mkushi, and gosh, when you look at how the number of trees has reduced since 1986 to now, it's a sad state of affairs."
2	Charcoal Burner FGD 1	"The people blame us for the lack of rain, but we are not the only ones cutting down trees. Those doing farming are sometimes even worse. And a lot of people cut trees for timber and other purposes too, so they cannot heap the entire blame on us, it's not fair."
3	Commercial Farmer Interview 7	"When you look at the villages and the areas where rural people live, all the trees are gone compared to the area on the side of the commercial farmers, which is well preserved. It's sad."

contributors, though their views diverged on who holds primary responsibility.

5.3. Reforestation, land use, resource access

The evidence in Table 3 points to uneven reforestation efforts, with reported tree scarcity near settlements forcing individuals to travel longer distances for forest products. Participants noted that local leadership dynamics and perceived inequities in land governance may be contributing to ongoing unsustainable use of forest resources.

5.4. Beekeeping, honey harvesting and forest use

The testimonies in Table 4 indicate that while honey collection remains economically valuable, participants linked certain harvesting methods such as tree cutting and fire-setting to broader forest degradation. These accounts suggest tensions between livelihood practices and sustainability objectives in forest management.

5.5. Other forest product extraction

The data in Table 5 raise concerns about the sustainability of harvesting practices related to products like Masuku fruits and Munkoyo roots. Participants observed that these resources, while critical to livelihoods, are being harvested in ways that may jeopardise species regeneration and forest diversity over time.

5.6. Mopane worm harvesting

The findings in Table 6 indicate that the commercial value of mopane worms may be contributing to increased pressure on host trees such as Mutondo and Mpasa. Participant accounts suggest that the felling of these trees to access caterpillars could have broader ecological implications, including risks to long-term food security.

Table 3
Reforestation, Land Use, Resource Access.

c	Participant	Illustrative Direct Quotation
1	Commercial Farmer Interview 9	"We have planted about 3 ha of gum trees and eucalyptus, which we allow our workers to use for firewood"
2	Commercial Farmer Interview 1	"Both charcoal and agriculture contribute to deforestation, but charcoal is worse."
3	Charcoal Burner FGD 2	"The nearby trees close to the villages and roads have been depleted. Hence, for someone to find good trees, they have to travel long distances..."
4	Charcoal Burner FGD 1	"Some chiefs and headmen are corrupt and are actually at the forefront of charcoal burning since they have huge traditional portions of land by virtue of their positions, which they use to make charcoal and cut trees."

Table 4
Beekeeping, Honey Harvesting and Forest Use.

d	Participant	Illustrative Direct Quotation
1	CF Interview 10	"Look at this big tree that has just been cut down...There was something in that tree he wanted, either the Mopani worms or the honey..."
2	Chongwe Interview 12	"I collect 'Ubuchi' (Honey) from different places like trees, anthills, or underground burrows...I use smoke to collect the honey from beehives. The problem these days is that there are very few trees."
3	Mkushi Interview 3	"...a 2.5ltr sells for \$15 US (K300), and natural honey is always on high demand...it sustained me and helped me buy a good bicycle, household items and even pay back the solar lighting loan..."
4	Kapiri Interview 13	"When the beehive is in a tree..., I start a fire around or in the tree...If the beehive is in a difficult position..., I may cut off the branch or...the tree..."
5	Kapiri FGD 1	"Sometimes the honey collectors... cut down trees to access the honey. We have seen big trees that end up completely burnt or destroyed in the process... In other cases, they accidentally start forest fires..."

Table 5
Other Forest Product Extraction.

e	Participant	Illustrative Direct Quotation
1	Chongwe Interview 2	"Masuku tree numbers are dwindling because some people use them for charcoal burning... and ...cut down... during agricultural land clearing..."
2	Kapiri FGD 2	"We dig to get the roots of the munkoyo shrub, which ultimately dies..."
3	Kapiri FGD 2	"Due to excessive harvesting of munkoyo roots, loss of forest, and land clearing for agriculture, the munkoyo shrubs have reduced in number..."

Table 6
Mopane Worm Harvesting.

f	Participant	Illustrative Direct Quotation
1	CF Interview 14	"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..."
2	CF Interview 10	"Look at this big tree that has just been cut down!... Obviously, there was something in that tree he wanted, either the Mopani worms or the honey..."
3	Mkushi Interview 2	"I sell the worms at \$25 US (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..."
4	Mkushi Interview 1	"Mopane worm numbers have drastically reduced in the past decades because of overharvesting and cutting down of trees..."
5	Mkushi FGD 1	"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..."

5.7. NTFPs and biodiversity depletion

Participant narratives in Table 7 suggest that non-timber forest products (NTFPs), including mushrooms and medicinal plants, are central to local diets and incomes. However, these products are reported to be declining in availability, potentially linked to land clearing and reduced tree cover in surrounding areas.

5.8. Forest fires and their origins

The data in Table 8 point to rising concerns among participants about the frequency and impact of forest fires, which are often attributed to

Table 7
NTFPs and Biodiversity Depletion.

g	Participant	Illustrative Direct Quotation
1	CF Interview 9	"...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 warn them against cutting trees."
2	Mkushi FDG 2, Mkushi Interview 3	"Mushroom thrives well under trees and health forest, sadly the tree numbers have reduced... Land clearance for agricultural purposes is another contributing factor."
3	Kapiri FDG 2	"...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..."
4	Kapiri Interview 21	"When I find animals that thrive in trees while hunting, and they run up a tree, I cut down the tree."
5	CF Interview 6	"...certain trees, fruits, roots, and other plants have medicinal properties that locals use..."

Table 8
Forest Fires and their Origins.

h	Participant	Illustrative Direct Quotation
1	CF Interview 15	"One of the biggest dangers to crops, trees and property that we face is forest fires which we have to deal with almost on a yearly basis. They sometimes started by boys hunting small animals in grass, or by charcoal burners or by honey collectors and sometimes naturally. One time the fire almost reached the farm filling station... it's a real danger."
2	Kapiri FDG 3	"We guard against forest fires because we have thatched houses and for the sake of our crops and trees. Burning helps improve the soil but if not done properly it goes out of control. Sometimes it starts naturally or by kids in the bush or by our charcoal burners etc."
3	Kapiri FDG 1	"Sometimes the honey collectors... cut down trees to access the honey. We have seen big trees that end up completely burnt or destroyed in the process... In other cases, they accidentally start forest fires..."

human activities such as hunting, charcoal production, and honey harvesting. These accounts suggest that such fires may pose risks to property, crops, and remaining forest resources.

5.9. Agricultural expansion and fertiliser use

Responses in Table 9 describe how declining soil fertility, attributed to repeated fertiliser use, has driven some respondents to clear new farmland. Unlike charcoal production, agricultural expansion was described as involving the removal of all vegetation, which may carry more extensive ecological consequences.

Table 9
Agricultural Expansion and Fertiliser Use.

i	Participant	Illustrative Direct Quotation
1	Charcoal Burner Interview 7	"Fertiliser has destroyed the soil to such an extent that it's almost impossible to get yield without fertiliser and treated seeds..."
2	Charcoal Burner FDG 1	"The introduction of fertiliser and total dependence on it has seen many portions of land quickly lose fertility due to chemical use, meaning that new farms need to be opened."
3	FGD Mkushi, Luano, Kapiri, Chongwe.	"Land clearing for agriculture is worse for the environment than agriculture because all trees including small trees are cut and burnt but charcoal burners only pick the mature trees and leave the small ones as they are not useful."

5.10. Medicinal tree use and knowledge

The findings in Table 10 illustrate that indigenous tree species continue to play a vital role in local health systems. However, participants expressed concern that these species are becoming increasingly scarce, which they linked to forest degradation and expanding human pressures on forest resources.

5.11. Deforestation from tree multi-use

The accounts in Table 11 highlight that certain tree species are reportedly used for multiple purposes such as fuel, food, medicine, and income generation, placing them under mounting pressure. This perceived overuse may be weakening forest resilience and accelerating localised deforestation.

5.12. Carbon stock loss and future sequestration calculations

The results presented in Tables 12, 13, and 14 illustrate the estimated carbon stock loss and the foregone carbon sequestration potential resulting from forest degradation linked to fires, charcoal and fuelwood extraction, and timber harvesting across Zambia and the four study districts. Among these drivers, charcoal and fuelwood production dominate both carbon stock loss and foregone carbon sequestration. In the case of carbon stock loss, they are followed by forest fires, while timber harvesting causes no direct loss because the harvested carbon remains stored in timber products. By contrast, for foregone carbon sequestration, timber harvesting represents the next largest contribution, with forest fires having the smallest effect. Fig. 3 further highlights both major and subtle drivers of deforestation, showing how social, economic, and environmental pressures collectively shape forest loss. Together, these findings demonstrate the continuing strain on forest resources and their significant implications for Zambia's carbon balance and broader climate mitigation efforts.

5.13. Major and minor (subtle) drivers of deforestation

Fig. 3 presents the major and minor drivers of deforestation as identified through interviews and focus group discussions across the study sites. The main drivers which include, charcoal production (largely driven by urban demand), timber extraction, firewood collection (for cooking and heating), and agricultural expansion, emerged as the dominant causes of forest loss, linked to increasing rural energy needs, expanding cultivation, and market pressures for charcoal in urban areas experiencing frequent power outages, high tariffs, and dependence on wood-based fuels and products. In addition, several secondary but important factors were reported, including the use of firewood for funeral gatherings, uncontrolled forest fires, hunting,

Table 10
Medicinal Tree Use and Knowledge.

j	Participant	Illustrative Direct Quotation
1	CF Interview 12	"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."
2	Mkushi FDG 2	"... 'Chibangalume' [Zanha Africana] tree bark used to treat headaches and colds, 'Umunsokansoka' [Cassia abbreviate] used to treat stomach pains and malaria, guava leaves used to treat diarrhoea, and avocado roots used to boost blood levels, etc."
3	Charcoal Burner FDG 1	"We use both rubber ropes and ropes made from certain tree bark called 'Inshishi' to tie our charcoal. The bark-made ropes are also very useful for making fences, binding firewood together, etc."
4	Charcoal Burner FDG 2.	"Though we produce charcoal, we rarely use it for cooking as it's meant for sale. All of us here depend on firewood... Charcoal is for the wealthy... laughs."

Table 11
Deforestation from Tree Multi-Use.

k	Participant	Illustrative Direct Quotation
1	Mkushi FGD 1	"Mpasa [<i>Julbernadia globiflora</i>], Mutondo [<i>Cordyla Africana</i>] and Miombo [<i>Brachystegia boehmii</i>] trees are mainly the trees that host the caterpillars, and which have been cut down during Mopane worm collection..."
2	CF Interview 10	"Look at this big tree that has just been cut down...There was something in that tree he wanted, either the Mopani worms or the honey ..."
3	CF Interview 11	"If I take you through this forest, you'll see some beautiful trees that have been cut..."

harvesting of medicinal plants and bark, honey collection, and the extraction of Mopani worms. Although these minor activities occur on a smaller scale, their combined and sustained impact contributes significantly to ongoing forest degradation. Together, these ten drivers indicate that deforestation in the study areas is influenced by a complex

interplay of economic necessity, subsistence practices, and cultural traditions. There is, therefore, a need for integrated forest management strategies that address both direct and indirect human interactions with forest ecosystems.

6. Discussion

This study reveals a striking contradiction at the heart of Zambia's rural energy transition: while solar PV technologies are promoted as instruments of environmental stewardship, their grassroots uptake is often seemingly financed through practices that contribute directly to ecological degradation. This phenomenon (the clean energy-deforestation paradox) suggests a complex feedback loop wherein clean energy aspirations intersect with unsustainable livelihood strategies, ultimately challenging prevailing assumptions about energy transitions in Sub-Saharan Africa (SSA).

At the core of this paradox lies the structural dependency on biomass

Table 12
Carbon Stock Loss and Future Sequestration Calculations - Forest Fire.

Forest Fire										
Carbon Stock Loss	Zambia		Chingola		Kapiri Mposhi		Mkushi		Chongwe	
	2008~	2016~	2008~	2016~	2008~	2016~2023	2008~	2016~	2008~	2016~
	2015	2023	2015	2023	2015		2015	2023	2015	2023
Forest area loss due to Forest Fire (ha)	4975.18	10,374.64	0.21	0.03	43.53	37.33	6.16	2.99	1.26	5.12
AGB (t/ha)	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6
Emission Factor	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Carbon Fraction	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Carbon stock loss(tC)	81,374	169,687.60	3.44	0.53	711.91	610.56	100.79	48.90	20.58	83.77
Carbon stock loss(tCO ₂)	298,642	622,753.49	12.64	1.94	2612.70	2240.74	369.90	179.46	75.53	307.45

Future Carbon Sequestration loss	Zambia		Chingola		Kapiri Mposhi		Mkushi		Chongwe	
	2008~	2016~2023	2008~	2016~	2008~	2016~	2008~2015	2016~	2008~	2016~
	2015		2015	2023	2015	2023		2023	2015	2023
Forest area loss(ha)	4975.18	10,374.64	0.21	0.03	43.53	37.33	6.16	2.99	1.26	5.12
AGB Growth Rate(t/ha/yr)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Carbon Fraction of	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Future Carbon Sequestration Loss (tC/yr)	3741.33	7801.73	0.16	0.02	32.73	28.07	4.63	2.25	0.95	3.85
Future Carbon Sequestration Loss (tCO ₂ /yr)	13,730.69	28,632.34	0.58	0.09	120.12	103.02	17.01	8.25	3.47	14.14

Table 13
Carbon Stock Loss and Future Sequestration Calculations - Charcoal and Fuelwood.

Charcoal and Fuelwood										
Carbon Stock Loss	Zambia		Chingola		Kapiri Mposhi		Mkushi		Chongwe	
	2008~2015	2016~	2008~	2016~	2008~	2016~	2008~	2016~	2008~	2016~
		2023	2015	2023	2015	2023	2015	2023	2015	2023
Forest area loss (ha)	620,733	1,074,226	2502	5611	18,985	38,765	20,226	40,804	3377	6431
% of Forest Loss: Charcoal/Fuelwood	90 %	90 %	90 %	90 %	90 %	90 %	90 %	90 %	90 %	90 %
Forest Loss: Charcoal/Fuelwood (ha)	558,660	966,803	2252	5050	17,087	34,889	18,203	36,724	3039	5788
AGB (t/ha)	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6
Emission Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Carbon Fraction of Aboveground Biomass	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Carbon stock loss(tC)	18,274,876	31,626,073	73,661	165,192	558,934	1,141,273	595,470	1,201,302	99,422	189,334
Carbon stock loss(tCO ₂)	67,068,795	116,067,687	270,335	606,256	2,051,286	4,188,470	2,185,374	4,408,780	364,877	694,855

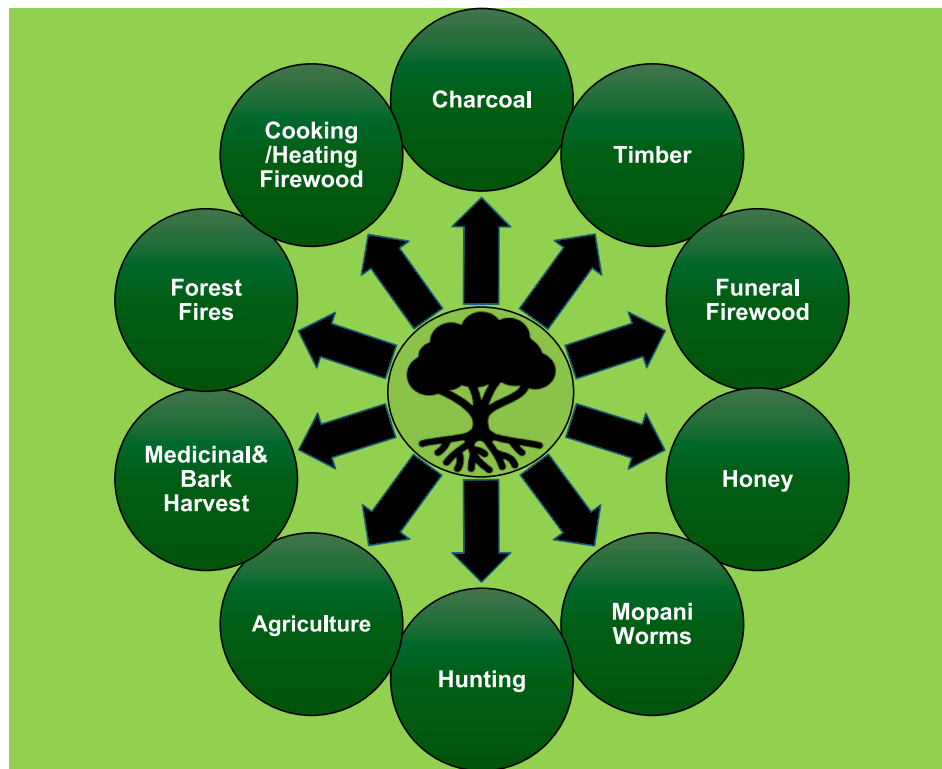
Future Carbon Sequestration loss	Zambia		Chingola		Kapiri Mposhi		Mkushi		Chongwe	
	2008~2015	2016~	2008~	2016~	2008~	2016~	2008~	2016~	2008~	2016~
		2023	2015	2023	2015	2023	2015	2023	2015	2023
Forest Loss: Charcoal/Fuelwood	558,660 ha	966,803 ha	2252 ha	5050 ha	17,087 ha	34,889 ha	18,203 ha	36,724 ha	3039 ha	5788 ha
AGB Growth Rate(t/ha/yr)	1.6 t	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Carbon Fraction	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Future Carbon Sequestration Loss (tC/yr)	420,112	727,036	1693.35	3797.52	12,849.05	26,236.15	13,688.96	27,616.15	2285.55	4352.50
Future Carbon Sequestration Loss (tCO ₂ /yr)	1,541,811	2,668,223	6215	13,937	47,156	96,287	50,238	101,351	8388	15,974

Table 14

Carbon Stock Loss and Future Sequestration Calculations - Timber Harvesting.

Timber Harvesting										
Carbon Stock Loss	Zambia		Chingola		Kapiri Mposhi		Mkushi		Chongwe	
	2008~ 2015	2016~ 2023	2008~ 2015	2016~2023	2008~ 2015	2016~ 2023	2008~ 2015	2016~ 2023	2008~ 2015	2016~ 2023
Forest area loss (ha)	620,733	1,074,226	2502	5611	18,985	38,765	20,226	40,804	3377	6431
% of Forest Loss: Timber Harvesting	3 %	3 %	3 %	3 %	3 %	3 %	3 %	3 %	3 %	3 %
Forest area loss: Timber Harvesting(ha)	18,622	32,227	75	168	570	1163	607	1224	101	193
Emission Factor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Carbon Fraction	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Carbon stock loss(tC)	0	0	0	0	0	0	0	0	0	0
Carbon stock loss(tCO ₂)	0	0	0	0	0	0	0	0	0	0

Future Carbon Sequestration loss	Zambia		Chingola		Kapiri Mposhi		Mkushi		Chongwe	
	2008–2015	2016~ 2023	2008–2015	2016~ 2023	2008–2015	2016~ 2023	2008–2015	2016–2023	2008–2015	2016–2023
Forest area loss: Timber Harvesting (ha)	18,622	32,227	75	168	570	1163	607	1224	101	193
AGB Growth Rate(t/ha/yr)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Carbon Fraction	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Future Carbon Sequestration Loss (tC/yr)	14,003.74	24,234.54	56.45	126.58	428.30	874.54	456.30	920.54	76.19	145.08
Future Carbon Sequestration Loss (tCO ₂ /yr)	51,393.71	88,940.76	207.15	464.56	1571.87	3209.56	1674.62	3378.38	279.60	532.46

**Fig. 3.** Major and Minor (Subtle) Drivers of Deforestation.

energy and forest-derived incomes. As shown in the findings, many rural households appear to resort to charcoal production and non-timber forest product (NTFP) harvesting to generate income which is partly used to buy solar PV systems. This mirrors patterns highlighted by Gumbo et al. [45] and Kazungu et al. [50], who demonstrate that forest exploitation often serves as both a direct and indirect energy access mechanism. However, unlike traditional biomass use where firewood or charcoal is the end-use fuel, in Zambia's case, biomass becomes a transactional intermediary and an economic bridge to modern energy

access [48]. This reveals a deeper structural vulnerability embedded in Zambia's decentralised energy model. As noted by Nygaard et al. [3], PAYG solar systems have enabled rural uptake, but the financial burden remains high relative to rural income levels. The absence of inclusive financing mechanisms such as micro-credit, subsidies, or cooperative models, may force marginalised populations to monetise natural capital. Consequently, as Chanda et al. [7] argue, clean energy adoption without corresponding financial safeguards has the potential to exacerbate environmental injustice, whereby the costs of sustainability are

offloaded onto ecologically vulnerable communities [61].

A salient pattern across the findings is the multi-functionality of forest resources. Tree species such as Mutondo, Mpasa, and Miombo simultaneously serve as hosts for mopane worms, sources of firewood, charcoal, food, and medicine. This multifunctionality appears to create cumulative pressure on biodiversity hotspots and echoes concerns raised by Guedje et al. [17] regarding the unsustainable harvesting of multi-use species. The Jevons Paradox becomes increasingly relevant in this context. Even as solar PV ostensibly reduces reliance on biomass for lighting, the economic incentive to harvest forests for income to finance such technologies may undermine ecological gains, as supported by Goulart et al. [44] and Tazebew et al. [49]. Furthermore, the role of ecosystem degradation in reinforcing poverty cycles is particularly pronounced. Soil degradation from excessive fertiliser use, documented in both the findings and by Tyagi et al. [42], compels continuous agricultural expansion into forested areas, further escalating deforestation. This dynamic illustrates a negative feedback loop where reduced soil fertility leads to deforestation, which in turn diminishes ecosystem services, such as water retention and pollination, thereby reducing agricultural productivity and pushing households further toward environmentally harmful income-generating activities [52]. In support, Mubanga & Bwalya [43] and Verma [40] have noted that such trade-offs are frequently rooted in short-term adaptation strategies that prioritise survival over sustainability.

A critical contribution of this study is the foregrounding of under-acknowledged practices which include honey harvesting, bark stripping, medicinal plant extraction, and mopane worm collection, as possible significant contributors to forest degradation. These are often excluded from policy assessments and conventional land-use metrics. This finding aligns with Chungu et al. [18], who emphasise the ecological significance of ‘invisible drivers’ in forest decline. More importantly, the commodification of these practices, particularly when linked to the financing of solar technologies, complicates simplistic binaries of “clean” versus “dirty” energy [23,51]. This calls for an integrated understanding of sustainability that accounts not only for carbon displacement but also for the socio-ecological conditions under which clean technologies are acquired. As Mohammed [31] and UN-REDD+ [32] contend, sustainability must be evaluated holistically, considering lifecycle impacts and local trade-offs. A solar lantern displacing kerosene may reduce indoor air pollution and carbon emissions, but if it is financed through the felling of medicinal trees or the ignition of forest fires, its net environmental benefit might arguably be reduced or become questionable [41].

Governance failures appear to further compound these contradictions. Zambia's forest and energy policies remain siloed, with limited cross-sectoral coordination [25,29]. The findings illustrate how weak enforcement, local leadership complicity, and inequitable access to reforestation programmes exacerbate unsustainable forest use. This institutional fragmentation prevents the alignment of rural energy access goals with forest conservation imperatives. REDD+ and similar mechanisms have struggled to integrate energy needs into conservation frameworks, often neglecting the economic realities of rural households [56]. As a result, communities are left navigating an unsustainable middle ground and are caught between conservationist imperatives and the pressing need for energy and income [47]. The political ecology of forest access also emerges as a key consideration. As seen in the participant testimonies, rural communities often face inequitable land and resource governance structures. Chiefs and headmen, by virtue of traditional authority, are sometimes reported to exploit forests for personal gain, undermining collective stewardship. This aligns with Moreira-Dantas & Söder [57], who identify corruption and elite capture as persistent threats to community-led conservation. These dynamics also skew energy equity, as wealthier households and actors, such as commercial farmers, are often better positioned to adopt solar technologies without resorting to forest exploitation [7].

Ecologically, the degradation of Zambia's Miombo woodlands and

associated biodiversity presents potential cascading consequences. Reduced forest cover may jeopardise not only flora and fauna but also microclimatic stability and agricultural viability [34,52]. The decline of NTFPs such as mushrooms, honey, and mopane worms signals an erosion of dietary diversity and rural livelihoods. These losses are not just ecological but profoundly socio-economic, threatening food security, cultural practices, and resilience in the face of climate stressors [58,59]. At the same time, there are glimmers of adaptive potential. The study notes that some commercial farmers have initiated small-scale reforestation efforts and provide controlled access to firewood. While limited in scope, such examples point to the possibility of hybrid energy-environment arrangements, where local actors serve as intermediaries in supporting both clean energy and sustainable resource use. However, these efforts must be scaled and institutionalised within a coherent policy framework [61].

This discussion suggests that sustainability is not a function of technological substitution alone. It is also a function of social equity, governance architecture, and ecological interdependence. Without addressing the structural conditions under which solar PV systems are financed and adopted, the clean energy transition runs the risk of inadvertently accelerating the very environmental degradation it seeks to resolve. As SSA continues to scale up decentralised energy systems, the Zambian case offers a cautionary lesson: energy justice must be pursued alongside, not in isolation from, ecological justice.

6.1. Carbon and sequestration loss analysis

Carbon stock loss in Zambia (see Tables 12 to 14) exhibited significant variation based on the underlying drivers of forest loss (see Fig. 3). Across both periods (2008–2015 and 2016–2023) (see Fig. 4 to 23), charcoal and fuelwood emerged as the dominant contributors to carbon emissions in all regions. Nationally, emissions from charcoal-related forest degradation increased markedly from 67,068,795 tCO₂ in 2008–2015 to 116,067,687 tCO₂ in 2016–2023. These values were estimated by applying a 90 % attribution factor to total forest loss, reflecting national-level trends that identify charcoal and fuelwood as the dominant drivers of deforestation in Zambia. By contrast, emissions from forest fires remained comparatively lower, rising from 298,642 tCO₂ to 622,753 tCO₂ over the same timeframe. Timber harvesting, by its nature, did not contribute to immediate carbon stock loss, as much of the biomass remains stored in long-lived wood products. Patterns in future carbon sequestration loss mirrored those of immediate emissions.

Zambia's estimated annual loss in carbon sequestration capacity from charcoal and fuelwood rose from 1,541,811 tCO₂/year (2008–2015) to 2,668,223 tCO₂/year (2016–2023). Timber harvesting accounted for lower annual losses of 51,394 tCO₂/year and 88,941 tCO₂/year, respectively. Losses from forest fires remained modest, at 13,731 tCO₂/year and 28,632 tCO₂/year across the two periods.

At the district level, Mkushi experienced the most severe impact, recording 4,408,780 tCO₂ in emissions from charcoal and fuelwood between 2016 and 2023, with an associated sequestration loss of 101,351 tCO₂/year. Kapiri Mposhi and Chongwe followed, while Chin-gola exhibited the lowest values, with 606,256 tCO₂ in emissions and 13,937 tCO₂/year in sequestration loss. Although emissions from forest fires increased slightly across districts, they remained consistently lower than other sources throughout the study period. Deforestation is also partly driven by NTFP extraction, including bark harvesting, mopane worm collection, and honey production. However, the trees lost are also eventually largely used for charcoal production contributing to localised deforestation and carbon loss. However, due to a lack of spatially disaggregated data, these drivers could not be separately quantified.

Legend: Tree Cover (Green)  Tree Loss (Red) 

7. Recommendations

A number of policy recommendations are made below that reflect the challenges posed by the deforestation-clean energy paradox. Rather than treating clean energy expansion and environmental preservation as separate pursuits, policymakers must embrace a holistic, systems-based approach. This entails aligning incentives, restructuring financing mechanisms to reduce dependency on forest incomes, and strengthening institutional capacities across the forestry, energy, and agriculture sectors.

7.1. Integrate forestry and energy policies

A cohesive policy approach is required to bridge the gap between clean energy promotion and forest conservation. The Ministry of Energy and the Ministry of Green Economy and Environment must collaboratively develop integrated policies that consider how rural solar PV adoption is financed and the potential forest costs of such transitions. Synergies between energy access targets and forest preservation efforts can be achieved through joint planning and inter-ministerial coordination.

7.2. Implement Forest-sensitive solar subsidies

To reduce reliance on income from environmentally harmful practices, solar PV financing mechanisms must be designed to accommodate the economic realities of forest-dependent households. The Ministry of Finance, in partnership with the Rural Electrification Authority, should pilot targeted subsidies and zero-interest solar loan schemes for vulnerable groups. International aid organisations such as the United

Nations Development Programme (UNDP) and the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) can provide technical support and financing for these programmes.

7.3. Scale up sustainable livelihood alternatives

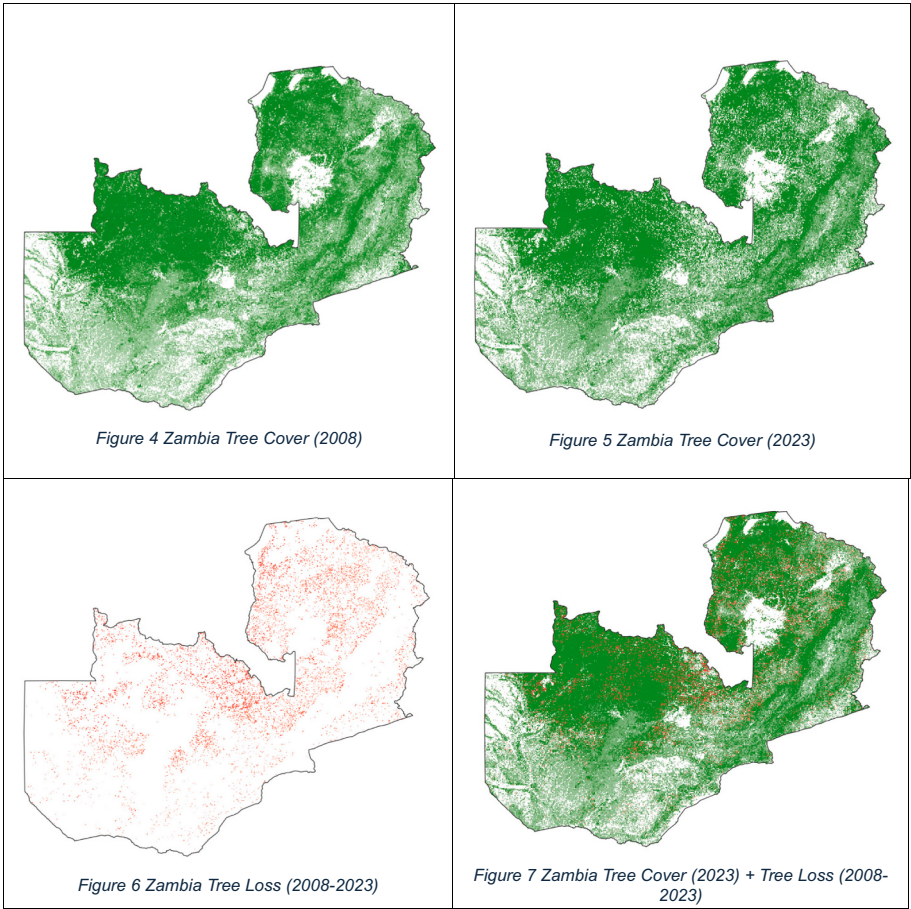
The promotion of alternative income-generating activities that do not rely on forest degradation is vital. The Ministry of Community Development and Social Services, alongside development partners like the World Food Programme (WFP) and SNV Netherlands Development Organization, should invest in training and support for value chains such as agroforestry, apiculture, mushroom cultivation, and eco-tourism. These options can provide income without further depleting natural resources.

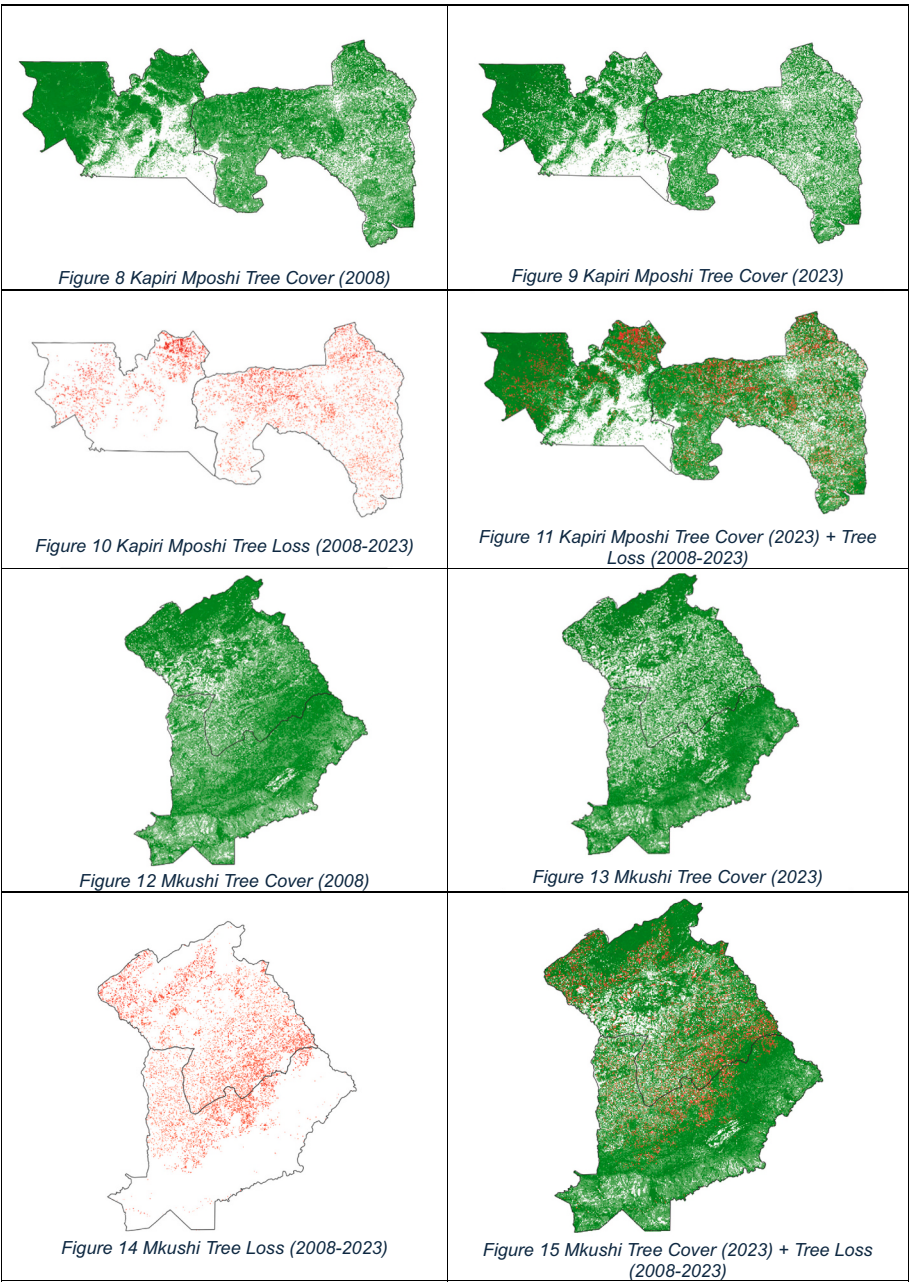
7.4. Strengthen local forest law enforcement

Empowering community-based forest management structures is key to sustainable forest use. The Forestry Department should work closely with traditional authorities to enforce tree harvesting regulations, monitor deforestation hotspots, and promote reforestation. Local resource user groups can be equipped with tools, training, and legal backing to act as stewards of their natural environment.

7.5. Integrate environmental education into outreach

Awareness-raising campaigns on solar energy should incorporate forest conservation messages. The Ministry of Education, working with civil society organisations and media outlets, can develop culturally relevant materials that highlight the long-term risks of financing solar





. (continued).

systems through deforestation. Including environmental ethics in school curricula can cultivate a new generation of forest-conscious energy consumers.

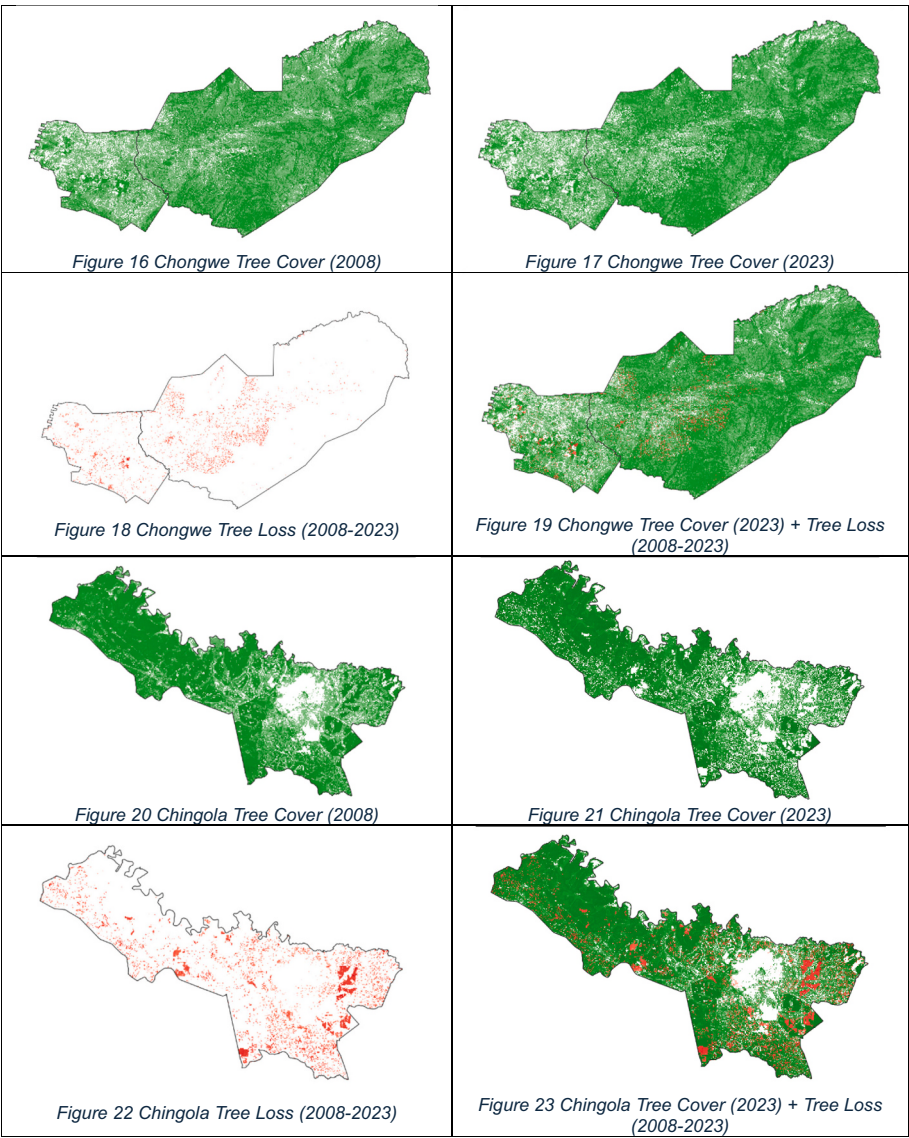
8. Conclusion

8.1. Key findings and contributions

This study uncovers a rarely addressed dilemma in rural energy transitions called “The Clean Energy-Deforestation Paradox” - where the adoption of clean technologies like solar PV is financed through ecologically damaging activities such as charcoal burning, bark harvesting, mopane worm collection, and land clearing etc. which drive deforestation. While solar PV provides clean lighting solutions, its household-level acquisition strategies in rural areas sometimes involves unsustainable income sources that exacerbate deforestation and biodiversity loss.

One of the most significant contributions of the research is its empirical demonstration of how micro-level economic behaviours link energy aspirations to environmental degradation. These links have been largely overlooked in mainstream clean energy and forestry debates. The study highlights not only the major drivers of deforestation but also subtle, under researched ones such as bark removal for ropemaking, tree cutting for; honey collection, mopane worm gathering and hunting access, and multi-purpose exploitation of the same tree species across different sectors. Methodologically, the study is grounded in the Rural Development Stakeholder Hybrid Adoption Model (RUDSHAM), which provides a holistic framework to examine sustainability trade-offs. RUDSHAM enables the integration of household-level socio-economic dynamics with ecological outcomes, allowing a deeper understanding of how rural actors navigate energy transitions under constrained conditions.

This research advances knowledge by problematising the assumption that clean energy uptake is universally positive. It presents an



. (continued).

alternative lens through which to evaluate sustainability, one that considers not just outcomes, but the means through which those outcomes are achieved. By focusing on the financing behaviours behind solar PV adoption, the study contributes new insight into the environmental cost of clean energy in low-income, forest-dependent settings.

8.2. Future research directions

While this study offers a comprehensive qualitative exploration of the clean energy - deforestation paradox, future research could expand its scope through spatial modelling and life-cycle assessments. Quantitative studies tracking forest degradation over time in high-solar adoption areas would offer valuable insights into land-use change dynamics. Additionally, there is a need to examine the gendered dimensions of forest-product-based solar financing, as women and girls often bear disproportionate burdens in both energy provision and environmental labour.

8.3. Study limitations

One limitation of the study is its 28-month data collection window, which, while extensive, may not fully capture the seasonal fluctuations

in deforestation-related activities or long-term changes in solar financing trends. A longer study period would enable more robust tracking of deforestation patterns and solar adoption behaviours over time. Expanding the sampling of income-generating activities across a broader geographic area could offer additional perspectives and help enrich the understanding of patterns that may also be relevant in other parts of Zambia and the wider Sub-Saharan African region. As with many qualitative studies, the findings are grounded in participant narratives and observational accounts, which, while rich in contextual depth, do not offer precise quantification of ecological impacts such as bark stripping, mopane worm harvesting, or medicinal tree extraction. Future research would benefit from mixed-methods or ecological field studies to empirically measure the extent and ecological consequences of these practices, thereby validating or refining the patterns observed in this study.

8.4. Summary

The study stresses the urgent need to reconcile rural energy access goals with environmental sustainability objectives. Addressing this paradox requires not just improved solar distribution but a fundamental rethinking of how clean energy transitions are financed and governed in

forest-dependent communities. By surfacing hidden costs and overlooked drivers of deforestation, this research offers a critical step toward more inclusive, integrated, and ecologically sound development planning in Zambia and beyond.

CRedit authorship contribution statement

Hillary Chanda: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Eugene Mohareb:** Writing – review & editing, Validation, Supervision, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Michael Peters:** Writing – review & editing, Supervision, Software, Methodology, Data curation, Conceptualization. **Chris Harty:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Martin Green:** Validation, Software, Methodology, Conceptualization. **Nao Shibata:** Writing – review & editing, Software, Formal analysis, Data curation. **Edwin Bwanga Kasanda:** Writing – review & editing, Investigation, Data curation.

Funding

This research was funded by the UK Commonwealth Scholarship Commission.

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.

Acknowledgements

We express our gratitude to Dr., Stella Zulu Chisanga for the Commonwealth Scholarship funding acquisition. We are grateful to Pastor Maybin Mulofwa Kamfwa, Mr. Evans Chola, Mr. Golden Gilbert Maluma and Mr. Francis Kaunda for facilitating the data collection. We are thankful to all the participants who furnished the data required for the study. We are grateful to Reading University and the Copperbelt University for their support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.erss.2025.104389>.

Data availability

Data will be made available on request.

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