Use and management of energy resources from Water, Energy, and Food (WEF) nexus perspective: The case of Vhembe District Municipality (VDM), Limpopo Province

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DECLARATION

I, Mulalo Mudau (student number 16008470), hereby declare that this thesis was submitted to the Department of Earth Sciences of the University of Venda in fulfilment of the Master of Earth Sciences degree requirements not been submitted to any university. It is entirely my own design and implementation work, and all references cited have been fully acknowledged in the text and the list of references.

Name of student: Mulalo Mudau Sign.……. Date: 24 February 2025

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DEDICATION

This thesis is dedicated to my late mother Ms Mudau Martha. I wouldn't be who I am today without your motivation, encouragement, and inspiration. You have my undying love.

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ABSTRACT

Water, Energy, and Food (WEF) are necessity resources required by human beings for sustenance, social, and economic development. Energy is at the centre of the WEF nexus due to its dual role as a driver of economic activity and the largest contributor to global warming and climate change risks. In response, most countries following the 2015 Paris Agreement on climate action have adopted renewable energy (herein referred to as smart energy practices and innovations) policies to mitigate the adverse impacts of energy on climate change, as well as address health and environmental crises. Such measures and policies are also pursued to enhance energy security and economic prosperity. Though South Africa is one of the countries that has adopted an ambitious renewable energy policy, there is a paucity of information on factors influencing the adoption of renewable based energy resources and potential outcomes at the household level, where most of the envisioned policy objectives are expected to be pursued and realised. The current study was conducted in the Nzhelele and Luvuvhu River catchment areas in the Vhembe District Municipality (VDM) of Limpopo Province. A mixed methods approach was used to gather information on energy access and use at the household level through household questionnaires and triangulated through key informant interviews (KII) and Focus Group Discussions (FGDs). Economic analysis of existing energy practices and innovations was analysed using a Net Present Value (NPV) analysis, and environmental performance assessed through Partial Life Cycle Analysis (LCA). Analysis of data was done in Excel and IBM^{R} SPSS^{R} Statistics version 28 based on weight estimation and multinomial logistic regression approaches. Biomass and mains electricity are the main sources of energy, with energy stacking being a universal strategy observed in majority of households. Renewable energy sources such as solar energy are rarely used at the household level. Approximately 62% of the respondents cited lack of knowledge (inadequate access to information) on the smart energy technologies and their availability as the most significant limiting factor in their adoption. This was followed by poor reliability of smart energy technologies at about 53%, cost saving potential at about 45%, and availability of finance at about 48%. For those in agriculture, market access at about 21% and return on investment at about 19% is an important consideration in the choice of smart energy technologies. Ease of availability and cost of energy type at 35% and 39% respectively were the main factors likely to influence the choice of smart energy innovations. Cost of alternatives at about 13%, load shedding at about 14 %, and socio-economic lockins i.e., culture and past policies at about 12% of the respondents. Employment and to a greater extent, total household income status, emerge as the only factor that significantly ($P< 0.005$) influences the adoption of smart energy innovations. The use of biomass and LPG are significant predictors of reliability in existing energy innovation. Though renewable energy sources such as solar can reduce environmental footprints, the initial cost and intermittent supply due to weather constrain their adoption. The adverse impact of non-renewable resources such as biomass on health and environment are inherent through higher emission levels. The same applies to coal generated electricity. However, the fact that such sources are cheaper and easily available due to economic lockins also constrains the transition to cleaner energy sources at household level. In conclusion, WEF approach can inform sustainability transition and energy security with economic empowerment and awareness creation, including access to higher education and income earning opportunities being more likely to mediate the transition to smart energy at household level.

Keywords: Household; Energy ladder; Energy mix, Energy stacking; Energy Security, Renewable energy, Vhembe district municipality, WEF nexus.

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LIST OF ABBREVIATIONS

WEF	Water, Energy, and Food
VDM	Vhembe District Municipality
KII	Key Informant Interviews
FGDs	Focus Group Discussions
NPV	Net Present Value
LCA	Life Cycle Assessment
SPSS	Statistical Package for the Social Sciences
GHGs	Greenhouse Gases
COP	Conference of Parties
JETP	Just Energy Transition Partnership
UNCCC	United Nations Climate Change Conference
JET	Just Energy Transition
SDGs	Sustainable Development Goals
LPG	Liquefied Petroleum Gas
WEC	World Energy Council
GDP	Gross Domestic Product
IEA	International Energy Agency
FAO	Food and Agriculture Organisation
ISO	International Organisation for Standardisation
LCI	Life Cycle Inventory analysis
LCIA	Life Cycle Impact Assessment
ALCA	Attributional Life Cycle Assessment
CLCA	Consequential Life Cycle Assessment
UNEP	United Nations Environnement Programme
SETAC	Society of Environmental Toxicology and Chemistry
SFA	Substance Flow Analysis
SANEDI	South African National Energy Development Institute
IPCC	Intergovernmental Panel of Climate Change
IPPs	Independent Power Producers
SO_2	Sulphur Dioxide
CO_2	Carbon Dioxide
IRR	Internal Rate of Return

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CBA	Cost Benefit Analysis
BCA	Benefit Cost Analysis
BCR	Benefit Cost Ratio
WLS	Weighted Least Squares
LPWW	Larger Solar Panels with Water storage accessories
LPWTW	Larger Solar Panels without Water storage accessories
SPWW	Smaller Solar Panels with Water storage accessories
SPWTW	Smaller Solar Panels without Water storage accessories

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CHAPTER 1: INTRODUCTION

1.1 Preamble

This chapter includes background information, problem statement, motivation, objectives, and research questions of the study.

1.2 Background

One of the most essential resources discussed by the WEF is energy. Energy resources refer to all forms of fuels used, either for producing heat, powering life, moving objects, or producing electricity (Novakovic and Nasiri, 2016). Energy is widely used in agriculture and related industries, including those that produce and supply pesticides, fertilizers, and farm equipment. At the household level, energy is widely used for cooking, lighting, and heating. Accordingly, any country's economic development highly depends on energy access and energy security (Raheem *et al.*, 2016). In turn, energy security is influenced by the number of energy sources or energy mix.

The energy mix consists of both renewable and nonrenewable sources. Energy sources that are regenerated naturally by the planet are referred to as renewable energy sources (United Nations, 2022). Biomass (i.e., plant fuels such as wood used by human civilization) and hydropower are some of the traditional renewable resources. Non-renewable resources generally refer to energy sources that do not regenerate quickly, at least in the lifetime of a human being (Hodana *et al*., 2020). These consist of oil, uranium, natural gas, hard coal, and lignite. Renewable and nonrenewable energy resources are combined to determine access, stability, and energy cost, herein referred to as energy security.

Nonrenewable energy sources such as fossil fuel sources adversely impact the environment and climate through the production of Greenhouse gases (GHGs), as well as negatively impact human health through pollution (Geeks, 2022). As a result of such adverse impacts, energy policy globally is focused on promoting the use of renewable energy. The expansion of renewable energy is thus largely underpinned by policies that aim to increase energy security, protect the environment, and promote economic prosperity (Benedek *et al.,* 2018).

Independent power producers (IPPs) provide 7% of South Africa's electricity from renewable energy sources like solar, hydro, biomass, and nuclear energy, while Eskom, a parastatal power utility, produces 92% of the country's electricity from coal (Akom *et al.,* 2021). The generation

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and distribution of electricity in South Africa is entirely dependent on a steady supply of water, as well as intricately linked water transmission and storage systems created especially to support this sector. In addition to its detrimental effects on the environment, coal is getting harder to locate, and its extraction and processing costs are increasing for both the public and the government. These issues are reflected in the nation's frequent and occasional blackouts caused by the significant deterioration of the infrastructure and older coal-generating plants.

According to Baker and Phillips (2019) and the International Energy Agency (IEA, 2022), Eskom, the country's power utility, has not been able to keep up with the energy demand, which has led to more frequent power outages and increased energy rationing (Lawrence, 2020). This supports the need for energy diversification and especially a switch to alternative renewable energy sources, which have the potential to enable South Africa to meet its international commitments on climate change under the Paris Agreement and pursue various Sustainable Development Goals (SDGs). For instance, poor access to electricity has adversely impacted productivity, education, nutrition, and gender equity (Winther *et al.,* 2017).

Most households in rural areas, where the majority of the population resides, rely on government social grants, pension payments, and remittances from relatives who move to neighbouring provinces to find employment. Limpopo Province is one of the poorest provinces in South Africa because of its high unemployment rate, which is primarily present in the rural areas of the Vhembe district municipality (Stats, 2022). Some studies show that most rural communities of the Vhembe district do not have access to cheap, clean energy sources, which causes them to rely on traditional biomass (Muhumuza *et al.,* 2018). Significantly, high dependence on traditional biomass has exposed residents to hazardous health risks brought on by air pollution (Adeeyo et al., 2022; Muller and Yan, 2018).

WEF Nexus paradigm has been suggested as a framework for analysing and addressing energy insecurities across the world (Endo *et al.,* 2015). To fully comprehend the development of renewable energy in South Africa and the formulation of responsive interventions, it is important to understand the socio-economic factors influencing access (interchangeably referred to as energy security), as well as the impact pathways of various energy mixes. The study thus analyses the socio-economic factors influencing energy mix and energy security at the household level, as well as the environmental impacts of the existing energy mix, innovation, and practices at the household level. The findings have the potential to contribute to energy policy in South Africa in general and the just energy transition, as well as extend

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knowledge on sustainability transitions. In the context of the WEF nexus, access to clean energy and water sources, and a sufficient food supply are interrelated in terms of economic and environmental impacts. Having limited access to either of the WEF resources might affect how to secure a country's food supply and the well-being of the people (Dlamini *et al.,* 2023).

1.3 Problem statement

One of the most persistent development challenges for many countries is improving the substantial living conditions of citizens such as access to clean energy, improved health outcomes, education, and economic opportunities (Rasimphi *et al.,* 2020). Renewable energy sources are integral to the pursuit of Sustainable Development Goals (SDG 6) for clean and safe energy. However, this is undermined by inadequate access to clean and safe energy sources. Notably, the energy-poor people, estimated to be about 2.67 billion globally, largely depend on hazardous and environmentally damaging energy sources, such as coal (Muhumuza *et al.,* 2018).

Due to its heavy reliance on coal as a primary energy source, South Africa is ranked among the top twenty countries in the world for fossil fuel greenhouse gas emissions (Bekun *et al.,* 2019). Coal has a major negative effect on the environment and is increasingly expensive to extract necessitating high electricity costs to final users. This is exacerbated by aging coal-based energy-generating infrastructure. Such adverse socioeconomic and environmental impact pathways need to be considered in planning for just energy transitions.

Over the last decade and particularly over the 2021-2023 period, South Africa has experienced one of the most crippling power outages, popularly known as load shedding, with far reaching impacts at scale. Several factors are thought to have contributed to the load shedding. These include aging and low energy capacity required to power the national grid. The supply of off-grid connections (solar home systems) in South Africa is part of the government's commitment to transforming the socioeconomic conditions of rural and underprivileged areas (Chidembo *et al.,* 2022). However, a lack of information on socioeconomic factors and the performance of the alternative energy mix that is critical in off grid pathways is lacking.

The pursuit of energy security, environmental protection, and economic prosperity is an interrelated national policy objective that also positively contributes to global climate mitigation and the SDG agenda (Nkoana, 2018). Specifically reducing GHG emissions while advancing the nation's socioeconomic growth could see South Africa contribute to the

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achievement of the Paris Agreement (COP26) agenda, notably through decreased reliance on coal and adoption of smart energy resources (renewable energy) in its development agenda. Assessing socio economic factors influencing the uptake of planned renewable energy mix at the household level could inform policymakers and contribute towards the formulation of responsive interventions.

1.4 Motivation

The WEF nexus approach is a holistic planning and analytical tool for addressing conflicts and enhancing the constructive collaboration of policy objectives on natural resources and development. This is especially critical given the high environmental footprint of current energy uses. For example, many gallons of water are needed to safely operate power facilities that use non-renewable fuel sources such as coal. This can result in a substantial reduction of water availability for irrigation, more so under changing climate. Conversely, the use of renewable energy practices and innovations such as solar and wind power could greatly mitigate such negative impacts i.e., irrigation costs in food production (Moss, 2022). The ensuing positive environmental impacts are likely to inform policy buy-ins more so the pursuit of international obligations on curbing GHG emissions.

The rapid post COVID-19 economic recovery and the war in Ukraine have increased focus on the importance of energy security (Mottaleb *et al.,* 2022). The resulting high energy costs from the disrupted energy supply chain and ensuing energy shortages have negatively impacted economic output and socio welfare across all nations. In turn, this has been one of the drivers in pursuit of energy security policies with renewable energy options being the focus of energy security policies. Information on socio economic factors at the household level and how they could impact such transitions could be critical in planning regarding using and managing energy resources policy objectives toward clean energy.

There are several ways in which countries can boost their energy security including short-term energy supply partner diversification, long-term energy mix diversification with low-carbon alternatives, and increased energy efficiency (World Economic Forum, 2022). This study addresses existing knowledge gaps on energy mix from the Water-Energy-Food (WEF) nexus perspective with a view of informing policy and decision makers on impactful and responsive interventions for sustainable energy transitions at the household and community level.

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1.5 Objectives

1.5.1 Main objective

This study aims to establish the use and management of energy resources, factors influencing access (security), and their implications for energy planning in a midst of climate change and WEF discourse.

1.5.2 Specific objective

I. To assess energy mix and their use in the context of WEF nexus at a household level, VDM.

II. To evaluate social economic factors influencing energy access at the household level, VDM.

III. To analyse the environmental and technical dimensions of energy innovations and WEF practices at the household level.

1.6 Research questions

I. What are the renewable and non-renewable resources used by households in the context of WEF framing?

II. What are the social economic factors influencing access to and use of various energy mixes at the household level?

III. What are the social and economic costs of various energy innovations and WEF practices at the household level?

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CHAPTER 2: LITERATURE REVIEW

2.1 Preamble

The literature on the energy mix, social and economic factors that affect the energy mix, energy security, renewable energy in the Water Energy and Food (WEF) nexus, energy security, life cycle assessment, the smart energy concept in WEF, and conceptual frameworks is reviewed in this chapter.

2.2 Energy mix

The energy mix in South Africa is characterised by renewable as well as non-renewable energy sources as discussed hereunder. Independent power producers (IPPs) produce 7% of South Africa's electricity from renewable energy sources such as solar, hydro, biomass, and nuclear power, while Eskom produces 92% of its electricity from coal (Akom *et al.,* 2021). Coal, a non-renewable energy resource, thus dominates energy generation for various uses at the national level, with studies by Asumadu and Adams (2020) concluding that South Africa has reached the peak of its coal-dependent energy supply capacity. In many rural towns, electricity is primarily used for lighting and to power devices like radios, televisions, and phones (Rahut *et al*., 2011). The generation of energy from solid fuel sources such as coal and its mining is characterised by energy transformation inefficiency, generates huge amounts of harmful emissions i.e., Carbon dioxide (CO2) and sulfur dioxide (SO2), as well as adversely impact ecological health due to land destruction, desertification, and salinisation following coal mining (Li *et al*., 2021; Tang *et al.,* 2021; Yang *et al.,* 2018).

Biomass energy is generated from a variety of sources, including plant resources and agricultural wastes, sewage and municipal waste, the food industry, and animal waste (Zahedi *et al.,* 2022). Use of biomass for cooking and heating is thus a common occurrence even where 100% connection to the electricity grid, as well as incentives for utilising it (such as promotional units) by the service provider exist (Chidembo *et al.,* 2022). The use of biomass energy sources is thus expected in South Africa. In most contexts, households prefer the less expensive biomass energy sources, the adverse environmental effects notwithstanding (Uhumanure *et al*., 2017, Tucho *et al.,* 2014).

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Paraffin is a common energy source for homes, primarily for lighting. Poor and vulnerable households use paraffin because they have little access to alternative energy sources. Paraffin is an unclean energy source that is bad for the environment and human health (Uhunamure *et al*., 2017). In addition to meeting the demands of consumers, Liquefied Petroleum Gas (LPG) may significantly reduce the time required for kitchen cleanup and cooking. The high cost and limited availability of LPG in rural areas are the main obstacles to its widespread use (Synák *et al*., 2019). Furthermore, there is a lack of awareness regarding LPG and apprehension about possible disasters within households.

Combustible gas can be generated from organic material through anaerobic fermentation in biodigesters. Biogas is among viable renewable energy alternatives (Msibi and Kornelius, 2017). Since biogas is classified as green energy, it is considered sustainable (Parawira, 2009). Accordingly, biogas energy has the potential to complement conventional power generation sources and meet cooking and heating needs in rural areas (Van Nes *et al.,* 2007). Given that rural areas are disproportionately disadvantaged in energy supply, it is expected that biogas could play a critical role in meeting energy supply gaps in such setups (Rasimphi *et al.,* 2020).

The high environmental footprints of fossil fuels have seen many governments all over the world advocating for clean energy (Daneshgar *et al.,* 2022). Most clean energy is generated from renewable sources such as solar, wind, and hydropower (Zahedi *et al.,* 2021). As renewable energy resources, such as solar, wind, and biogas, are readily available, in most countries they hold potential in managing energy demand gaps (Budak *et al*., 2019). For instance, a global assessment estimates that wind energy potential could be double the current global electricity production levels (Saiffodin *et al.,* 2021).

Though biomass energy is considered one of the less costly energy alternatives, it is associated with a number of adverse health and environmental impacts (Chidembo *et al.,* 2022; Lam *et al.,* 2012). According to the World Health Organization (WHO, 2016), pollution from inefficient stoves causes over 500,000 deaths in Africa. The adverse health outcomes mostly impact women and children. Overexploitation of biomass such as charcoal for energy influences environmental degradation with drought and flooding episodes as some of the direct and indirect impacts (Smith *et al.,* 2024). This has been observed to accelerate environmental damage and forest loss across Africa (Kiruki *et al.,* 2016). Further reliance on biomass energy

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sources negatively impacts the livelihoods of agriculturally dependent households (Mchakulu, Erasmus, and Sonnenberg, 2019). The low conversion efficiency of biomass fuel into useful energy for heating, cooking, and lighting also implies a lot of labour and time constraints in its collection (Kebede, Bekele, and Kedir, 2002). Accordingly, households that depend on biomass such as firewood invest a lot of time and effort in sourcing it from nearby and distant sources (Muhumuza *et al.,* 2018).

Though South Africa generates a lot of electricity, access to and affordability of electricity remain the main challenge (Muhumuza *et al.,* 2018. Such challenges are exacerbated by low grid connections, poor stability in transmission, hence low reliability, low economic sustainability, as well as inefficient supply management in rural settlements (Ahlborg and Hammar, 2014). This has informed a focus on solar powered mini grids as one possible energy transition objective. Solar energy applications are essential for meeting energy demands in sectors like agriculture, healthcare, civil engineering, and the environment (Matasane and Kahn, 2019), as it can be used directly from the sun or in the form of photovoltaics (PV). Compared to other energy sources, solar energy is among the most vital, affordable, and environmentally friendly energy sources on Earth (Zahedi *et al.,* 2021). Food processing (drying) is one direct use of solar energy. Limpopo Province places a higher value on solar energy programs.

2.3 Social economic factors and energy security

There are several definitions of energy security. The World Energy Council (WEC, 2007) defines energy security to encompass accessibility, acceptability, dependability, quality of the energy sources, consistency of supply, and affordability to all. According to Hildyard *et al*. (2012), having access to fuel for use as well as being able to afford energy is a key component in energy security. Several indicators are used to measure energy access in a country. These indicators include availability and use of clean fuels for preparing food, proportion of renewable energy in total final energy consumption, energy intensity as measured by primary energy and GDP, foreign financial flows to developing nations in support of clean and renewable energy and installed renewable electricity generating capacity (Shaurya and Balachandra, 2024). Governments and practitioners can better implement the 2030 goal for access to electricity by knowing the current state of power availability. Such indicators are

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critical in decision making concerning energy access by Governments, energy utilities, financing agencies, private sector companies, and multilateral development organizations, as well as the monitoring the progress on electrification.

Cooking uses a lot of energy at home. The number of people who use cleaner fuels and technologies as their main source of energy for cooking at home determines access to these resources (Rosenberg, 2011). Access to clean cooking is therefore thought to be measured by the amount of electricity, biogas, solar energy, alcohol fuels, natural gas, and LPG used for cooking. The study examines the socioeconomic characteristics of households that affect the availability and utilization of different energy mixes as well as the probable effects on human welfare.

To lift rural communities out of poverty and advance a sustainable environment, access to clean, renewable, and efficient energy options is essential (Chiwaridzo, 2023). Since households account for 15–25% of global energy consumption, they are a primary target group in the study for behavioural changes on the use of fossil fuels. Numerous factors, including age, gender, employment status, income, education level, and the number of household members, influence energy use at the household level (Rahut *et al.,* 2017). According to existing literature, low-income households usually rely on firewood and other inexpensive energy sources because they are unemployed, which can be detrimental to both their health and the environment (World Bank, 2011; IEA, 2020; Barnes and Floor, 1996; Sehjpal *et al.,* 2014).

Education has the power to change people's beliefs, attitudes, and actions regarding the use and management of fossil fuels. According to Onyeneke *et al*. (2015), elderly people would rather use traditional biomass as a source of energy to meet their household needs. These elements make it more challenging for policymakers to successfully target smart energy investment priorities. To ensure an inclusive energy transition and support user behaviour, there is a need for unpacking socioeconomic factors influencing various innovations and their chain impact. Academia, social media, public and private extension service providers have a critical role in influencing behaviours on energy innovations (Mutumbi, Thondhlana and Ruwanza, 2022).

According to the integrated planning report (2013), coal accounts for 67% of South Africa's primary energy supply, with crude oil coming in second at 20% (Ndlovu & Inglesi-Lotz 2019).

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Natural gas, hydropower, and biomass account for about 13% of the energy mix (Akom *et al.,* 2021). Despite using only 2% of the country's water resources, the energy sector employs over 250,000 people and contributes 15% of its GDP, suggesting renewable resources have untapped potential for employment than the traditional coal-based energy sources.

Several socioeconomic factors, including age, gender, income, education, and the absence of steady employment income, may limit the shift to renewable energy. These efforts are also exacerbated by the high cost of electrifying rural areas, inadequate facilities, lack of political will, and weak institutional framework (Yao *et al*., 2012). The limited availability and affordability of renewable energy sources are another barrier to energy switching (Majeed *et al.*, 2023). Implicitly, socioeconomic factors are important to consider when switching to renewable energy, especially at the household level. However, little is known about how prevalent these factors are in rural households.

According to Meir *et al.* (2022), the development of an integrated policy framework should view energy as a cross-cutting issue as it impacts many economic and socio dimensions such as agricultural development, environmental protection, and poverty reduction. Renewable energy is thought to be critical in such a direction. However, financing of renewable energy infrastructure hardly focuses on small and medium sized producers and users. Integrated approaches, i.e., through solar cooperatives, in which households capture and sell excess electricity to the national grid, could complement the energy production and security objectives, a win-win strategy across many livelihoods and socio-economic sectors (Brennan & Cherry, 2021). According to Meir *et al.* (2022), viewing energy should be viewed as a cross-cutting issue, hence an integrated approach to its planning, as it impacts agricultural development, environmental protection, and poverty reduction.

Renewable energy is thought to be critical in such a direction. Notably, financing of renewable energy infrastructure hardly focuses on small and medium sized producers and users. Integrated approaches, i.e., through solar cooperatives, in which households capture and sell excess electricity to the national grid, could complement the energy production and security as a win-win strategy across many livelihoods and socio-economic sectors (Brennan & Cherry, 2021). The Saltuba Cooperative in KwaZakhele Township (Nelson Mandela Bay) exemplifies this approach, where a 5-kW community-owned solar array feeds into the municipal grid. The off

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grid solar generation project raises income for 36 households in addition to economic and environmental gains. Nonetheless, the project struggles with regulatory barriers, protracted licensing procedures, unstable municipal buy-back mechanisms, and a lack of access to finance for expansion (Joint Action for Water, 2023) as an example of policy barriers to promoting renewable energy sources in South Africa.

2.4 The centrality of energy in WEF nexus at household level

During the extraction, processing, and transportation stages, several renewable energy sources, including wind, solar power, and tidal, require minimal resource inputs, including water (Rabia *et al.,* 2015). it is anticipated that the share of renewable energy in the world's energy mix will rise dramatically in the medium term (IEA, 2023). Currently, renewable energy accounts for at least 19% of global final energy demand, with traditional biomass accounting for 9% (Lins *et al.,* 2015). The study attempted to analyse the socio-technical and environmental factors in renewable energy and how this impacts sustainability transitions. For instance, water consumption is tightly bound to the energy supply, as each process requires the use of energy. As illustrated in Figure 2.1, the water supply chain begins with a source, after which water is extracted (for example, by pumping groundwater) and transported, either directly to an end-user (such as irrigation, or commercial) or to a treatment or desalination plant, where it is supplied to customers (Rabia *et al.,* 2015).

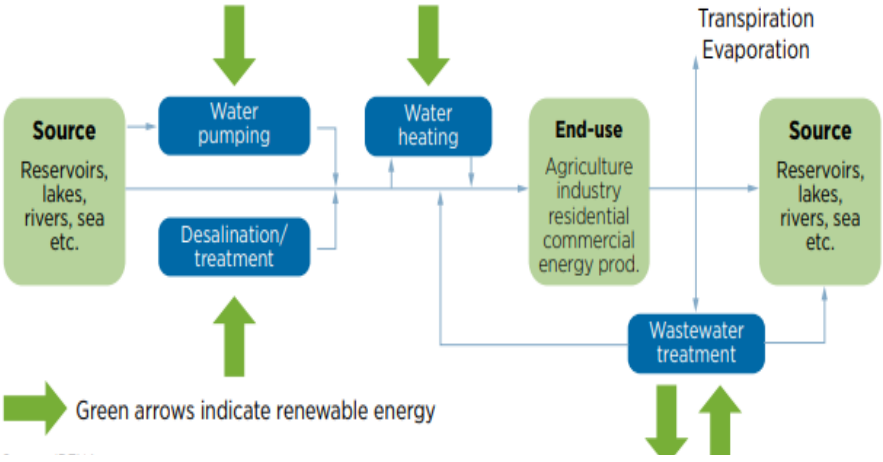


Figure 2.1: Renewable energy across the water supply chain (adapted from Rabia et al., 2015*)*

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The energy sector uses varying amounts of water, depending on the energy harvesting technology, the fuel type, and the water source. For example, diesel powered power generation plants require vast quantities of water in their nonstop cooling operations (Rai, 2023). Similarly, hydropower plants are dependent on reliable and high volumes of water (Lundaqvist *et al.,* 2008). The high environmental footprint associated with energy generation is evident in some countries, such as the United States of America, where hydropower energy generation systems use at least 41% of surface water with serious implications for freshwater depletion (Rogers, 2013). The environmental footprints could be higher when GHG emissions and climate change impacts are considered.

Improving access to safe drinking water is an energy-intensive process, especially if it is pursued through desalination. The energy is also required for wastewater treatment (Figure 2.1). At least ten times as much energy is required to treat brackish and saline water as freshwater, a process that has gained importance in some nations like Saudi Arabia and Sub-Saharan Africa (IEA, 2016). The hydraulic infrastructure requires a lot more energy to transport larger volumes of water over longer distances. This raises the energy input intensity of water supply schemes (Rabia *et al.,* 2015). Such considerations are integral to WEF nexus framing in household level life cycle assessments.

Water and energy are interconnected and dependent on each other, as water resources provide 90% of the world's power generation (FAO, 2014). Accordingly, global water withdrawals are expected to rise because of an 85% increase in the demand for water for energy production (Bekchanov *et al.,* 2016). This contrasts with a projected 35% increase in global energy demand by 2035, which could result in a 20% rise in water demands (Urpelainen and Van de Graaf, 2013).

In agriculture, energy is used across multiple food system value chains, such as land preparation, packaging, transportation, refrigeration, and food preparation (Ingram, 2011). For instance, tube-well engines used to pump in surface irrigation account for most of the direct energy use in food systems (Molajou *et al.,* 2021). Food systems thus are major energy users, with most of them being invariably non-renewable fossil fuels and contributors to GHG emissions and ultimately global warming risks (FAO, 2011). In response, climate smart agriculture

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(CSA) has been adopted as an approach to mitigate climate change risks and increase productivity (FAO, 2013). Energy efficiency is thus one of the objectives in promoting CSA, where farmers are encouraged to adopt energy-efficient practices that minimise production costs (Motola *et al.,* 2015) as well as reduce GHG emission intensities (Masuda, 2016) associated with a product or process commonly referred to as eco efficiency in food systems.

According to Rasul (2016), a nexus lens can optimize ecosystem services such as the provisioning of water, energy, food security, as well as reducing conflicts and increasing resource efficiency. Given the growing demand and competing interests surrounding the food, water, and energy nexus, it is imperative to enhance governance and management strategies for sustainable economic development. Water is essential for energy production, extraction, transportation, fossil fuel processing, crop irrigation, and food processing (Rasul, 2016; Mabhaudhi *et al.,* 2018). Thus, water is essential to the production of energy. However, energy is required for the mechanization of various agricultural and food processing processes (Mabhaudhi *et al.,* 2018) as well as for the distribution, treatment, and security of water (Hamiche *et al.,* 2016). The efficiency of resource use, equitable access to necessities like food and water, and sustainability in general are all likely to be significantly impacted by the nexus approach, household-level innovations, and practices (Musetsho *et al*., 2024).

From the aforementioned, it is crucial to manage the water-energy-food nexus, in terms of potential synergies and conflicts, as the interconnected and interdependent subsystems impact resource productivity, climate, and resource security (Albrecht *et al.* 2018). Solar energy is one of the technological innovations with the potential to reduce GHG emissions, thus mitigating global warming. Adoption of solar energy innovations could also have spillover effects on sustainable development and justice (Grubler *et al.,* 2018). At a practical level, for instance, the use of solar energy for irrigation (food production) addresses the WEF conflicts and synergies in agricultural production from several angles in terms of energy cost and efficiency as well as resource depletion outcomes (Patel *et al.,* 2024). The study assesses environmental footprints at the household level through partial life cycle lenses and the WEF nexus perspective as a proxy for sustainability objectives.

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2.5 Socio environmental and technical assessment of WEF innovations and practices

An increased emphasis on spillover effects and chain impacts from energy resources, such as solar, wind, biomass, water, and geothermal energy, is a result of the growing environmental challenges at the local to global scale (Agrawal and Soni, 2021). Renewable energy is very accessible, less expensive than conventional energy, and linked to very low greenhouse gas emissions into the atmosphere. As a result, governments and other energy-related policies around the world have started programs to encourage households in both urban and rural areas to reduce their use of fossil fuels or switch to much safer and cleaner renewable energy sources (Chidembo *et al*., 2022). This is a component of the green development and decarbonization initiative.

Countries transitioning towards more domestically produced, low carbon energy sources are expected to be more independent and less dependent on the global energy system. Such initiatives are in line with the climate action agenda under the Conference of the Parties (COP). South Africa is one of the signatory countries in the COP21 Paris Agreement for the energy transition from coal to clean energy. One of the key outcomes of the 2021 United Nations Framework on Climate Change Conference (UNFCC) was the reduction of emissions in South Africa through the Just Energy Transition Partnership or JETP (André van Wyk, 2022). South Africa's JET Program (Usman, 2022) is an evidence-based tool for policymaking, as South Africa transitions from a carbon-intensive economy to a more environmentally friendly one is one of the urgent needs.

Life cycle assessment (LCA) is an analytical process that examines the environmental impacts associated with a process, goods, or services from the point of acquisition of raw materials to the point of disposal. It is essentially a summary and assessment of a product system's life cycle inputs, outputs, and possible environmental effects. For instance, the LCA of coal is evaluated at every phase of its transformation, from mining to energy and waste products like greenhouse gases (GHGs).

Two types of LCA exist: Attributional LCA (ALCA), which monitors material and energy flows throughout a product's supply chain, as well as during use, disposal, and recycling (Plevin *et al.,* 2014). On the other hand, consequential LCA (CLCA) models the "activities included in the product system to the extent that they are expected to change as a consequence of a change

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in demand for the functional unit′ (UNEP/SETAC, 2011). Material flows and inventories in well-defined systems can be quantified using substance flow analysis (SFA), a mass balance-based analytical technique that makes it easier to determine the efficiency of resource production (Han *et al*., 2021). SFA is primarily concerned with the metal elements' metabolic processes (Mao *et al.,* 2008; Chen *et al*., 2018; Li *et al*., 2021). In this study, secondary data from the South African National Energy Development Institute (SANEDI) is utilized to evaluate the socio-economic and environmental footprints.

Benefit Cost Analysis (BCA) quantifies the extent to which benefits from a project exceed its costs over a specified period. It is essentially an economic method for weighing the advantages and disadvantages of a particular project or activity. The BCA criterion is a component of the project selection evaluation and prioritization process. Aggregating discounted future monetary values allows for comparison of the identified investment options (Yao *et al.,* 2018) at individual (private) as well as societal scale (Teot′onio *et al.,* 2021), i.e., the assessment of environmental and social third-party externalities (Neumann and Hack, 2022). Benefits include potential losses avoided, such as the prevention or avoidance of morbidity and mortality associated with pollution. Qualitative benefits, such as quality of life and natural and beneficial functions of ecosystems, can also be included in BCA. BCA technique can thus be applied to assess the potential benefits of an investment project in terms of reduced risks, such as GHG emissions. In essence, BCA enables decision-makers to arrive at informed solutions when faced with several investment options (Johson *et al.,* 2020).

The discount rate that brings the net present value to zero is known as the Internal Rate of Return (IRR) (Kay *et al.,* 2008). The intended investment is considered financially feasible when the Benefit Cost Ratio (BCR) is greater than 1. Conversely, the payback period is the amount of time that passes before the investment's benefits equal the initial costs of the investment, or the discount rate at which a project's net present value drops to zero. It makes sense that investments with shorter payback periods would be more attractive than those with longer payback periods. The investment amount is divided by the annual cash flow to determine the payback period. The project can be deemed economically viable if the IRR is higher than the rate of return on alternative investments with comparable risks (Johnson *et al*., 2020). For long term economic evaluation, IRR and Net Present Value (NPV) are the suggested

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methods since they consider both the time value of money and the amount of cash flow for the full investment life cycle (Kay *et al.,* 2008). Net cash flow was used to determine the profitability of both systems based on the NPV and IRR.

2.6. The Smart Energy concept in WEF

The water-energy-food nexus (WEF) is one of the tools for examining the interrelationships between resources and addressing intractable sustainability challenges (Schlör *et al.,* 2021). In essence, it has many practical and policy applications. For example, Malago *et al.* (2021) use the concept as an analytical tool for assessing the interconnection of SDG targets, concluding that the effect of renewable energy sources on sustainability is multifaceted, i.e., facilitating access to clean water and sanitation, enhancing affordability, access to clean energy, and meeting climate mitigation goals. In essence, failure to balance conflicts and optimise synergies of various sectors could result in incoherent policies and inconsistent outcomes (Blanc, 2015).

Metrics for evaluating any WEF innovation and related climate change impacts are provided by the chain impact or environmental footprints (Zebisch, 2021). The pursuit of WEF resource security goals in the face of climate change and sustainability transitions could thus benefit greatly from intelligent WEF innovations. According to Østergaard *et al*. (2019), smart energy systems in the energy sector concentrate on entire energy systems, including infrastructure designs and operation strategies that lead to the most efficient and least expensive solutions through sub-sector integration. Given that energy efficiency is a key factor in determining the intensity of GHG emissions, this is particularly crucial. Improving energy efficiency, herein defined as smart energy innovation and practices, could also be an economical way to satisfy demand without significantly raising energy production (Carli *et al.,* 2017). Therefore, when designing interventions for a sustainable energy mix, energy efficiency or smartness is crucial (World Bank, 2021).

In a study conducted in the Vhembe District Municipality, Musetsho *et al*. (2021) suggest impact pathways for evaluating WEF practices and innovations. The extent of energy intensities in production activities is accordingly traced to economic activities, i.e., food preparation and irrigation, as one of the common impact pathways at the household level. Intuitively, the substitution of non-renewable energy sources for renewable ones in economic and livelihood activities such as lighting, heating, and producing farm power and traction (Rabia *et al*., 2015) is

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considered a smart energy pathway. A partial life cycle analysis of some of the identified WEF innovations and practices at the household level is conducted with a view to informing policy and decision makers on just energy transition.

2.7. Conceptual framework for assessing energy mix and its impact

Two theoretical methods for analysing household energy choices and the energy transition process are "energy ladder" and "energy stacking" (Pachauri *et al*., 2004). According to the energy ladder theory, households are more likely to use advanced or modern energy sources as their incomes increase. This theory intuitively views primitive and/or transitional fuels as low-quality goods (Das *et a*l., 2014). Energy ladder principles state that when household income increases, there should ideally be a shift from one fuel type to another where energy alternatives are available. Three different energy ladders are identified by Pandey and Chaubal (2011).

1) Primitive i.e. fuelwood, crop wastes, and dung cakes.
2) Transitional i.e. coal, kerosene, and charcoal
3) Advanced (Modern,) i.e., LPG, electricity, biogas, and biofuels

Innovation can be defined as a pathway, idea, good, or service, including processes and procedures that are deemed novel in solving specific problems (Douthwaite & Hoffecker, 2017). From an energy perspective, the definition of innovation goes further to include various policy narratives on the type of energy, energy mix, and efficiency measures, as well as user behaviour on energy resources (Di Felice *et al.*, 2021). The energy ladder model could thus be essential in informing the innovation of responsive policies in energy transition and encouraging households to switch from dirty to clean fuels.

In a study of fuel use, peri-urban Dar es Salaam, Tanzania, Grimsby *et al.* (2024) characterize different energy ladder typologies as “innovations”. According to this logic, households leverage complementarities offered by different fuel types or innovations to overcome multiple constraints and meet their livelihood objectives by adopting multiple energy types (energy stacking). The energy stacking strategies offer opportunities for cost savings, income smoothing, and ultimately household energy security, all of which are critical in informing energy stacking innovation options. At the social level, motivations for energy stacking are largely underpinned

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by the need to meet the high energy needs of large sized households, as well as a coping mechanism on fuel price risks.

Though not always observable, poor households in a linear manner switch to cleaner fuels as their income increases (Khandker, 2012). Domestic energy choice behaviour and transition processes, particularly in developing nations, rarely take the form of linear energy switching behaviour between fuel types. Rather than switching straight from traditional to modern fuels, households that embrace "multiple fuels," or energy stacking, i.e., diversify their energy portfolio while maintaining the same income levels (Masera *et al.,* 2000). This could partly be explained by socio-economic and cultural lock ins that distort income energy ladder logic.

In this study, lockins could qualify as what Villamayor-Tomas *et al*. (2015) term institutionally mediated human agency factors that either mediate or constrain decision making. The case of South Africa, where the ease of connection to mains electricity is common irrespective of income status, fits this description. The popularity of using fuelwood to roast meat, commonly referred to as “braaiing” across socioeconomic strata, specifically serves as an example of cultural lockin that, to a greater extent, contradicts energy ladder theory. The factors that influence energy stacking decisions and transitions can thus be useful in examining the long-term effects of these fuels on the environment and human health (Masera *et al*., 2015; Anenberg *et al*., 2017; Quinn *et al*., 2018; Makonese, Ifegbesan, and Rampedi, 2018). Poor households often use solid fuel for cooking, heating, and lighting, which is detrimental to the environment and harmful to individual well-being (Lhendup *et al*., 2010; Heltberg, 2004).

The study, among other objectives, characterizes the effect of socioeconomic factors influencing households' energy choices in a rural setup in the context of the WEF nexus. Figure 2.2 provides a conceptual framework adopted for the study. Energy type and use are hypothesized to be influenced by socioeconomic characteristics of the household head. This includes educational attainment, age, income, and employment status. At the social level, motivations for energy stacking are largely underpinned by the need to meet the high energy needs of large sized households, as well as an economic coping response mechanism towards price volatility and inflation (Grimsby, 2024). This is in addition to cultural lock-ins, primarily in terms of perceived differences in the taste of food associated with specific energy types.

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Though household socioeconomic factors such as education level, on-farm and off-farm income characteristics are critical in the type of energy mix, such factors are likely to be impacted by intervening variables such as technological and economic lock-ins. For example, the tariff levels on solar and monopoly by Eskom at the time of this survey on energy generation may negatively impact the adoption of high-level energy sources, and the household income level.

Intervening variables such as policy and cultural lockins, for example, preference of fuel wood for roasting meat or "braaiing" may also influence energy type and use at the household, the household socioeconomic characteristics notwithstanding. Concisely, the socio-economic characteristics and lockins have a direct or indirect influence on each other and the energy type used. In turn, both singularly or jointly affect the choice of energy resources used at the household level and the ensuing impacts on the environment, social outcomes, health, as well as welfare outcomes such as health and educational attainment for school-going members of a household. The welfare effects could be direct when economic output is disrupted (as in load shedding) as well as indirectly when decreased access to electricity, for instance, interrupts mobility and undermines access to basic social services such as health care and learning (IEA, 2011).

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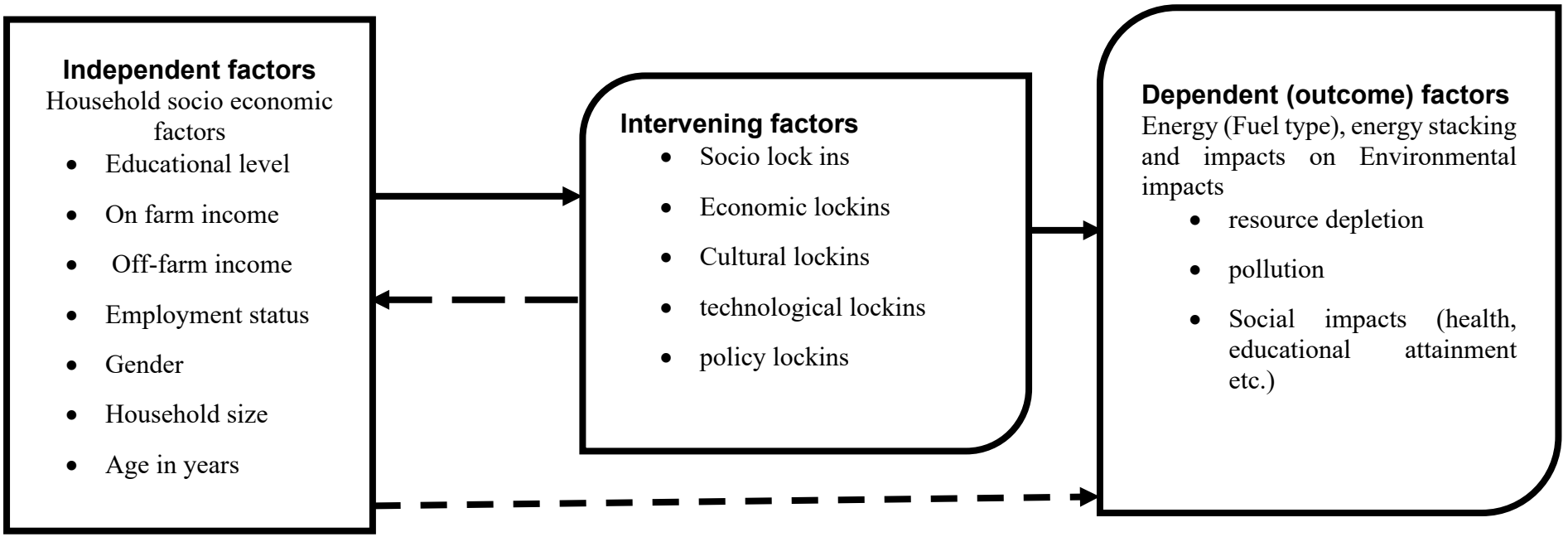


Figure 1.2: Conceptual framework on socio economic factors influencing energy mix at the household level in VDM.

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2.8 Summary

The review of literature presented in this chapter has demonstrated that energy access and use, particularly in rural areas such as the Vhembe District Municipality (VDM), remain complex and multifaceted issues. While South Africa has made notable strides in energy generation, particularly through the integration of renewable energy sources into the national grid, the dominance of coal and the uneven distribution of energy access remain pressing concerns. The country's heavy reliance on fossil fuels continues to contribute to environmental degradation, health risks, and socioeconomic inequalities.

At the household level, energy decisions are influenced not only by income and employment but also by education, gender roles, cultural norms, and access to infrastructure. The persistent use of traditional biomass and paraffin, despite electricity grid connections, highlights the relevance of the energy stacking model over the linear progression suggested by the energy ladder theory. Furthermore, cultural practices such as the preference for firewood in cooking specific foods alongside institutional and policy lock-ins, complicate the adoption of modern energy solutions even in grid-connected communities.

The literature further emphasized the importance of incorporating the WEF nexus perspective in understanding household energy dynamics. Energy access is inextricably linked to food production, water security, and environmental health. For example, water treatment and agricultural productivity require reliable energy inputs, while the extraction and processing of fossil fuels often place stress on water resources. Thus, the sustainability of energy systems cannot be assessed in isolation. Interventions in one resource domain frequently impact others, either positively or negatively.

Additionally, studies underscore the importance of LCA, BCA, and smart energy frameworks in evaluating the long-term impacts and feasibility of renewable energy technologies. Such tools offer critical insights into the environmental, social, and economic trade-offs of energy innovations, especially in rural and low-income contexts. The role of the JETP and South Africa's participation in international climate commitments further reinforce the urgency of inclusive, bottom-up strategies that engage local realities and capacities. In this context, the study is both timely and necessary. It responds to a significant gap in the empirical understanding of

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how socioeconomic factors, behavioural practices, and institutional conditions shape the household energy mix in rural South Africa. Moreover, it seeks to explore how WEF nexus thinking can inform a more integrated and sustainable approach to energy planning and innovation at the local level.

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CHAPTER 3: MATERIALS AND METHOD

3.1 Preamble

The section provides materials and methods to be employed in the study. This includes a description of the study area, design, data collection, and sampling methods.

3.2 Study area

The Nzhelele and Luvuvhu River Catchment Areas are in the northeastern region of South Africa's Limpopo Province (Figure 3.1). They are in the Municipality of Vhembe district.

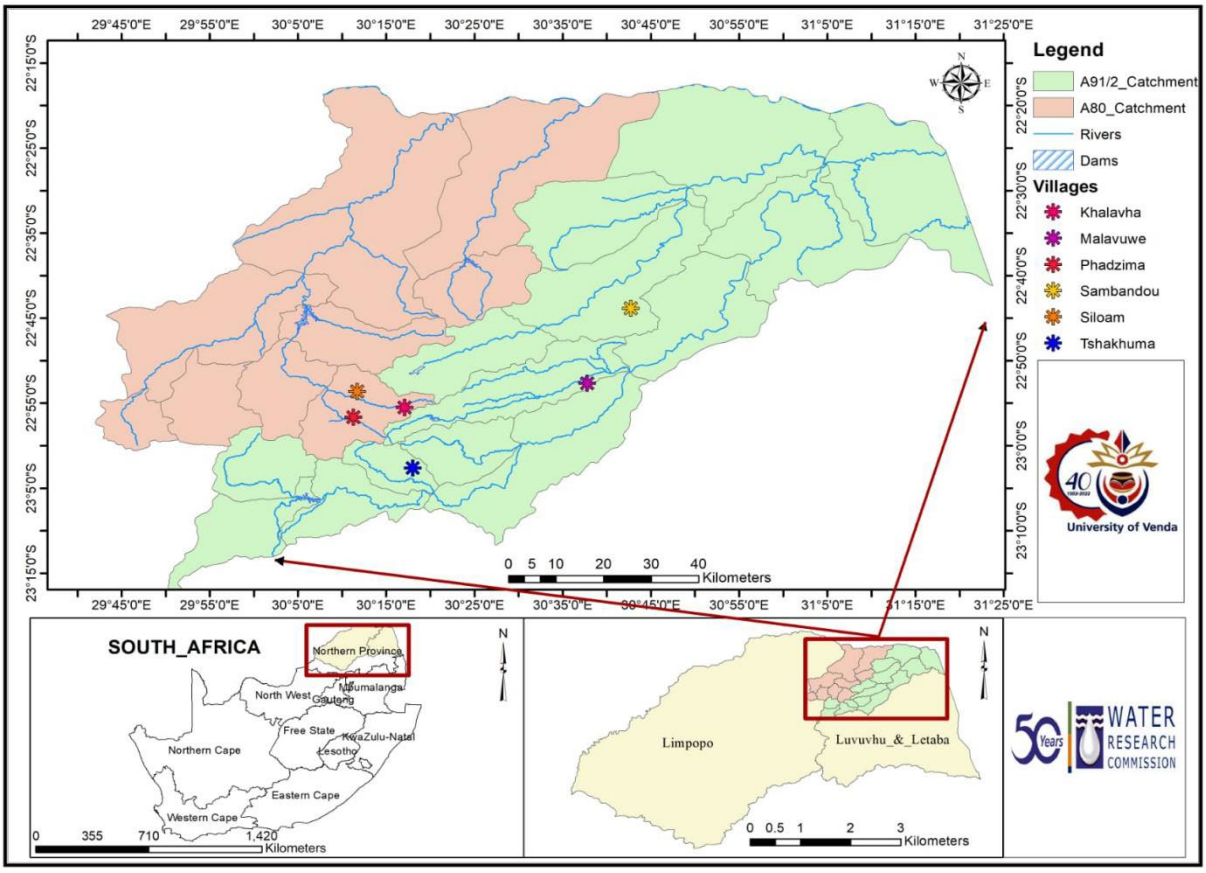


Figure 2.1: Map showing the study area.

Geographically, the Luvuvhu River Catchment is situated between latitudes 22.17°S and 23.17°S and longitudes 29.49°E and 31.23°E, while the Nzhelele River Catchment area is roughly 2,436 km2 and lies between 22°21′08″S and 30°22′19″E (Mazibuko et al., 2021). The

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summer months of October through April see the majority of rainfall, which is primarily seasonal (Nkuna and Odiyo, 2016). Makungo and Odiyo's (2017) study found that the mean annual precipitation for the Luvuvhu River Catchment ranges from 1800 mm in the northwest mountainous regions to 300 mm on the eastern side where the catchment joins the Limpopo River (Kagoda and Ndiritu, 2009), while the Nzhelele River Catchment has a range of 350 to 400 mm.

The study area is located within the Mokolian age's severely faulted Soutpansberg Group. The South African province of Limpopo contains fractured crystalline basement aquifers that include the Soutpansberg Group. The Soutpansberg rocks are rich in diabase dykes and sills (Brandl, 2003). Water table aquifers (the matrix regolith) are typically located on top of semi-confined (fractured bedrock) crystalline basement rocks (Holland, 2011).

According to Seeliger et al. (2018), South Africa is energy-rich, water scarce, and food insecure, as well as being one of the most economically unequal in the world. Implicitly, many households are at risk of food insecurity, more limited affordability and access to nutritious food (Simpson and Jewitt, 2019). The largest users of water resources are agriculture (62%), domestic (27%), energy production (6%), mining (2%), and industry (3%). This affects energy resource use. The primary source of income and livelihood in the area is predominantly agriculture, with small-scale seasonal gardening being prevalent. The main crops grown at the household level are vegetables, fruit trees such as oranges and avocadoes, maize, and peanuts. On a commercial scale, fruits, nuts, maize, tomatoes, and maize are common (Mpandeli, 2014). Summer is preferred as the most suitable season for farming because there is adequate rainfall to irrigate crops and enough solar energy to dry and preserve harvested crops, vegetables, and fruits (Raidimi, 2014).

In the rural households of Vhembe District Municipality, fuelwood is mostly used for space heating, water heating, and ironing clothes (Chidembo *et al.,* 2022). Since many households in rural South Africa lack stable employment and income (Uhumanure *et al.,* 2017), fuelwood is the preferred source of energy for cooking and water heating needs. Residents believe that using firewood saves the usage of electricity and that electricity should arguably be used for lighting and appliances. A partial life cycle assessment of various WEF innovations and

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practices could inform the formulation of responsive policy interventions, especially the envisaged Just Energy transition.

3.3 Data collection

Data on the use and accessibility of WEF resources in the study area were gathered from locals as well as relevant stakeholders using questionnaire surveys. The study employed a mix of qualitative (open-ended questions) and quantitative (closed-ended questions) research methods. Data on energy use in the study area were gathered through the survey. Residents suggested solutions, household energy use, demographics, and the factors influencing the adoption of smart energy technologies were the main topics of the questions. Ten initial pilot surveys were distributed to the households to assess the methodology and ascertain whether any revisions to the questionnaires were necessary. Additionally, the pilot process helped with survey planning and estimating the time needed to complete a questionnaire. A few sections of the questionnaire were revised after the pilot stage. The interviews were conducted in English for clarity, and where required, translation into the respondent's native Tshivenda language.

3.4 Research Design and Sampling Technique

The study adopted a mixed methods approach. A cross-sectional survey involved the administration of a semi-structured questionnaire to gather household data from household heads or their appropriate representatives. The households that were chosen for interviews were chosen using a multistage sampling technique. The selected catchments were separated into upper, middle, and lower regions in the first stage. Purposively chosen villages were used in the second phase. The local village administration supplied a sampling frame from which households were chosen at random for the third stage. A lottery procedure to assign random numbers in the selection of target household respondents was used to include households for administering the questionnaire. For convenience and to avoid security breaches during the data collection period, the consenting households were invited and interviewed at communal facilities such as community halls.

The household data was complemented with Key Informant Interviews (KIIs) and Focus Group Discussions (FGDs). The contents of the household questionnaire focused on biogas

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digesters, gas/Liquefied Petroleum Gas (LPG) usage, solar photovoltaic (PV), wind energy as possible innovations and practices at the household level. Additionally, it covered details about access to and use of water, energy, and food (WEF) resources, challenges faced, and reasons for choosing a particular water, energy, or food technology innovation. The semi-structured questionnaires (Appendix i) were administered to volunteering households among the randomly included households at a central location. To increase validity, triangulation of the data collected from household key informant interviews (KII) and focus group discussions (FGDs) was employed to supplement the household data collection instrument. A schedule between the researcher and local administration was agreed a priori on the administration of the questionnaire to the household head or appropriate representative (spouse or adult dependant over 18 years of age).

3.5 Sample size determination

The sample size was determined according to Fisher *et al. (*1983), which is as follows

$$n = Z^2 \left[\frac{pq}{d^2}\right] \quad \text{(3.1)}$$

Where:

n = desired sample size,

Z = Standard normal deviate at 95% level of confidence = 1.96,

P = proportion of the target population estimated to have the characteristic under investigation (10% or 0.1) to maximize sample size (precision),

q = proportion of target population without the characteristic (1-p = 90% or 0.9),

d = level of precision corresponding to a statistical significance level of 0.05 or 5%.

Substituting for the values $n = Z^2$ [(pq)/d2] = 1.962 (0.1* 0.9)/ (0.05)2 = 138.28, hence 139 households. However, the study was guided by fast and frugal heuristic logic (Hafenbrädl et al., 2016) in actual sampling and sample size determination. As suggested by Volenzo & Odiyo (2019) and Hafenbrädl et al. (2016) use of a few representative cases in risk assess-ments, as in the study, does not compromise accuracy, especially where the target population is relatively homogeneous. Pilot studies undertaken in the study catchment suggested WEF innovations and practices at the household level are characteristically similar across the water-

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energy-food i.e. food production in home gardens and use of mains electricity and biomass as main energy sources.

Based on sampling theory, sample cases above 30 are likely to be representative of a population, more so in the context of relatively homogeneous WEF practices and innovation studies. Accordingly, though 138 households were obtained from the calculations, only 128 were available for the administration of the questionnaire. The 128 respondents used in the study were thus considered adequate in exploring the socio-economic factors influencing energy use at household level. At least 30 households were targeted from each of the six villages forming the sampling frame. The target households were randomly identified, and willing participants were interviewed at a central location based on agreed schedules, followed by ground truthing whenever the need arose. However, the actual number of households sampled per village fell below 30, as shown in Table (3.1) due to insecurity challenges at the time of the survey. However, only 128 out of a possible 150 were interviewed. This was caused by a long-standing water scarcity protest and social disruption following some abductions and murders in the community. Accordingly, fast and frugal heuristic logic (Hafenbrädl *et al.*, 2016) was assumed in settling on a few representative cases. Few representative cases do not compromise accuracy in the analysis of the obtained data (Hafenbrädl *et al.,* 2016; Volenzo and Odiyo, 2020) where the target population is socio economically homogeneous as revealed by the pilot study undertaken prior to the main survey. According to the pilot study findings, the study area is mostly characterised by irrigated home gardens, use of wood as a major energy source, as well as off farm income employment, and clustered settlement.

Table 3.1: Sampled households in each village

Village	Catchment	Sampled households
Siloam	Nzhelele	13
Phadzima	Nzhelele	18
Khalavha	Nzhelele	35
Sambandou	Luvuvhu	24
Malavuwe	Luvuvhu	12
Tshakuma	Luvuvhu	20
Total		128

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3.6 Analysis of the data

3.6.1. Assessment of energy mix at household

This involved the assessment of various renewable and non-renewable resources as captured in the survey questionnaire. The available energy mix in the study area was analysed using descriptive and inferential statistics such as tables, frequency tables, and pie charts.

3.6.2. Evaluation of social economic factors influencing energy mix

Regression analysis using the multinomial logit model was applied in assessing socio economic factors influencing energy mix. The socio-economic factors include level of education, income, gender, employment status, age, and household size. Multinomial logit analysis in IBM^{R} SPSS^{R} statistics version 28.0 (SPSS Inc.) and a generalized linear logistic weight estimation procedure (Chicago, IL, USA) were used for the statistical analysis. A weight estimation process uses weighted least squares (WLS) to calculate a linear regression model's coefficient. This guarantees that when calculating the regression coefficients, more accurate observations i.e., those with lower variability are given more weight. A variety of weight transformations that best fit the data are tested by WLS. When a predictor variable changes by one unit, the weights are interpreted as a change in the logarithm of the odds ratio E(β). Equation (3.2) provides the odds equation. As the predictor variable is increased, a positive E(β) indicates a greater chance of falling into the target group, whereas a negative E(β) suggests a decreasing chance.

$$\Omega = ez/(1 + ez) \quad \text{(3.2)}$$

Where:

Ω = the probability of the event,

e = the base of the natural logarithms (2.718),

z = the linear combination calculated.

z is derived by formula in equation 3

$$z = a + \beta 1x1 + \beta 2x2 + \beta 3x3 \ldots + \beta ixi \quad \text{(3.3)}$$

Whereby,

a = a constant (intercept)

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βs = coefficients (the log odds) estimated from the data

xi = the values of the predictors.

The log of the odds ratio E(β) or logit expression is given as:

z = log (p/ (1 − p)……..……...……(3.4)

where:

P = Probability of falling into the target group which is the adoption of smart WEF technologies/ practices at the household level

q = no adoption of smart WEF technologies/ practices at a household level.

Pearson correlations were used to test for heteroscedasticity, which makes estimated ß's ineffective and therefore unsuitable for use in forecasting dependent variables (Appendix ii). Even though it is possible to examine a hypothetical aspect of any social phenomenon, responses could be skewed, particularly if the respondents are unfamiliar with the variable under investigation. Respondents' experiences reduced the likelihood of such biases because extreme weather events are frequent in the study area.

- **Student t-Test**

To assess the variation in adoption patterns related to the study area, a paired t-test of significance was used. The t-ratio was used to determine the significance of each regression coefficient for an explanatory variable Xi. The hypothesis that corresponding independent variables do not have a statistically significant linear impact on the dependent variable for the coefficient is tested by the t-statistic, also known as the Student t-test. It is calculated as the standard error (S.E.) divided by the estimated regression coefficient. Where the absolute value of t is less than the value of t corresponding to a specific level of significance, the null hypothesis is not rejected; if the absolute t exceeds this value, it is rejected. The coefficient is not significant in determining the dependent variable, according to a low t-ratio. However, the coefficient is considered statistically significant if the t-ratio is greater than the critical value at the selected significance level. Equation (6) yields the t-statistic for βi for a sample, and Table

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3.2 lists the independent variables used, their descriptions, and their levels. t = βi/βˆ , where s is the sample standard deviation and βi is the estimated value of the coefficient.

3.7 Socio environmental and technical assessment of WEF innovations and practices

Various techniques were applied to analyse the socio economic, technical, and environmental impacts of existing innovations and practices such as solar energy and comparisons made with conventional practices. Both primary and secondary data were used in the analysis. Data on energy, and water consumption, unit cost, and environmental footprints was calculated. The various techniques in socio technical and environmental assessment are summarised below.

- **Cost benefit analysis \ net present value**

The costs of different energy innovations and practices were compared at the household level using net present value (NPV) analysis. The present value of all costs (capital, replacement, operation and maintenance, fuel costs, and emissions penalties) less all revenues (primarily salvage) over the component's lifetime is the total net present value, according to Khare *et al.* (2016). The sum of the project's net present costs is its overall net present cost.

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Table 3.2: summary operationalisation of socio-economic factors used in analysis of SMART energy adoption, VDM

Independent variable	Description	Levels	Hypothesised relationship
Employment status	Type of employment	1= not employed; informal/self-employed; 3= formal (salaried)employment; 4= Retired/ pensioners	Positive correlation with smart energy innovation and practices
Education level	Highest level of education attained	1= no schooling; 2= primary level; 3= secondary; 4 TVET/ diploma or matrix; 5= University and above	Positive correlation with smart energy innovation and practices
Income by household head	Farming or employment Income in Rands (R) per month by household head	Income in Rands1= R2000; 2= R2001-4000, 3=R4001-6000; 4=6001- 8000; 5=8001-10000; 6= above 10,000	Positive correlation with smart energy innovation and practices
Total household income including remittances	Total income including remittances received by household	Income in Rands 1= R2000; 2= R2001-4000, 3=R4001-6000; 4=6001- 8000; 5=8001-10000; 6= above 10,000	Positive correlation with smart energy innovation and practices
Gender	Sex of the household head	Nominal, 1= female; 2= male	Neutral correlation with smart energy innovation and practices
Age	Age in years of the household head	Scale; actual years stated	Negative correlation with smart energy innovation and practices
Family size	Number of people under a roof of a household	1= 1-3 people; 2= 4-7 people and 3= above 7 people	Negative correlation

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NPV = Pn/(1+r)t -c……(3.5)

Where:

NPV = the Net Present Value,

Pn = the net cash flow in n^{th} year

r =the discount rate (interest)and

C= is the initial cost of the investment

- **Benefit Cost Ratio (BCR)**

The Benefit Cost Ratio (BCR), a measure of a project's cost effectiveness, is calculated by dividing its total net benefits by its total project cost. A project is deemed cost-effective when its BCR is 1.0 or higher. However, the incapacity of CBA to distinguish between distributional impacts regarding who pays and who benefits is one of its main weaknesses. Choosing the discount rate and the analysis's time horizon are two crucial decisions that must be made when conducting a CBA because they can affect the results (Chelli, Brander, and Geneleti, 2024). Sensitivity analysis, for instance, enables the economic assessment to be robust by employing multiple interest levels (Locatelli *et al.,* 2020). The average discount rate with sensitivity analysis considered a possibility for subsidies and inflation thus interest rate of 5, 10, 15, and 20 was assumed for all energy mix and innovations cases in the analysis.

- **Partial life cycle assessment**

A standardized methodology known as life cycle assessment (LCA) takes resource consumption and emissions into and out of the environment into account when estimating the environmental effects of a product or service throughout its life (ISO 14040, 2006). LCA is thus a valuable method for assessing, comparing, calculating, and developing products and services concerning their possible environmental effects (Rebitzer *et al.,* 2004). In this, one can select technology based on LCA (Khoo *et al.,* 2010). This study compared various household energy mixes based on consumption level and associated with GHG emissions. Solar based and coal fired power systems provided the baseline reference point for comparison. Based on the calculated results, the energy and environmental performances of the two models were compared.

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A free online software openLCA v1.9.0 (GreenDelta,2019). A thorough and recently updated impact assessment method tool for modeling Life Cycle Assessments (LCAs) is ReCiPe 2016 v.1.1. This includes narrowly modeling the life cycle by visually or tabularly connecting processes, evaluating them for their effects on the environment, the economy, or society, and analyzing the results to identify hotspots. The hierarchist approach is used in this study because it considers climate change over a 100-year time horizon (GWP100) and incorporates climate-carbon feedback in accordance with the IPCC's Fifth Assessment Report (2014). The chosen characterization factors in this study are at the midpoint level because of their relatively low uncertainty and stronger relationship to the environmental flows (Huijbregts *et al.,* 2017). The study adopted midpoint impact categories as listed in (Table 3.3). The assessed mid-point categories were limited to those that are relevant to the study area and data availability, hence a focus on water and carbon footprint only. The findings from the partial life cycle assessment were used in inference on other impacts such as health and climate change risks.

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Table 3.3: Overview of Mid-point impact categories and related indicators in life cycle assessment of main energy resources

Midpoint category	Indicator	Unit
Climate change	Infra-red forcing	$KgCO_2eq$ to air
Fine particulate formation	PM2.5 intake	Kg $PM_{2.5}$ eq to air
Land use	Occupation and time integrated land transformation	Agricultural land M^2 annual crop equivalent
Water use	Increase in consumed water	M^3 water equivalent
Photochemical oxidant formation (human health)	Tropospheric ozone population intake increases	Kg NO_X equivalent to air

Source: Adapted from Huijbregts *et al.,* 2017

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3.8 Research ethics

This study received ethical clearance from the University of Venda's Higher Degrees Committee, under the Faculty of Science, Engineering and Agriculture. The ethics approval reference number is FSEA/23/ES/11 (Appendix ix). Following the institutional approval, further permission to conduct the research was obtained from traditional authorities, including the local chief and headman, in recognition of customary leadership structures and the importance of engaging with gatekeepers in rural communities.

Before participation, all respondents were given a clear verbal and written explanation of the research aims, procedures, and potential risks and benefits. This was done in the participants' preferred language to ensure full understanding. Informed consent was obtained from each participant in writing, in accordance with ethical research guidelines. Participants were assured that their involvement was entirely voluntary and that they could withdraw from the study at any time without any consequences.

Confidentiality and anonymity were strictly maintained throughout the study. No personally identifiable information was recorded or shared, and all data was stored securely. The privacy of participants was safeguarded in line with the recommendations of Musakwa *et al*. (2020), ensuring that all information provided remained confidential and used solely for academic purposes.

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CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Preamble

The results of a study on energy management and use in the Nzhelele and Luvuvhu river catchment areas in the Vhembe district municipality of the province of Limpopo are addressed in this chapter. Tables and graphs are used to present the results.

4.2 Socioeconomic dynamics of the sample population

Understanding the socioeconomic factors influencing access (interchangeably referred to as energy security), as well as the impact pathways of various energy mixes, is critical in energy transition and sustainable development. Table 4.1 gives a summary of the household socioeconomic characteristics and energy mix in the study area. The sample of 128 consisted of about 51% male and 49% female respondents. About 56% of the respondents were unemployed, with only about 14% being in formal employment and about 26% being self-employed (informal employment). A myriad of energy types are used at the household level. This includes mains electricity at about 95% and solar at about 6% being the least energy type. Most of the households, about 95% of the respondents, used energy for cooking, and about 72% for heating. The factors influencing energy type are explained in later chapters.

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Table 4.1: Summary socio economic characteristics and energy mix at household level, VDM

		N	Marginal %
Gender of the respondent	Male	65	50.8%
	Female	63	49.2%
Highest level of education attained	No schooling	10	7.8%
	Primary education	19	14.8%
	Secondary education	79	61.7%
	TVET/College education	16	12.5%
	University education	4	3.1%
Employment status	Formal employment	18	14.1%
	Informal (Self) employment	33	25.8%
	Unemployed	71	55.5%
	Retired	6	4.7%
Mains Electricity	No	6	4.7%
	Yes	122	95.3%
Biomass	No	41	32.0%
	Yes	87	68.0%
Solar	No	121	94.5%
	Yes	7	5.5%
LPG	No	122	95.3%
	Yes	6	4.7%
Paraffin	No	122	95.3%
	Yes	6	4.7%
Uses Energy for heating	No	36	28.1%
	Yes	92	71.9%
Uses Energy for lighting	No	17	13.3%
	Yes	111	86.7%
Uses Energy for cooking	No	6	4.7%
	Yes	122	95.3%
Uses Energy for cooling	No	113	88.3%
	Yes	15	11.7%
refrigeration/freezer	No	47	36.7%
	Yes	81	63.3%
Run TV/Radio	No	34	26.6%
	Yes	94	73.4%
Uses energy for appliances	No	20	15.6%
	Yes	108	84.4%
Valid		128	100.0%

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Income is a crucial determinant of the type of energy use at the household level. According to a study by Uhunamure *et al*., (2017), low-income households, typically utilize firewood because they lack the means and options to fully transition to modern technologies. About 37% of the respondents earn between R0 and R 2000; 27% of respondents earn between R2001 and R4000; 15% of participants earn between R6001 and R10000; and lastly, 7% earn above R10000 (Figure 4.1).

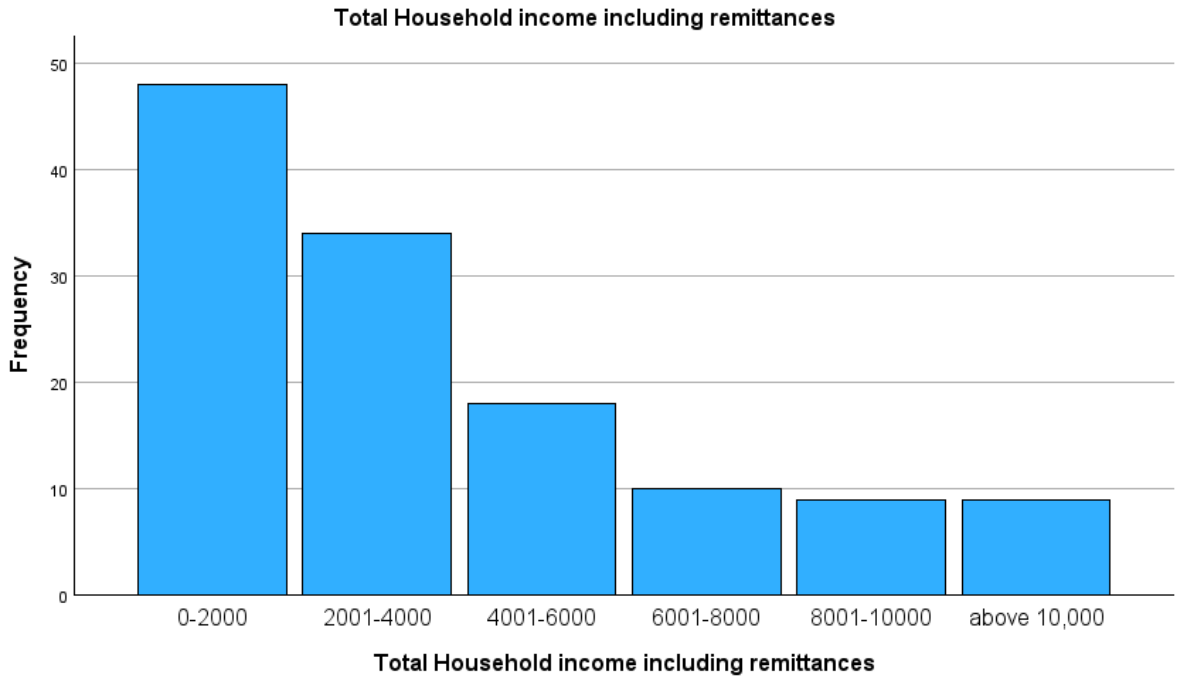


Figure 3.1: Total household income, VDM.

According to survey results, most of the respondents (about 48%) were low-income earners (R0-2000). The majority of respondents earned R2000 or less a month. In this category were mostly elderly people and recipients of government grants. This category of income earners has limited options when it comes to using alternative energy sources to meet their household needs (Lusani *et al.,* 2022). The findings of this study indicate that 4.7% of households in the study area use LPG (Table 4.1). Participants indicated that they use LPG for cooking and water heating when there are inconveniences with using firewood, such as during rainy days. However, due to high purchase price fewer households in the study area use LPG.

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Table 1.2: Cross tabulation on education attainment total and total household income (in Rands)

Highest level of education	0-2000	2001-4000	4001-6000	6001-8000	8001-10000	above 10,000	Total
No schooling	7	0	2	1	0	0	10(7.8%)
Primary	11	6	1	1	0	0	19(14.8%)
Secondary	26	25	11	6	6	5	79(61.7%)
TVET/College	4	2	2	2	3	3	16(12.5%)
University	0	1	2	0	0	1	4(3.1%)
Total	48(37%).	34(26.7%)	18(3.7%)	10(7.8%)	9(7%)	9(7%)	128

Figures in parentheses () indicate percentage (%).

None of the respondents without schooling or with only primary level education earned above R8000. Though many of the respondents (about 62%) had attained secondary level education, the majority earn between R2000- R4000 (Table 4.2). In general, income directly corresponds with educational attainment. As seen later in the education attainment is critical in smart energy adoption, and funding education becomes an important aspect in smart energy policy objectives.

The income at the household level has a high correlation with the type of employment. Figure 4.2 provides the employment status of the respondents. Approximately 12.5% of participants have formal employment; 25.8% of participants are self-employed or have informal employment; 55.5% of participants are unemployed; 4.7% of participants are retired. The results indicated that most participants were unemployed. Employment status is a proxy for the level of income, hence the energy mix used by the household.

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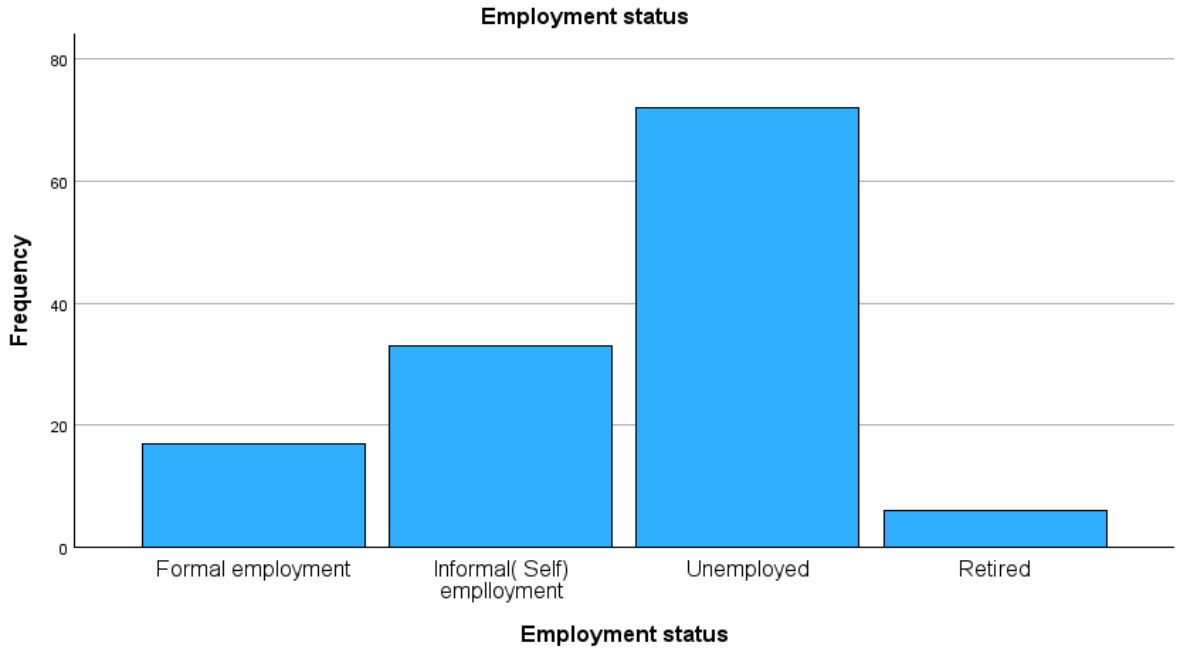


Figure 4.2: Employment status of respondents at VDM.

Individuals without formal jobs also disclosed that they depend on social grants as well as relatives' remittances to sustain themselves. According to Lusani *et al.* (2022), the majority of such low-income households are more likely to use firewood in meeting their domestic energy needs, for heating, lighting, and cooking. Implicitly, employment and income are major determinants of the choice of energy type and thus correlated with adverse environmental/ health outcomes.

Since the head of the household's literacy level affects the information available to the household, education is an important factor in determining the type of energy used in a household. Participants were questioned about their greatest level of education in order to assess how education affects the energy source. The respondents' educational status is shown in Figure 4.3. 7.8% of participants have no formal education, 14.8% have completed primary school, 61% have completed secondary school, 12.5% have completed TVET or college, and 3.1% have completed university. According to the findings, 61% of the respondents had completed at least secondary school.

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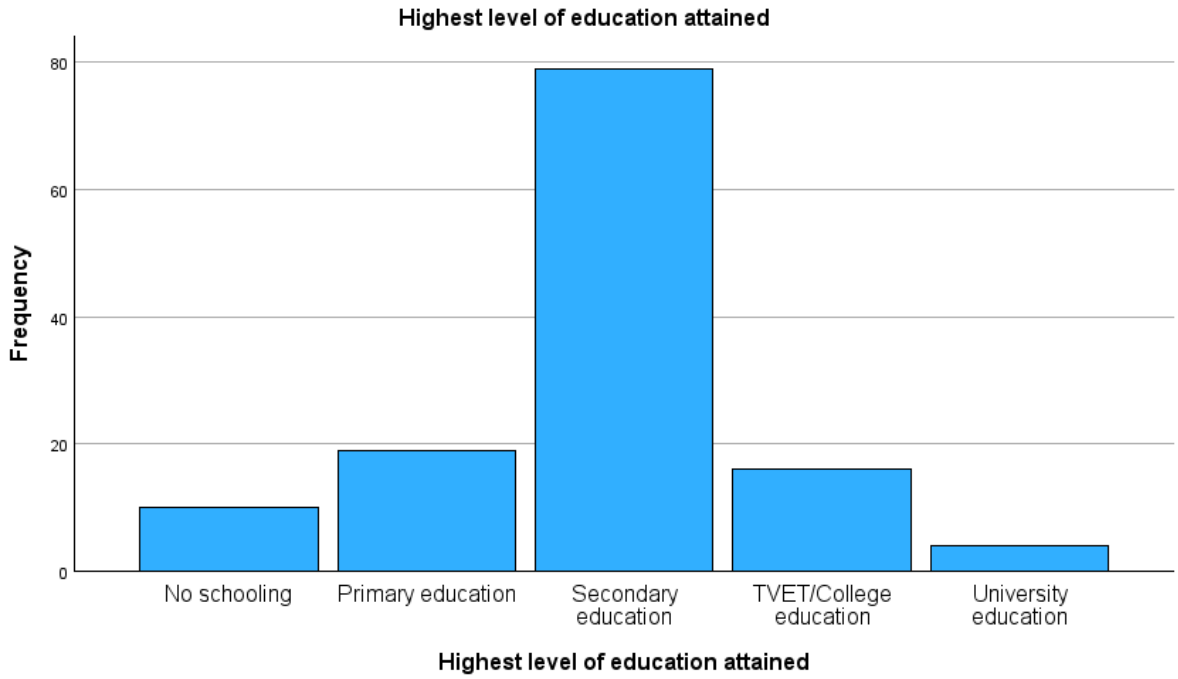


Figure 4.3: Level of education among respondents at VDM.

Regarding the type of energy that the household should use, participants have different opinions and attitudes. Most knowledgeable participants favored using modern energy technologies while also preserving and protecting natural resources for future generations. According to the relationship map (Figure 4.4), most households with no schooling and primary education were less likely to use level 3 of the fuels in the ladder of energy when compared with those of secondary and tertiary education. This is logically anticipated as those without schooling and /or low education are less likely to be employed, hence earn less income, and or have low disposable income. However, biomass use occurs across all levels of educational attainment, suggesting that socio-cultural factors could be responsible for influencing biomass use. Though the same pattern occurs in the use of LPG and solar, their use is slightly higher with the attainment of the secondary education level and above.

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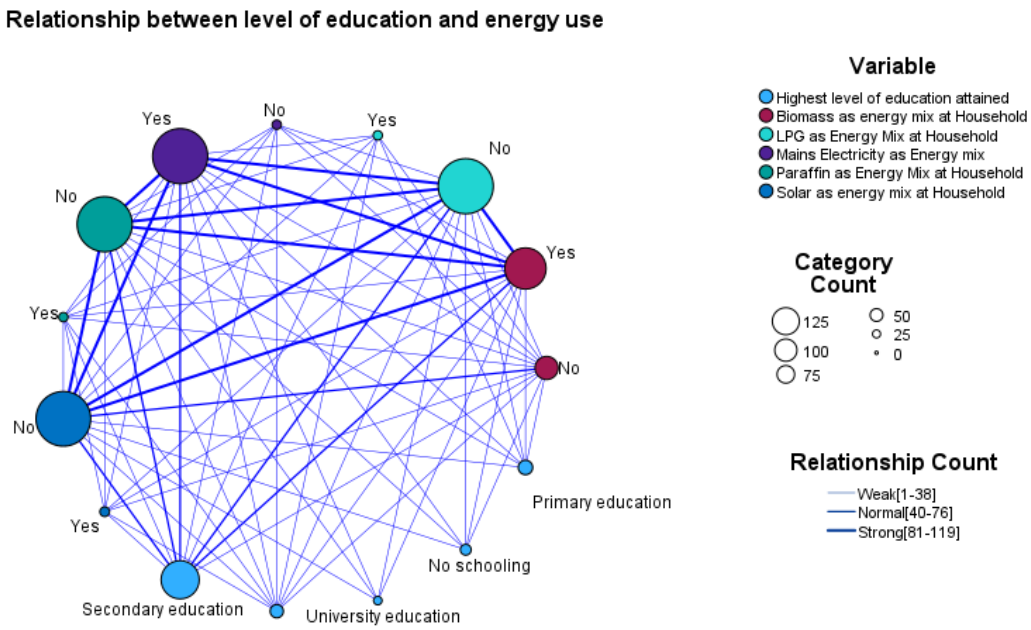


Figure 4.4: Relationship map between education and energy mix at the household level

Figure 4.5 shows the gender distribution of the respondents. About 49% of the participants are males and 51% are females. The distribution is characteristic of South Africa's population demographics. The study conducted by Semenya and Machete (2019) revealed that most women are in control of cooking, firewood selection, and sourcing for household needs. The conclusion was confirmed by a study conducted by Ateba *et al*. (2018), who concluded that women are traditionally expected to take care of the households by cooking, gathering firewood, and doing other household chores. As a result, these women may be responsible for making decisions about energy use in the house.

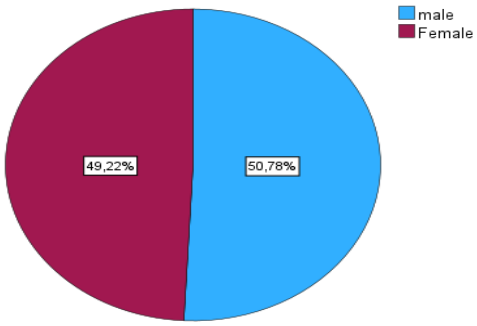


Figure 4.5: Gender distribution of respondents

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Table 4.3 provides the use of biomass energy by gender. Overall, about 71% of the households used distinct types of biomasses. About 56% (51 out of 91 respondents using biomass) of female-headed households' biomass, against 44% (40 out of 91 respondents using biomass) for male-headed households. As expected, most female headed households fall into low-income categories based on their low educational attainment and/ or caring for larger household sizes.

Table 4.3: Cross tabulation of biomass against head of household gender

Gender	No	Yes	Total
male	25	40	65
Female	12	51	63
Total	37	91	128

Figure 4.6 gives the age distribution of the respondents. 1.56% of households are headed by participants below 20 years; 3.91% of participants are aged between 21-30 years; 19.53% of participants are aged between 31-40 years; 17.19% of participants are aged between 41-50 years; 29.91% of participants are aged between 51-60 years; and lastly 28.91% of households are headed by participants above 60 years. Most respondents are aged between 51-60 years, followed by those above 60 years. According to the study conducted by Hooper *et al.* (2018), elderly family members, in particular, who are the head of the household, prefer to use traditional biomass like firewood, which, in their opinion, improves the flavour when compared to food cooked using electricity or other energy sources.

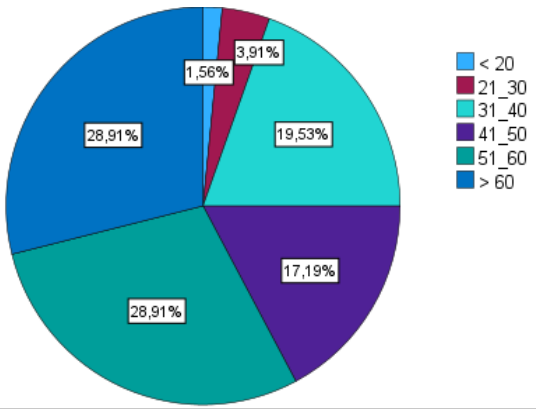


Figure 4.6: Age distribution of respondents.

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The relationship map in Figure 4.7 shows that mains electricity is used across economic strata regardless of income levels. Main electricity reflects the technological and economic lockins for most households in South Africa. This could have locked most households from investing in alternative energy sources higher up the energy ladder. Nonetheless, it becomes apparent that households with low earnings are less likely to use solar and LPG as energy sources as opposed to those earning R6000 and above. An increase in age (above 61 years) increased the likelihood of using biomass energy sources. Paraffin was less likely to be used by those under 20 years old. LPG was commonly used by those aged 41-60 years. The findings are consistent with existing literature on biomass use.

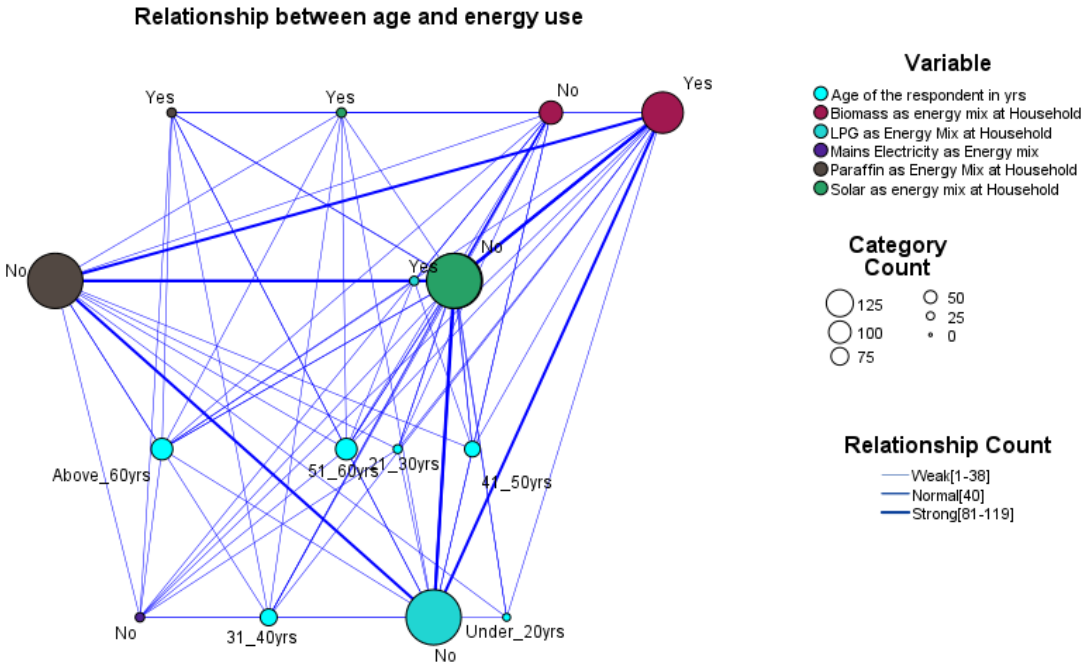


Figure 4.7: Relationship map on age, gender, and fuel type, VDM

Figure 4.8 shows the results of the number of members living in a household. The results show that households have members between 1-3 (20.3%); members between 4-6 (60.2%); and members between 7 and above (18.8%). The higher the number of people living in a household the more energy is needed to meet the household's needs. Households with many members (7 and above) were more likely to use an energy mix in the ladder of energy than households with fewer members. The observation may be attributed to low disposable income among such households, as previously explained, such households are also likely to female headed and in informal employment or unemployed.

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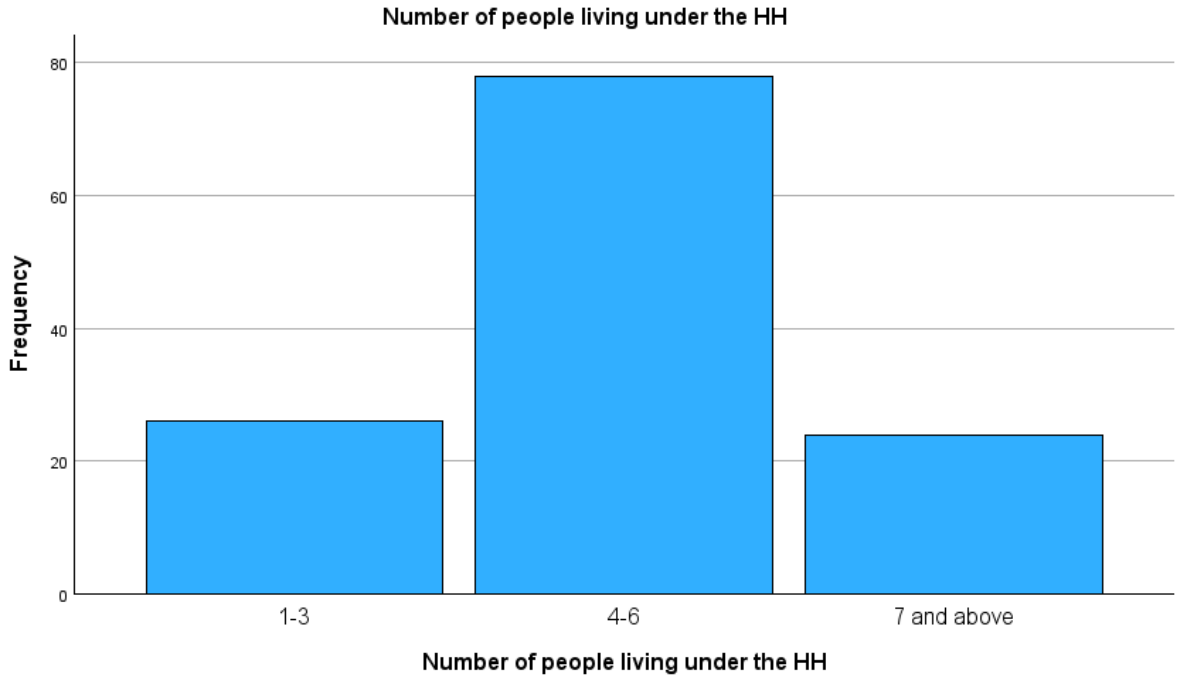


Figure 4.8: Number of people living in a household.

4.3 Energy mix at household level, VDM

The findings of the study indicated that there are various energy sources in the area, such as electricity, biomass, solar, Liquefied Petroleum Gas (LPG), and paraffin, as shown in Table 4.4. At least 96% of the households have a connection to mains electricity. This is one of the economic and policy lockin that may influence the adoption of alternative smart energy options. Biomass is used by almost 69% of households. The high use of biomass may suggest the population in VDM are likely to cause ecological harm from desertification, salinization, and land destruction as suggested in studies by Li *et al.,* (2021) Tang *et al.,* (2021); Yang *et al.,* 2018) and are also highly exposed to indoor pollution and associated adverse health risks (Uhunamure *et al.,* 2017; WH0, 2016) as well as causing environmental degradation as suggested by (Kiruki *et al.,* 2016; Chidembo *et al.,* 2022; Lam *et al.,* 2012).

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Table 4.4: Energy mix at Household level, VDM

Energy mix at a household level	Responses	
	N	%
Mains electricity as energy mix at household	122	53.
Biomass as energy mix source at household	87	38.2
Solar as energy mix source at household	7	3.1
LPG as energy mix source at household	6	2.6
Paraffin as energy mix source at household	6	2.6
Total	228	100

Table 4.5 provides statistical tests on the types and use of energy. There are significant differences in the use of biomass and solar, as well as paraffin ($P< 0.05$), and this could be due to different reasons such as income and educational attainment. As for use, a significant difference only exists in use for cooking. The use of paraffin was mostly in brooding of chicken and could partly explain the significant difference in its use. Only a few households practiced commercial poultry production in general and broiler production in particular. Solar energy was only adopted by a few households. According to FGDs and KII, the high cost and lack of awareness, coupled with an unsupportive legal framework, hindered solar energy adoption. Indeed, most of the panels were only installed following the extensive load shedding.

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Table 4.5: Measure of statistical differences in energy type and use at the household level, VDM

	-2 Log Likelihood	Chi-Square	Sig.
Mains Electricity	134.320	1.161	.281
Biomass	136.865	3.705	.054
Solar	137.018	3.859	.049
LPG as Energy Mix at household	133.706	.547	.460
Paraffin	144.459	11.299	<.001
Uses Energy for heating	140.215	7.055	.008
Uses Energy for Lighting	133.209	.050	.823
Uses Energy for cooking	140.074	6.915	.009
Uses Energy for Cooling	135.315	2.155	.142
Uses Energy for refrigeration/Freezer	133.271	.111	.739
Uses Energy to run TV/Radio	133.769	.609	.435
Uses Energy for Appliances	133.195	.035	.851
-2 log-likelihoods =133.159; Nagelke =.377; Sig.004			

Table 4.6 provides an analysis of reasons for the use of energy at the household level in the study area. About 96% (Table 4.4) of participants use electricity as the main source of energy. According to the survey results, electricity is used across all economic strata and reflects technological lock-ins in energy use in the area and mix in South Africa at large. However, according to the respondents, loadshedding related technical issues with energy supply, technical problems with their meter boxes, or the high cost of electricity make it largely unreliable in their area.

Lighting and other electrical appliances like TVs, phones, refrigerators, and machinery are the primary uses of electricity. Respondents indicated that electricity is crucial for water pumping. Alternative renewable energy sources such as solar energy hold the potential of being a viable pathway for achieving smart energy use at the household level. About 37% of the respondents attributed their use of mains electricity to its ease of availability. Approximately 30% cited convenience in use of mains electricity as the reason why they rank it higher than other energy sources, such as biomass.

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Approximately 14% of respondents attributed the use of mains electricity to policy and economic lockins (being the only option available to them). Only 6.3 % of the respondents attributed the high cost of alternatives as the reason why they use the main electricity.

Table 4.6: Reasons for the preference of mains electricity at Household level, VDM

Reason	Frequency	%
High cost of alternative	8	6.3
Easily available	47	36.7
Cheap	3	2.3
Convenient	38	29.7
lockins (modern, only source, culture)	18	14.1
Do not know	14	10.9
Total	128	100.0

Table 4.7 provides the perception of the respondents on electricity as an energy source at the household level. At least 20% of the respondents rank it as poor to poorest. The distinct reasons for this perception include load shedding and cost. About 10% of the respondents were not committed to ranking mains electricity, while at least 70% ranked mains electricity as good to excellent. The main reason for this is the ease of availability. The significance of this pattern implies that despite national electrification efforts, energy inequality persists within the district, potentially aligned with geographic, socio-economic, or infrastructural disparities. This inconsistency in perceived electricity service may impact household productivity, education, health outcomes, and willingness to adopt modern or smart energy alternatives. The data underscores the need for targeted infrastructure improvements, better maintenance of distribution networks, and more inclusive energy planning to ensure equitable access across all communities.

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Table 4.7: Ranking of electricity at the household level. VDM

Rank	Frequency	%
Extremely poor	16	12.5
Very poor	12	9.4
Poor	26	20.3
Good	41	32.0
excellent	21	16.4
Do not know	12	9.4
Total	128	100

Table 4.8 provides the main challenges in the use of mains electricity at the household level. Load shedding emerged as one of the major concerns for about 47 % of the respondents. About 12 % of the respondents were unable to identify any challenges, while 32% had issues with high cost. Lack of awareness regarding alternatives was identified by about 10 % of the respondents. Load shedding is a serious problem that needs urgent attention at the policy level. Resolving load shedding may mediate an increase in the use of mains electricity. In turn, this could reduce the use of biomass energy sources. In the long term, reduced reliance on biomass could reduce demand for fuelwood, hence reducing environmental degradation.

Table 4.8: Challenges in mains electricity

Challenge	Frequency	%
cost	41	32.0
lack of awareness	12	9.4
Do not know	15	11.7
Load shedding	60	46.9
Total	128	100

About 69 % of the respondent households used biomass (Table 4.9). According to the respondents, the primary reason most homes use firewood is that it is inexpensive, readily available, and universally affordable, making it a cost-effective option for meeting domestic demands. A truck is hired to bring a load of firewood purchased in bundles from the firewood market, or it might be harvested by hand. The findings concur with Rasimphi *et al.* (2020) on high use of biomass for heating and cooking. Compared to households headed by men, households headed by women use most of the biomass. Gender issues should therefore be considered when planning for the clean energy transition. Rural communities

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are dominated by impoverished households with limited or no access to energy services. In the process of obtaining fuelwood for cooking and heating, this could also indicate deforestation (WHO, 2002).

Table 4.9: Cross tabulation of biomass uses for heating by household head gender

Gender	No	Yes	Total
Male	45	20	65
Female	24	39	63
Total	69	59	128

Though biomass energy sources are associated with adverse environmental and health impacts, most of the respondents in the study ranked (Table 10) them as a good (44.5%) to excellent (33.6%) source of energy, with about 11 % of the respondents ranking them as either a poor or very poor source of energy. The findings suggest that majority of the respondents are not aware of the environmental and health risks associated with biomass energy use. Risk communication alongside economic empowerment programmes is thus likely to impact risk perception and adoption of safer energy alternatives at the household level.

Table 4.10: Ranking of biomass energy, VDM

Rank	Frequency	%
Very poor	6	4.7
Poor	8	6.3
Neutral	13	10.2
Good	57	44.5
Excellent	43	33.6
missing	1	0.8
Total	128	100

Table 4.11 indicates that the majority of households in the study area (87.5%) are not using solar energy, highlighting a low level of adoption within the Vhembe District Municipality. Among the few who do use solar energy, the most common reason cited is its easy availability (5.5%), followed by perceptions of it being cheap (2.3%) and convenient (2.3%). Other motivations, such as avoiding the high cost of alternative energy sources (0.8%) and mitigating the impact of loadshedding (1.6%), were mentioned by very few respondents.

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These findings suggest that while solar energy has certain recognized benefits, its uptake remains minimal, possibly due to barriers such as lack of awareness, access, or affordability issues that warrant further investigation and targeted intervention.

Table 4.11: Reasons for the use of solar

Reason	Frequency	Percent
High-cost alternative	1	0.8
Easily available	7	5.5
Cheap	3	2.3
Loadshedding	2	1.6
Convenient	3	2.3
Not using	112	87.5
Total	128	100.0

According to one respondent, load shedding was the main reason for starting to use solar technology.

> *"I installed solar to ensure my grandchild can read and complete her homework. Otherwise, she would be missing assignments as load shedding is a common occurrence. We experience load shedding almost daily, and times when she is supposed to be attending to her assignments".*

Results in Table 4.12 reveal that a significant proportion of respondents (64.1%) indicated a lack of knowledge regarding the challenges associated with solar energy, choosing the response "Don't Know." This suggests a widespread lack of awareness or understanding of solar energy technologies within the Vhembe District Municipality (VDM). A further 25.8% of responses were recorded as "N/A," possibly indicating that these respondents had no experience with solar energy. Only 7.0% identified the high initial cost as a barrier, which is commonly cited in existing literature as a major constraint to solar adoption. Meanwhile, weather-related challenges were reported by just 3.1% of respondents.

These findings suggest that while cost and weather are known technical barriers, the dominant issue in this context is informational or experiential, pointing to the need for community education, awareness campaigns, and possibly demonstration projects. Addressing this

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knowledge gap may be essential to increasing the adoption of solar technologies at the household level in VDM.

Table 4.12: Challenges associated with solar energy at household level, VDM

constraint	Frequency	%
High initial cost	9	7.0
Weather	4	3.1
N/A	33	25.8
Don't Know	82	64.1
Total	128	100.0

Table 4.13 provides the factors influencing solar energy adoption. Though all factors were not significantly different, total household income was positively correlated with solar energy use. Age and reliance on farming alone were negatively correlated with solar innovation adoption. The age of the household head and farming income seem to negatively influence the use of solar, while total household income positively influences the adoption of solar technology. However, neither factor is statistically significant. The findings are consistent with existing logic, as solar technology requires substantial initial investment. The results suggest that live-lihood diversification (off farm and on farm income sources) as well as policy interventions that enhance income at the household level could potentially enhance solar energy technology adoption.

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Table 4.13: Weighted Least Squares Regression Results on Factors influencing household use of solar energy

Factor	B	S.E.	Wald	df	Sig.	Exp(B)
Age of the respondent in years	-.366	.304	1.444	1	.229	.694
Farming source income	-.136	.282	.234	1	.629	.872
Total Household income, including remittances	.297	.223	1.778	1	.182	1.346
Constant	-1.778	1.477	1.449	1	.229	.169
2 Log likelihood = 51.032; Nagelkerke R Square= .073; Omnibus chi square sig 0.353						

The logit regression (Table 4.14) age and on farm income have a positive relationship with the adoption of LPG. However, they are not statistically significant. Gender, education, and total household income have a negative relationship with the use of LPG, though not statistically significant. The negative relationship between education and total household income is unexpected from an economic perspective. Most likely, the relationship is confounded with household size and gender. Only age and farm income seem to be positively correlated with the use of LPG (Table 4.14), with female headed households less likely to use LPG compared to males. According to the findings, large households are less likely to use LPG. This is expected given the cost and low income associated with such households (Table 4.2).

Table 4.14: Logit regression on the use of LPG at the household level

	Unstandardized Coefficients		Standardized Coefficients		t	Sig.
	B	Std. Error	Beta	Std. Error		
(Constant)	.093	.137			.679	.498
Gender	-.020	.035	-.390	.674	-.579	.564
age	.008	.015	.154	.302	.508	.612
education	-.028	.022	-.538	.423	-1.274	.205
HHeadIncome	$-4.167E^{-5}$	.010	-.003	.787	-.004	.997
HHincomeFarm	$2.504E^{-5}$	.000	.009	.090	.105	.916
Household_Size	$-3.616E^{-6}$	.000	-.010	.090	-.108	.915

Log-likelihood =25.536.

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Table 4.15 provides the use of paraffin at household level for the surveyed respondents as an energy source in the Vhembe District Municipality. The results show that 7% use Paraffin. Paraffin is usually used for cooking by 2.3 % of the respondents and water heating by 3.1 % of the respondents using small portable stoves, and for 1.6 % for lighting using small lamps

Table 4.15: use of paraffin at household level, VDM

Use of paraffin	Frequency	%
no	119	93,0
yes	9	7,0
Total	128	100,0

Table 4.16 reveals that paraffin is largely not used by households in the Vhembe District Municipality, with 93.0% of respondents indicating no use. Only a small minority reported using paraffin for heating (3.1%), cooking (2.3%), or lighting (1.6%). This low usage may reflect a shift away from paraffin due to concerns about cost, safety, availability, or the adoption of alternative energy sources. From the FGDs, the use of paraffin for heating was mainly in the operation of chicken brooders and incubators. The data suggests that paraffin no longer plays a significant role in meeting household energy needs in the area, indicating potential progress toward cleaner or more modern energy options, though further research would be needed to confirm the reasons behind this trend.

Table 4.16: Specific household uses of paraffin, VDM

Uses	Frequency	%
lighting	2	1,6
cooking	3	2,3
heating	4	3,1
Not used	119	93,0
Total	128	100,0

Table 4.17 provides the main uses for which various energy types are used at the household level. At 95 %, cooking emerges as the main use, lighting at about 87 %, heating at about 72 %, refrigeration at about 63%, and running of TV and radio at about 74 %. Other uses

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include appliances such as an iron. These uses provide interventions for which smart innovations can be targeted.

Table 4.17: Main uses of Energy at Household Level, VDM

Use	N	%
Heating	92	71,9%
Lighting	111	86,7%
Cooking	122	95,3%
Cooling	15	11,7%
refrigeration/Freezer	81	63,3%
run TV/Radio	94	73,4%
Appliances such as ironing	108	84,4%
Total	623	486,7%

The respondents were asked to identify energy type characteristics that attract them to a specific fuel type. Cost at 39% and ease of availability at about 35% emerged as the main factors (Table 4.18) in the choice of energy type. Cost of alternatives, load shedding, and socio economic lockins at about 13-14% were other factors influencing the choice of energy. Convenience of use at about 6% was the least. Load shedding was one of the major reasons for solar installation among households that could afford it. Importantly, about 82% of the respondents identified Load shedding as one of the major reasons for the use of wood fuel.

Table 4.18: Factors influencing main types of Energy, VDM

Reason	N	%
Cost of alternative	17	13,3%
Ease of availability	45	35,2%
Cost	50	39,1%
Loadshedding	18	14,1%
Convenience of use	8	6,3%
Socioeconomic locking	15	11,7%
Total	128	100%

4.4 Social economic factors influencing access to and use of various energy mixes at the household level, VDM

Numerous factors were found to likely influence the adoption of smart energy practices and innovation at the household level (Table 4.19). The analysis of factors influencing smart energy adoption in Vhembe District Municipality reveals that knowledge and awareness are the most

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critical drivers, with 61.9% of respondents identifying them as key, highlighting the need for improved education on smart energy benefits. Alongside this, reliability of the technology (52.5%) and financial considerations, including access to finance (47.5%) and cost savings (44.9%), significantly affect adoption decisions, emphasising economic feasibility as a major concern. While social influences such as social networks, peers, and family spillovers also impact uptake, their effect is comparatively smaller. Environmental values motivate some households, but government incentives and market access appear underutilized or less influential. Overall, these findings suggest that increasing awareness, ensuring reliable technology, and improving affordability are essential strategies to promote smart energy adoption in the region.

Table 4.19: Factors influencing adoption of smart energy technologies

Factor	N	%
Knowledge	73	61,9%
Finance	56	47,5%
Lockin	11	9,3%
Value for environment	33	28,0%
Social network	26	22,0%
Peers	16	13,6%
Family spillovers	11	9,3%
Market access	25	21,2%
Grant	8	6,8%
returns on investment	22	18,6%
reliability	62	52,5%
Cost saving	53	44,9%
Total	396	335,6%

Table 4.20 provides the likelihood of cost saving as a predictor of the adoption of smart energy technologies. Mains electricity and use of energy for refrigeration were significant predictors of whether cost saving emerges as a concern in adopting smart energy alternatives. Appendix (ii) provides the multinomial logistic model. Every increase in age by 1 year increases concern about cost by a factor of 1.22. Notably, there is a significant difference ($p< 0.034$) in concern for cost saving when the use of energy for refrigeration is considered. Overall, those not using refrigeration were more concerned about cost, with age being a statistically significant determinant in smart energy adoption.

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Though education is not statistically significant of smart energy innovations, the concern among those with secondary education is higher relative to all levels of education and relative to those who have achieved university education. Further, though concern over cost increases by a factor of 15, in terms of mains electricity use, it is not statistically significant determinant of smart energy innovations adoption.

Table 4.20: Likelihood of cost saving on smart energy adoption

	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept	119.188[a]	.000	0	.
Age of the respondent in years	119.452	.264	1	.607
gender of the respondent	122.178	2.989	1	.084
Highest level of education attained	121.616	2.428	4	.658
Employment status	124.260	5.072	3	.167
Mains Electricity as Energy	123.889	4.700	1	.030
Biomass as energy mix at Household	119.940	.752	1	.386
Solar as energy mix at Household	120.945	1.757	1	.185
LPG as Energy Mix at Household	120.941	1.753	1	.185
Paraffin as Energy Mix at Household	122.697	3.508	1	.061
Uses Energy for heating	121.914	2.726	1	.099
Uses Energy for Lighting	121.464	2.276	1	.131
Uses Energy for cooking	119.211	.023	1	.880
Uses Energy for Cooling	121.827	2.639	1	.104
Uses Energy for refrigeration/Freezer	123.857	4.669	1	.031
Uses Energy to run TV/Radio	120.309	1.121	1	.290
Uses Energy for Appliances	119.385	.196	1	.658

Table 4.21 provides the likelihood ratios on financing concerns. The overall use of solar, the use of mains electricity for heating and cooking, as well as the use of paraffin, are the most significant ($p< 0.05$) predictors on whether financing emerges as a concern in energy. Appendix (iii) provides a multinomial logistic model of factors that predict the effect of financing. Though concern on finance is only statistically significant for those who use energy for heating, the concern increases by a factor of 21 among those with the highest education level. This concern decreases proportionally with a decrease in the level of education. This is expected as the level of education can be taken as a proxy for income level and thus likelihood of seeking credit to finance energy innovations.

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Table 4.21: Weighted Least Squares likelihood ratio on finance as a predictor of smart energy technologies

	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept	133.159[a]	.000	0	.
Age of the respondent in years	133.186	.026	1	.871
gender of the respondent	133.822	.663	1	.416
Highest level of education attained	141.623	8.464	4	.076
Employment status	136.935	3.776	3	.287
Mains Electricity as Energy mix	134.320	1.161	1	.281
Biomass as energy mix at Household	136.865	3.705	1	.054
Solar as energy mix at Household	137.018	3.859	1	.049
LPG as Energy Mix at Household	133.706	.547	1	.460
Paraffin as Energy Mix at Household	144.459	11.299	1	<.001
Uses Energy for heating	140.215	7.055	1	.008
Uses Energy for Lighting	133.209	.050	1	.823
Uses Energy for cooking	140.074	6.915	1	.009
Uses Energy for Cooling	135.315	2.155	1	.142
Uses Energy for refrigeration/Freezer	133.271	.111	1	.739
Uses Energy to run TV/Radio	133.769	.609	1	.435
Uses Energy for Appliances	133.195	.035	1	.851

Concern on finance is also almost equal for those in formal and informal employment as compared to those who are unemployed. This is also expected as the unemployed are less likely to seek financing for smart energy innovations. Concern on finance among female respondents also increases by a factor of 1.45 compared to males, though not statistically significant.

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Table 4.22: Effect of knowledge of the likelihood of smart energy innovation adoption

	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept	124.004[a]	.000	0	.
Age of the respondent in years	124.143[b]	.139	2	.933
gender of the respondent	131.739[b]	7.735	2	.021
The highest level of education attained	121.697[b]	.	8	.
Employment status	120.986[b]	.	6	.
Mains Electricity as Energy mix	124.873[b]	.870	2	.647
Biomass as energy mix at Household	121.772[b]	.	2	.
Solar as energy mix at Household	126.744[b]	2.740	2	.254
LPG as Energy Mix at Household	123.899[b]	.	2	.
Paraffin as Energy Mix at Household	124.122[b]	.118	2	.943
Uses Energy for Heating	124.492[b]	.488	2	.783
Uses Energy for Lighting	126.911[b]	2.907	2	.234
Uses Energy for Cooking	126.269[b]	2.266	2	.322
Uses Energy for Cooling	129.521[b]	5.518	2	.063
Uses Energy for refrigeration/Freezer	127.131[b]	3.128	2	.209
Uses Energy to run TV/Radio	126.999[b]	2.995	2	.224
Uses Energy for Appliances	129.872[b]	5.868	2	.053

Table 4.22 provides the likelihood ratios of the effect of knowledge on smart energy innovations. Gender of the respondent was the only predictor of significance. Appendix (iv) provides the multinomial logistic model. In terms of information access (knowledge), employment status emerges as the only factor that significantly ($P< 0.005$) influences energy smart energy innovations in a negative direction. The negative effects in formal employment and unemployment status are almost equal to those of formal employment when retirement status is considered. The finding can be explained in terms of disposable income available and employment status on information searching. Retirees and those in formal employment have relatively stable income flows that can be used for information search and associated costs.

Table 4.23 provides the likelihood ratios of factors that are critical in reliability as a factor influencing smart energy technologies. Age, use of energy for cooking, use of LPG, biomass, and solar are predictors of reliability as a priority at the household level ($P< 0.05$).

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Table 4.23: Effect of reliability on adoption of Smart energy technologies

	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept	131.758[a]	.000	0	.
Age of the respondent in yrs	135.913	4.154	1	.042
gender of the respondent	132.428	.669	1	.413
Highest level of education attained	134.552	2.794	4	.593
Employment status	135.839	4.081	3	.253
Mains Electricity as Energy mix	134.142	2.384	1	.123
Biomass as energy mix at Household	138.467	6.708	1	.010
Solar as energy mix at Household	136.309	4.551	1	.033
LPG as Energy Mix at Household	142.378	10.620	1	.001
Paraffin as Energy Mix at Household	141.006	9.247	1	.002
Uses Energy for heating	131.849	.091	1	.763
Uses Energy for Lighting	133.010	1.252	1	.263
Uses Energy for cooking	152.715	20.957	1	<.001
Uses Energy for Cooling	132.583	.825	1	.364
Uses Energy for refrigeration/Freezer	131.947	.189	1	.664
Uses Energy to run TV/Radio	132.564	.806	1	.369
Uses Energy for Appliances	132.088	.329	1	.566

Appendix (v) provides the multinomial logistic model. The use of biomass and LPG is the only significant predictor on the reliability of an energy innovation and a determinant in the uptake of smart energy innovations. Non-use of biomass increases the likelihood of reliability emerging as a priority concern in the adoption of smart energy innovations by a factor of 4.75. The use of LPG increases the likelihood of reliability being a priority concern in the adoption of smart energy innovations by a factor of 96.5.

Though gender is not statistically significant ($P< 0.05$) in the adoption of LPG, LPG is likely to be considered more dependable by a factor of 1.479 among females than males. This is expected given that females are at the centre of energy use decision making at household level. These results highlight the importance of addressing perceptions of reliability in promoting the adoption of cleaner energy alternatives, especially among primary household energy users.

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4.5 Adoption model on energy mix at a household level, VDM

Table 4.24 provides a logit analysis of socio-economic factors influencing energy mix in the study area. Gender, age, education, farm income, and household size are all negatively correlated with the adoption of solar energy at a household level in the study area. However, neither is statistically significant ($p< 0.05$). None of the socio-economic factors were statistically significant ($P< 0.05$) in explaining the adoption of smart energy technologies at the household level. However, household income has a positive correlation with the adoption of smart energy technologies. Age, gender, and household size all have a negative correlation with the adoption of smart energy technologies at a household level. The negative correlation of education with smart energy practices adoption is probably due to the confounding effect of unemployment, as well as household size, on income levels. Further investigation could help in understanding such unexpected relationships.

Table 4.24: Weight Least Squares analysis of socio-economic factors influencing smart energy mix in VDM

	Unstandardized Coefficients		Standardized Coefficients		t	Sig.
	B	Std. Error	Beta	Std. Error		
(Constant)	.188	.155			1.213	.227
Gender	-.006	.040	-.803	5.179	-.155	.877
age	-.022	.017	-2.904	2.237	-1.299	.197
education	-.033	.025	-4.319	3.228	-1.338	.183
HHeadIncome	.012	.012	6.415	.6.138	1.045	.298
HHincomeFarm	$-1.291E^{-5}$	.000	-.004	.090	-.044	.965
Household_Size	-1.156^{-6}	.000	-.002	.090	-.024	.981

4.6 Barriers to smart energy

One of the best options for improving the challenges of the two billion people who lack access to smart energy sources, the majority of whom live in rural areas, has been suggested to be renewable energy (Luthra *et al.,* 2015). Table 4.25 highlights the key barriers to the adoption of smart energy solutions as reported by respondents in the study. The most frequently cited barriers were lack of capital (52.4%) and lack of information (51.2%), followed closely by high

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cost (50.0%). These findings suggest that both financial constraints and limited awareness are significant obstacles to smart energy uptake. Government regulation was also identified by a substantial proportion of respondents (43.9%), indicating possible policy or bureaucratic challenges. Other notable barriers include lack of alternatives (26.8%) and lockin effects (22.0%), which may reflect dependence on existing energy systems or technologies. The total percentage exceeds 100%, suggesting that respondents could select multiple barriers. Overall, the data points to a combination of financial, informational, and structural challenges that must be addressed to facilitate the transition to smart energy in the study area.

Table 4.25: Barriers to smart energy

Barriers	N	%
gov regulation	36	43,9
lack of information	42	51,2
lack of capital	43	52,4
lack of alternatives	22	26,8
High cost	41	50,0
Lockin	18	22,0
Total	202	246,3

4.7 Socio technical factors on Energy mix at Household level, VDM

To analyse the socio technical factors on energy mix at household level, the study identified various practices and innovations based on descriptions provided by the community during FGDs as well as observations made in the field. Table 4.26 provides a summary description of various WEF typologies identified in VDM. The typologies provide the basis for the economic and social analysis considered in the study.

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Table 4.26: Identification and description of WEF typologies at household level and potential impacts, VDM

Description	WEF nexus typology	Remarks
Water for energy During FGDs, the community identified a micro hydro power that was used to supply electricity for household use.	• Water Energy Nexus • Environment-Water- Energy Nexus	Hydropower is no longer in use. The community attributed this to reduced river flows.
Energy for Water FGDs and household interviews easily recognized the need for energy to pump water for drinking. The water is in turn used for food and sanitation	• Energy-water nexus • Energy-Water-food nexus • Energy-Water-Sanitation nexus	Energy security cuts across health, food and livelihoods
Energy for cooking and energy for food storage including refrigeration relationships was identified by the community and household interviews	• Energy for Food	Refrigeration is critical in household food security and energy is critical for cooking
Land-energy nexus from use of coal in energy generation	• Energy -Land-Environment Nexus • Energy-Health nexus	The nexus was identified indirectly through the impact of coal mining on land and chain impact on the environment and health
Water pumping through solar pumps and associated reduced emission from fossil-powered pumps in home gardens (and or for heating bathing) water and flushing toilets	Water-Energy-Carbon Nexus Water-Energy-Environment Nexus Water-Energy-Sanitation-Health Nexus Water- Energy – Nutrition (Food)-Health Nexus	The potential impact of renewable energy sources such as solar are apparent

The social technical assessment covers both the financial and environmental (life cycle assessment) of various energy innovations at household level based on various typologies described in Table 4.26. This section presents the economic (financial) analysis of some of the identified innovations based on existing practices at the household level (Table 4.27) and on methods that are defined in section 3.6.3. The study focused on renewable energy innovation alternatives in

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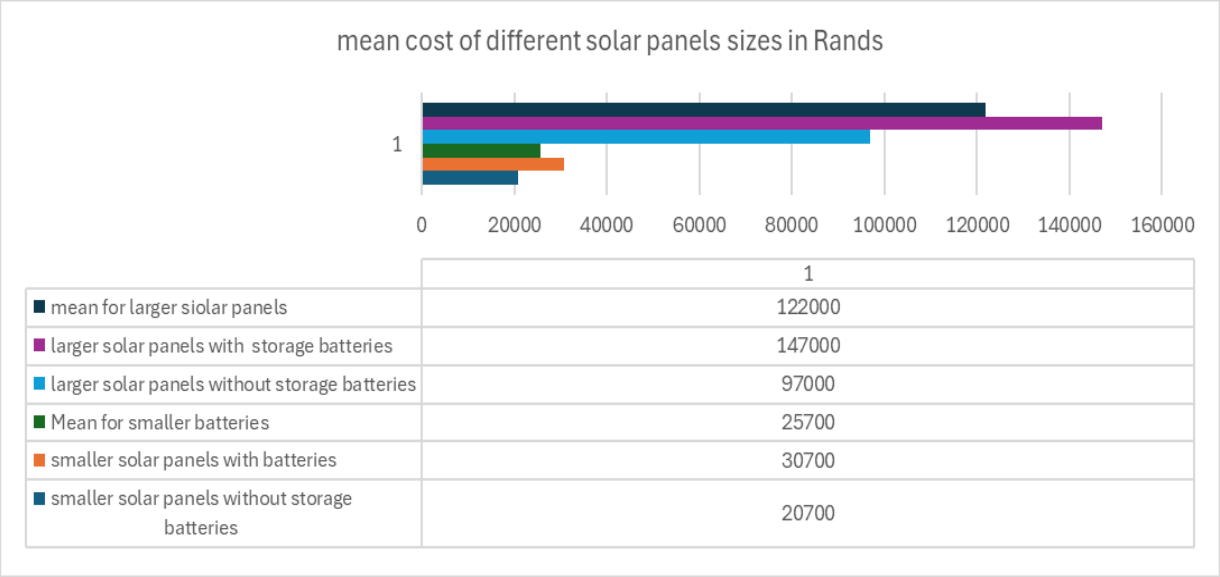
general and solar energy in particular, as it was the prevalent of the possible alternatives. The innovations are described hereunder.

Table 4.27: Economic analysis of some of the identified innovations based on existing practices at household level

Innovation	Description	Remarks
Larger solar Panels with Water (LPWW)	Larger panels with water at upper investment cost limit (R 155500) of existing options	Used for lighting, heating water, and pumping water
Larger solar Panels Without Water (LPWTW)	Larger panels with water at lower investment cost limit (R 147700) of existing options	Used for lighting, heating water, and pumping water
Small solar Panel with Water (SPWW)	Smaller panels with potential for lighting and pumping water and costing R 35000	Used for lighting and pumping water only
Small solar Panel Without Water (SPWTW)	Smaller panels with lighting as single possible use and costing R 30500	Only used for lighting only

The investment cost for alternative WEF innovations was based on data from SANEDI and analysis of household provided data, principally the cost and size of panels and uses for which the installations were undertaken. The data was supplemented by secondary data from Alumo Energy, 2023; Handymanhomes, 2023 and Sinetech, 2023). Figure 4.9. provides the calculated mean cost, which ranges from R 20 700 to R 147 000. The inclusion of professional fees increases the cost of solar installation to R 30500 for small sized solar panels and R 155 500 for large sized solar panels. The total costs, inclusive of professional fees, were used in the calculation of present value, BCR, and in judging the worthiness of such innovations.

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	1
mean for larger siolar panels	122000
larger solar panels with storage batteries	147000
larger solar panels without storage batteries	97000
Mean for smaller batteries	25700
smaller solar panels with batteries	30700
smaller solar panels without storage batteries	20700

Figure 4.9: Investment cost of various WEF innovations at household level, VDM.

Detailed data on discounted net cash flows are provided in Appendix (vi). Figure 4.10 provides discounted net cash flows for various solar innovations at various interest rates. Solar WEF innovations only make financial sense over a prolonged period at least 3 years for smaller panels and 7 years for larger panels. Furthermore, savings accrue more quickly when solar innovations serve multiple purposes simultaneously. For example, a combination of lighting and water heating was able to reduce the time needed to recoup the initial investment from 7 years to 3 years.

It is possible that the initial investment costs could be recouped faster if there were solar energy cooking innovations. The analysis shows that discounted savings are highest for systems with larger panels and water storage (LPWW), followed by larger panels without water storage (LPWWW), smaller panels with water storage (SPWW), and lastly, smaller panels without water storage (SPWTW). This suggests that larger systems, particularly those with integrated storage capabilities, offer greater long-term financial benefits when the time value of money is considered.

The size of solar panels does not significantly affect their physical lifespan, which typically ranges from 20 to 30 years. However, it does influence the financial payback period. Smaller solar panels generally have lower upfront costs and produce less energy, and a shorter payback period of around 3 years. In contrast, larger panels or systems require a higher initial investment but generate more electricity, though they have a longer payback period of about 7 years or more. Therefore, while both small and large panels have similar durability, their financial

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returns differ based on energy output and scale of use (diversification of use for lighting, cooking and water pumping)

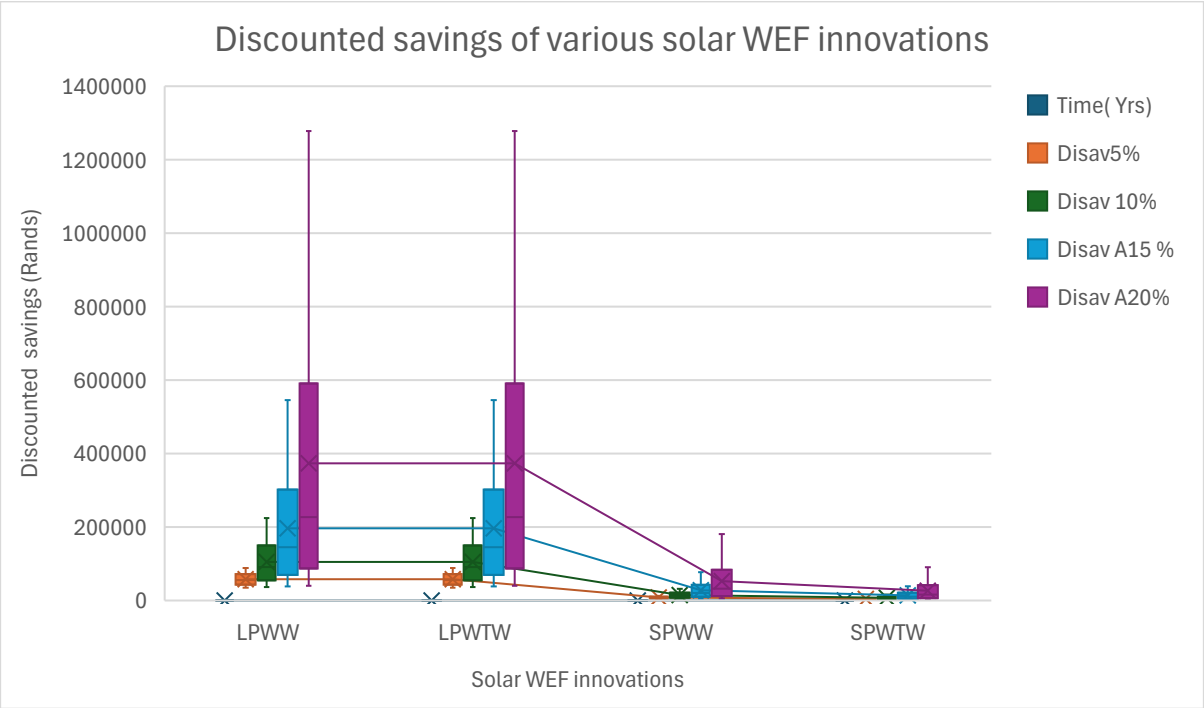


Figure 4.10: Discounted net cash flows for various solar innovations.

The discounted cash flows over time are provided in Figure 4.11. As the discount rate increases over time, the savings made in energy expenditures from existing energy sources decrease with increasing interest rates, reaching zero and then becoming negative when the discount rate goes beyond 10%. The discount rate is the most critical determinant in net cash flows from various solar WEF innovations. Further, the findings suggest that single utility smaller panels (only lighting) are not financially worth investing in as their net discounted cash flows over time are in the negative save for when interests are equal or less than 5% where the cash flows are barely zero, i.e. the investment costs are barely recovered. In a nutshell, at prevailing discount rates, it does not make financial sense to invest in smaller panels.

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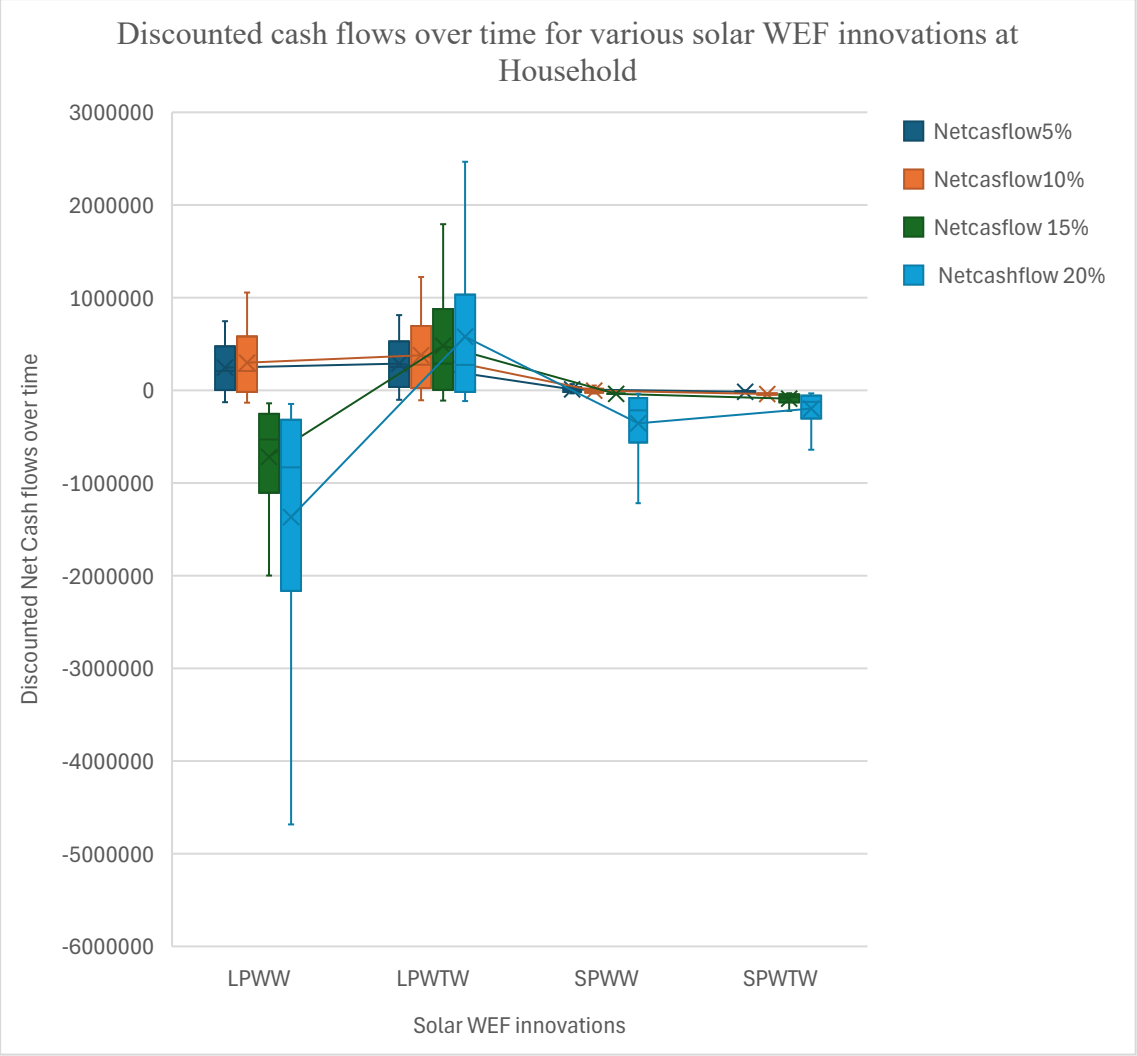


Figure 4.11: Discounted cash flows of various solar WEF innovations, VDM.

The same scenario of decreasing savings also prevails when the number of uses for the solar innovation is limited to lighting only. Figure 4.12. Provides the Benefit Cost Ratio (BCR) of the assessed solar WEF innovations, while Appendix (vii) provides detailed BCR values by year of investment and discount rate. Over time, BCR is determined by the discount rate and the number of uses of the innovation. All innovations record a positive BCR when the discount rate is 5 % or less. The highest BCR is attained where multiple uses (LPWW> SPWW> SPWTW) are being realised and when initial investment costs are lower (LPWTW< LPWW). As the discount rate increases, BCR decreases to the extent that it suggests that it is not financially prudent to invest in smaller panels when discount rates exceed 10%.

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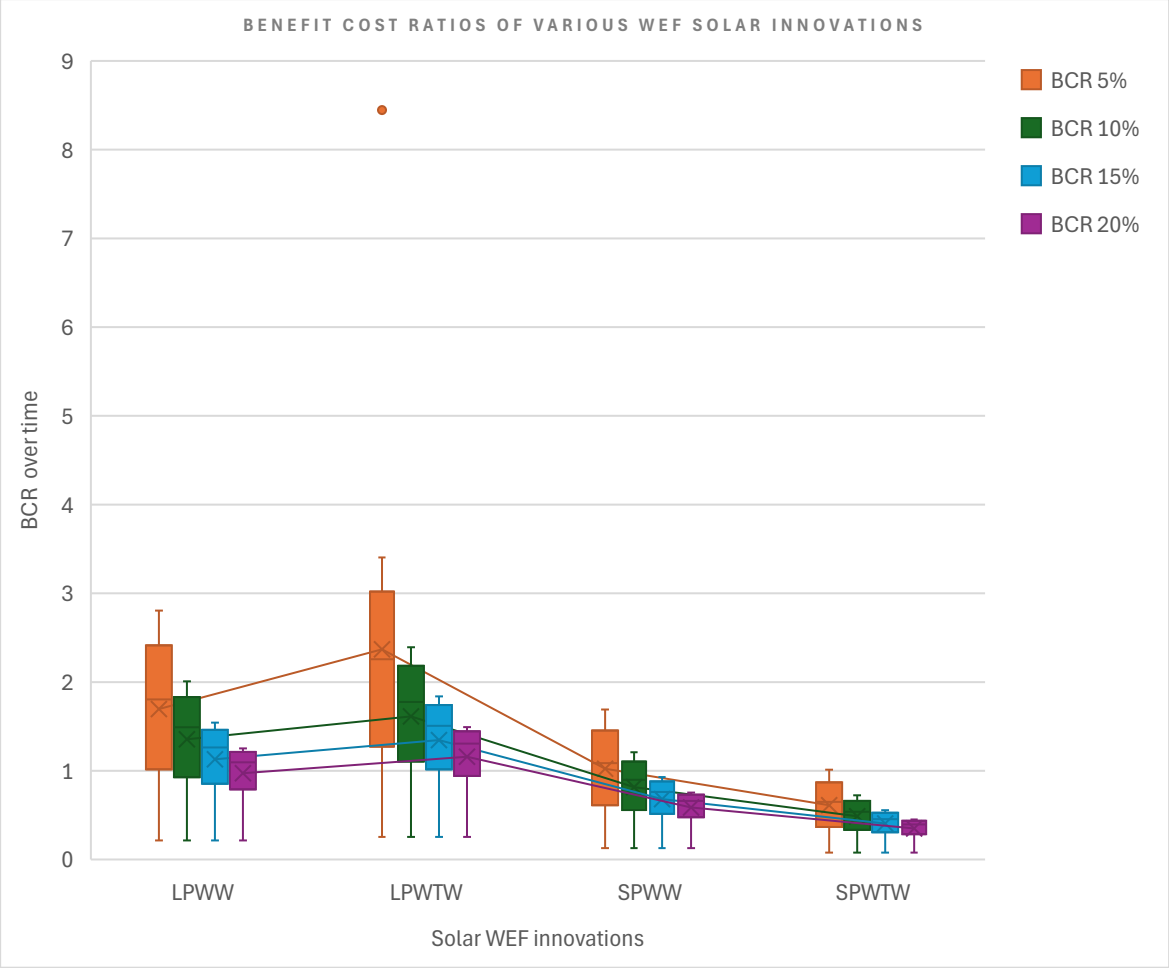


Figure 4.12: BCR of various solar WEF innovations.

The whisker plot (Figure 4.13) highlights the effect of discount rate and use of innovation on BCR (financial worthiness). The highest BCR is attained when an innovation has more uses for energy, thus LPTW> LPWW. The BCR is only positive and above 1 for smaller panels with multiple energy uses from the innovation at a discount rate below 10%. The BCR for smaller panels falls below zero and becomes negative with discount rates above 5%.

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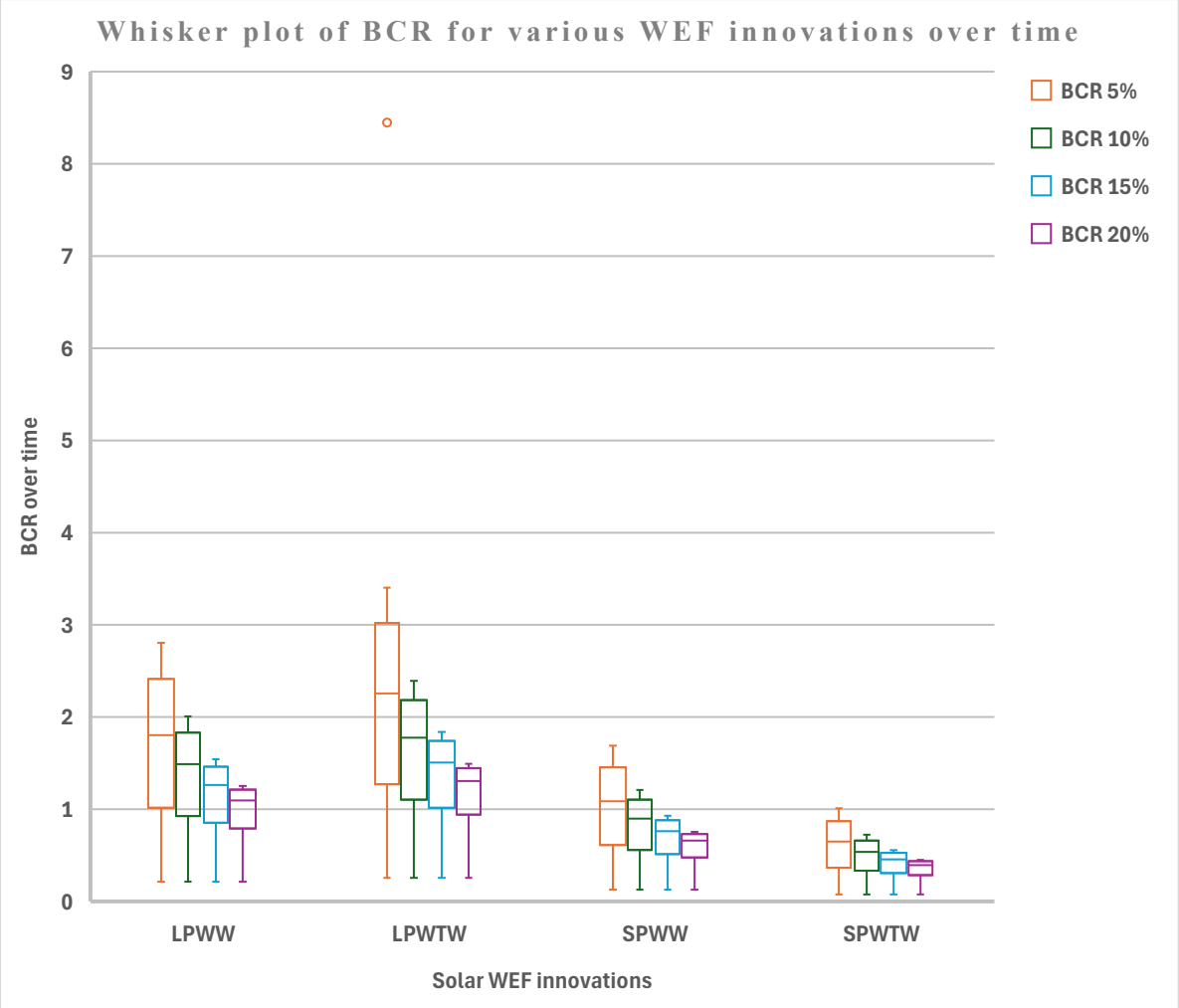


Figure 4.13: Whisker plot of BCR for various solar WEF innovations.

4.8 Partial life cycle assessment of some energy innovations at the household level

The study analysed and identified WEF relationships identified at household, FGD, and KII, as well as from the literature Review. This provides the basis for the partial life cycle assessment. The emission levels were standardised (Figure 4.14) based on the warming potential of distinct types of emission using warming potential carbon dioxide for 100 years as the baseline, hence carbon dioxide equivalent (CO2-eq). From the analysis, coal (2.27 CO2-eq/ kWh) and other non-renewable energy sources, primarily biomass resources (0.26-091 CO2-eq/ kWh), compared to solar at 0.061 CO2-eq/ kWh, were the highest emitters, suggesting that their replacement as a source of energy could positively impact health and environmental outcomes.

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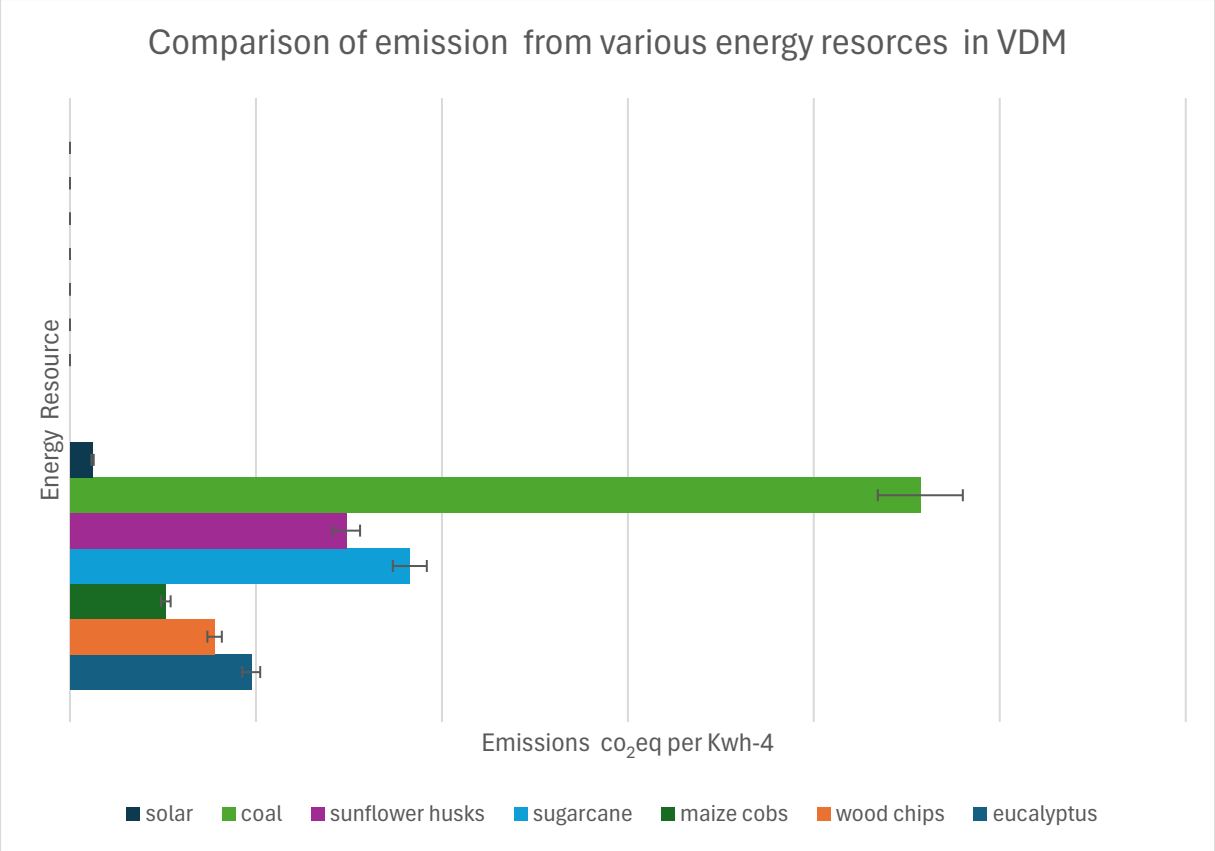


Figure 4.14: Carbon footprint from various energy uses at household level.

The water consumption footprint of various energy resources at the household level was also assessed. Figure 4.15 provides the analysed water footprint of some of the energy resources at household level. From the study, coal (0.64 M^3/kWh) and other non-renewable energy sources, including biomass (0.2-0.72 M^3/kWh), against solar 0.095 M^3/ kWh suggest that non-renewable energy water footprint uses substantial amounts of water compared to renewable resources, i.e., solar innovations. This could be critical to policy on energy transition in a water scarce South Africa.

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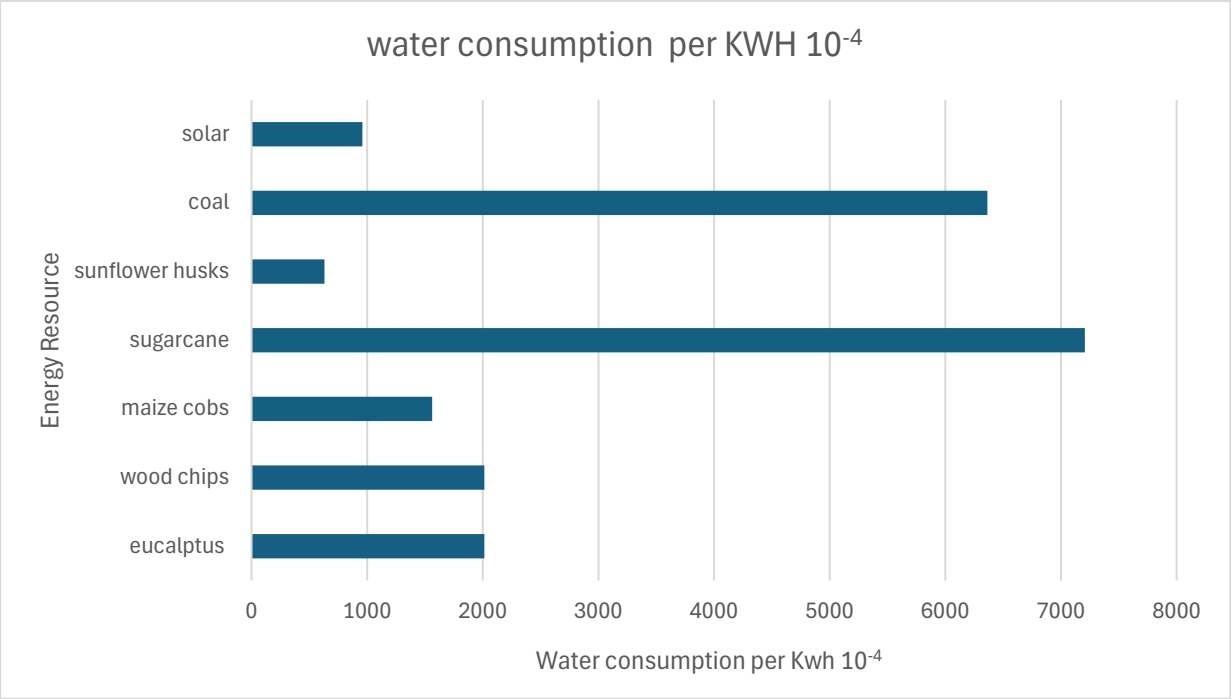


Figure 4.15: Water consumption footprint from various energy uses at the household level.

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CHAPTER 5: CONCLUSIONS, AND RECOMMENDATIONS

5.1 Conclusions

The study aimed to establish the use and management of energy resources, factors influencing access (security), and their implications for energy planning amid climate change mitigation from the WEF perspective. There is a wide range of intersecting socio-economic factors, such as policy and economic lockins, and lived course transitions such as gender, age, and educational attainment, all influence the choice of energy resource use at the household level.

Energy stacking is a strategy across socioeconomic strata and is often at variance with energy ladder trajectories. The cultural lockin is especially critical. The criticality of energy as a driver of economic and livelihood activities is exemplified by various WEF typologies identified in this study. The typologies cut across all spheres of livelihoods and economy, as well as impact pathways on the environment, food security, environmental security, and resource security at large. From the analysis of available data, there is ample evidence on the effect of socio economic and environmental intersections on energy use and its chain impact on the environment, health, and WEF securities. For example, harvesting fuel wood for cooking could negatively impact the environment. This is the case in the study area, where the mopane tree is being harvested for fuel wood with spillover impacts on the environment.

From the analysis, coal (2.27 co2-eq/ kWh) and other non-renewable energy sources, primarily biomass resources (0.26-091 co2-eq/ kWh), compared to solar at 0.061 co2-eq/ kWh were the highest GHG emitters, suggesting that its replacement as a source of energy could positively impact health and environmental outcomes and mitigate climate change risks. Further coal (0.64M3/kWh) and other non-renewable energy sources, including biomass (0.2-0.72 M3/kWh), against solar 0.095 M3/ kWh, suggest that non-renewable energy water footprint uses substantial amounts of water compared to renewable resources, i.e., solar innovations. This could be critical to policy on energy transition in a water scarce South Africa.

Multiple typologies of WEF with implications for environment and sustainability planning. Among other challenges of biomass use, the respondents (about 34%) recognise pollution as one of the biggest challenges. The fact that less than 50% of the respondents are aware of

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pollution risks from non-renewable energy resources, such as fuel wood, calls for awareness creation at the household level.

About 82 % of the respondents identified load shedding as one of the major reasons for the use of fuel wood. From the FGDs, it was apparent that solar energy as an innovation could positively impact socioeconomic outcomes of the community, such as health and schooling outcomes. For example, members of the FGDs with solar installations were able to identify the value of solar energy on educational outcomes.

Technical evaluations based on BCR and discounted cash flows have shown that alternatives to the prevalent nonrenewable energy resources, i.e., the use of solar energy innovations, are feasible alternatives in energy transitions at the household level. However, awareness and financing barriers constrain the adoption of such smart energy alternatives. Further innovations that offer multiple uses (i.e., cooking, heating, and lighting) are more likely to be more economical than single use innovations. More importantly, the low environmental footprint, i.e., reduced water consumption from such options, justifies the need to promote their adoption at the household level. In essence, policies with robust gender framing and intersectionality with socioeconomic dimensions are required to support transitions to smart energy transitions.

The study has investigated socioeconomic factors influencing energy typologies and their potential environmental impacts at the household level. According to the study, both renewable and non-renewable energy resources are used at the household level. However, non-renewable energy resources dominate at the household level. Though mains electricity dominates energy resources use, the concern about its use a rising because it is predominantly generated from coal, a nonrenewable resource with a high environmental footprint. Further, the use of biomass is also widespread despite electricity being widely available.

Socioeconomic and cultural lockins as well as a lack of awareness of adverse impacts in the use of biomass for cooking and heating, as well as high initial investment costs, tend to constrain the adoption of cleaner, renewable alternatives, such as solar. Household income is the most significant socio-economic factor influencing energy type in general and the adoption of smart energy innovations in particular at the household level. Further analysis shows that income is mediated through education level and employment. Economic empowerment and poverty alleviation interventions could be significant in transitioning to smart energy innovations.

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The discount rate and the extent to which an energy innovation has multiple uses also influence its financial viability. Given the positive impacts on the environment and health, policymakers need to focus on financing solutions and the promotion of renewable energy and smart energy innovations at the household level.

5.2 Policy recommendations and limitations of the study

The following recommendations can be extended from the study

- Detailed analysis of social technical data on energy innovations for sanitation, various irrigated crop production, heating, and cooking at the household level.
- Need for assessment and socio technical modelling (Agent based Modeling) of smart energy innovations by socio economic strata and livelihood trajectories.
- Detailed economic and financial analysis of various energy innovations to inform just energy transition and the pursuit of SDGs.

The main limitation of the study lies in the use of a survey design, which at household level relied on respondents' memory. The use of recall could thus negatively impact some data. However, the use of a mixed methods approach through KII and FGDs mitigated some of the shortcomings. The use of existing (secondary) literature data in some of the partial life cycle assessments could also impact the accuracy of the reported data. The use of primary data at the household level is recommended in future studies.

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Appendices

Appendix i: Household Questionnaire

Use and management of energy resources from Water, Energy, and Food (WEF) nexus perspective: The case of Vhembe District Municipality (VDM), Limpopo Province

APPENDIX 1: QUESTIONNAIRE FOR INDIVIDUALS / HOUSEHOLDS

BACKGROUND

This document presents the research data collection tools for the research project titled "**Use and management of energy resources from Water, Energy, and Food (WEF) nexus perspective: The case of Vhembe District Municipality (VDM), Limpopo Province.**". This research seeks to support the decision-making process on energy transition at the household level from the WEF nexus perspective.

ETHICAL CONSIDERATIONS

The data collection process will respect at its core the five ethical principles that researchers need to adhere to:

a) obtain informed consent from potential research participants.
b) minimize the risk of harm to participants.
c) protect the participants' anonymity and confidentiality.
d) avoid using deceptive practices, and
e) give participants the right to withdraw from the research.
f) integrity and transparency

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INFORMED CONSENT

The Questionnaire is designed to gather information about the study respondents (and/or participants). Respondents are those people who will be invited to participate in this research study and have taken part in the study. The data collection is undertaken on the premise that human subjects in any research project must participate willingly, having been adequately informed about the research. Informed consent in this study entails a process of telling potential research participants about the key elements of the research study and what their participation will involve. The consent process will also include providing the annexed consent form.

INTELLECTUAL PROPERTY (IP) CONSIDERATIONS

Regarding intellectual property (IP), data collected, data collection tool and reports of this study shall be an intellectual property of the WRC. This will be guided by the Intellectual Property Rights from Publicly Financed Research and Development Act 51 of 2008 (IP Act) (Republic of South Africa, 2008).

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SECTION 1: Household Socioeconomic background

Numbering	Required to fill-in/Question	Instruction	
1.1	Supervisor's Name	Indicate the name of the supervisor	
1.2	Enumerator's Name	Indicate name of the supervisor	
1.3	Supervisor's Check Date	yyyy-mm-dd To be completed by supervisor	
1.4	Name of the Respondent	Name and Surname	
1.5	Respondent's Household (HH) Status	Choose from:	
		- Household Head	
		- Spouse	
		- Child	
		- Relative	
1.6	Gender of the Head of the Respondent	Choose from:	
		- Male	
		- Female	
		- Prefer not to say	
1.7	Age category of the Respondent	Choose from:	
		- 20 and under	
		- 21-30	
		- 31-40	
		- 41-50	
		- 51-60	
		- Above 60	
1.8	Highest Education Level of the Respondent	Choose from:	
		- No schooling	
		- Primary Education	
		- Secondary	

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		Education	
		- TVET/College Education	
		- University Education	
1.9	Employment Status of the Respondent	Ask if the respondent is employed:	
		Employment status	Yes	No
		- Formal (public servant, teacher, others....)		
		- Informal employment (not salarised)		
		- Retired		
		- Umeployed		
		- Self employed		

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Section 2.0: Typology of Household Energy Uses

Numbering	Required to fill-in/Question	Instruction	
2.1	Indicate the type of household energy used (at HH level and/or field outside the HH)	Choose by ticking from the list (*multiple entry allowed*)	
		- Biomass (Fuelwood, animal dung, biogas etc.)	
		- Eskom/Municipality electricity	
		- Paraffin	
		- Liquid petroleum gas (LPG)	
		- Renewable energy technologies (solar panels, solar water heaters etc.)	
		- Coal	
		- Other (specify)	
		Name the main source among the selected ……	
2.2	Indicate the main uses of energy.	**Choose by ticking source from the list (*multiple entries allowed*):**	
		• Heating (water, pottery, space)	
		• Lighting	
		• Cooking	
		• Cooling	
		• Refrigeration	
		• Television	
		• Charging computers and other devices such as cellphones	
		- **Name the main use of the source selected** above……	

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Section 3: Energy Innovations and Practices

Numbering	Energy Innovation and Practices Choose from the list as dictated by the respondent		Details about the utilized technological Innovation and Practices (Required to fill-in/Question)			Prioritization[1]
	Indicate the sub-category as per WEF nexus	Utilized technological Innovation and Practices (Indicate Yes or No)	Indicate how you are using Innovation and Practice	Give us the reasons why you are using technological Innovation and Practices	Give us the challenges you are experiencing using technological Innovation and Practice	Rank the perceived benefit of the Water technological Innovation and Practices (Scale of 1 to 5)
3.1	Non Renewable	- Coal				
		- Electricity				
		- Firewood				
		- Paraffin				
		- LPG / Gas				
3.2	Renewable	- Biogas digester				
		- Solar (PV or Solar water heaters)				
		- Wind				
3.3	Other Indigenous energy related innovations and practices	Ask the respondent to list.				

SECTION 5: ACCESS TO AND USE OF WEF RESOURCES

Section 4.1: WEF resource use

[1] [1] The Likert scale used to prioritize the WEF identifies technological Innovation and Practice is: *1 = very poor, 2 = poor, 3 = neutral, 4 = good, 5 = excellent*

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Numbering	WEF Resource	Type and source	Main use for which resource is used (mark against as many uses for each as possible)
4.1.1	Food/Agriculture	Fruit trees	Consumption: windbreak; Sale; Landscaping; Cultural heritage
		Fodder	Livestock; sale
		Vegetables	Sale, consumption, both sale and consumption
		Cereals and pulses eg	Sale, consumption; both sale and consumption
		Livestock	Sale, consumption; both sale and consumption
4.1.2	Energy	Solar	Lighting, TV, radio, charging
		Mains Electricity	Lighting, cooking, heating; cooling
		Wind	Lighting, cooking, heating; cooling
		Biomass (Fuelwood, animal dung, biogas etc.)	Cooking; Heating; Sale
		River	Drinking; Cooking; Irrigation; sanitation only; Irrigation; Livestock
		Rainwater Harvesting	Drinking; Cooking; Irrigation; sanitation only; Irrigation; Livestock
		Dam	Drinking; Cooking; Irrigation; sanitation only; Irrigation; Livestock; Car Wash

Section 4.2: WEF resource access and use rights

Numbering	WEF Resource	Dimension	Is any of the dimension in the previous column an issue of concern Yes / NO	If Yes state, the issue (e.g. Permits, metering, rules, rationing for each of the dimensions)	Further comment if any
4.1.1	Energy	Regulation on type to use			
		Reliability of supply			
		Cost of alternatives			
		Access to			

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		alternatives			
4.1.2	Food Production	Land for crop production			
4.1.3	Land	Zoning restrictions			

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SECTION 5: FINANCIAL SUPPORT, EXTENSION AND ADOPTION

Section 5.1: WEF financing

Have you received any financing towards any of the following?

Numbering	WEF	Credit source	Yes/No		Specific Purpose on which credit was utilised	Any comment
5.1.1	Water development	Cooperative	Yes	No		
		Bank	Yes	No		
		Microcredit	Yes	No		
		Family	Yes	No		
		Local saving group	Yes	No		
		Grant (specify)	Yes	No		
5.1.2	Energy development	Cooperative	Yes	No		
		Bank	Yes	No		
		Microcredit	Yes	No		
		Family	Yes	No		
		Local saving group	Yes	No		
		Grant (specify)	Yes	No		
5.1.3	Food production	Cooperative	Yes	No		
		Bank	Yes	No		
		Microcredit	Yes	No		
		Family	Yes	No		
		Local saving group	Yes	No		
		Grant (specify)	Yes	No		

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Section 5.2: Communication channels and extension services on WEF technologies

For each of the information sources provide the frequency you have had in the last one year

Numbering	Source of information for each WEF	Source of information	Yes/ No		How frequent do you receive the information (for each source)					
5.2.1	Energy smart technologies	Public extension	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Private extension	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Radio / TV	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Newspaper	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Online	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Peers	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Scientific publication	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Innovation platforms	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
5.2.2	Water Smart technologies	Public extension	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually

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		Private extension	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Radio / TV	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Newspaper	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Online	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Peers	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Scientific publication	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Autonomous (own effort)	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Innovation platforms	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
5.2.3	Land use for food production smart technologies	Public extension	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Private extension	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually

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		Radio / TV	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Newspaper	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Online	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Peers	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Scientific publication	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Autonomous (own effort)	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Innovation platforms	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually

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Section 6: Actors in WEF technology promotion and adoption

Numbering	Smart technology	Specific WEF smart innovation	Who promotes	Constraints	Rank the constraints named (Use 1 for the most pressing)
6.1	Energy	Solar Energy saving Wind Any Other	Public extension Private Extension NGO/ CSO/ CBO Research Organisation Government agency International organisation Autonomous (own effort) Innovation platforms	Initial investment cost Maintenance costs Lack of market Lack of knowhow High Cost of alternatives Lack Access to alternatives Any other	

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Section 7.0: Factors influencing adoption of smart WEF technologies

What has influenced or likely to influence you adopt smart technologies?

Numbering	WEF Technology	Factor	List not more than 5 in order of importance (1 most important)
7.1	Energy smart technologies	Knowledge/ education	
		Finance	
		Care for environment	
		Social network	
		Peers	
		Family spillovers	
		Market access	
		Grant	
		High returns	
		Cost saving	
		Reliability	
		Finance	
		Value for environment	
		Social network	
		Peers	
		Family spillovers	

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		Market access	
		Grant	
		High returns	
		Cost saving	
		Reliability	
		Finance	
		Value for environment	
		Social network	
		Peers	
		Family spillovers	
		Market access	
		Grant	
		High returns	
		Cost saving	
		Reliability	

Section 8.0: Barriers to WEF smart technologies

Numbering	WEF resource	Barrier	Yes / No		Rank the barriers (Use 1 as the most pressing)
7.1	Energy smart technologies	Initial cost	yes	no	

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		Technical Knowhow	yes	no	
		Government regulation and policies	yes	no	
		Lack of information	yes	no	
		Lack of capital/ credit	yes	no	
		Lack of alternatives	yes	no	
		High cost of alternatives	yes	no	
		Any other	yes	no	
		Technical Knowhow	yes	no	
		Government regulation and policies	yes	no	
		Lack of information	yes	no	
		Lack of capital/ credit	yes	no	
		Lack of alternatives	yes	no	
		High cost of alternatives	yes	no	
		Any other	yes	no	
		Technical Knowhow	yes	no	
		Government regulation and policies	yes	no	
		Lack of information	yes	no	
		Lack of capital/ credit	yes	no	

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		Lack of alternatives	yes	no	
		High cost of alternatives	yes	no	
		Any other	yes	no	

SECTION 8: SUGGESTIONS ON WEF NEXUS SOLUTIONS

Numbering	**Required to fill in/Question**	**Instruction** *Please read the statements and ask the respondent to answer to their best ability.*
8.1	What are the main challenges in your household concerning Energy availability? 1. Energy availability? 2. Cost of Energy 3. Consistency in supply	
8.2	What should be done to eradicate energy scarcity (if any)?	

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SECTION 9: Family income

	Farm	**Formal Employment**	**Informal Employment**
Household Head			
Remittances from relatives			
1. 0-2000			
2. 2001-4000			
3. 4001-6000			
4. 6001- 8000			
5. 8001-10,000			
6. Above 10000			
		(can just indicate the job type)	

Focus Group Discussion and Key Informant Interview Schedule

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SECTION 1: GROUP OR INSTITUTION DETAILS

1. Actor name and mandate

Sector	Actor	Mandate	Instruments and tools on access and use of WEF resources
Energy			Permits Tariffs Education/ informational
Water			
Land and land use			

2. Do you have a coordination mechanism with other sectors (named in 1) at local and national levels?
3. Are there community engagement plans in your area regarding water use/ energy/ land use

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4. What are some of the resource conflicts and grievance redress mechanisms about access, use and control of the WEF resources in your area and how do you resolve them?
5. How is Environmental, social and climate impact assessment integrated into the planning processes of your area
6. How are financing intermediaries integrated into the planning processes of your area?
7. What incentives do you have regarding scaling of climate smart technologies?
8. Do you have partnership regarding research, implementation and steering of your mandate?
9. What are your intervention and strategies regarding the following?

Sector and actor	Access (poverty and equity)	Sustainability (economic, social, and environmental	Efficiency	Climate change vulnerability (adaptation and mitigation and resilience building)
Water – Water smart energy systems 1. 2. 3.				
Energy – Energy smart water systems 1.				

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2. 3.				
Land use=- Water land smart food systems 1. 2. 3.				

SECTION 2: GOVERNANCE SYSTEMS

Section 2.1: Governance actors and their role in WEF

Numbering	WEF sector	Actor (As many actors as there could be)	Role (Tick against the role for each of the actor)
6.3.2	Energy		Regulatory (Licensing/ permits) Advocacy Supplier Financing Training/ Awareness creation Policy

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			Capacity building Advocacy /lobbying Conflict resolution Sustainability and resilience building

Section 2.2: Institutional, regulations and policy support

2.2.1: Institutions

a) What institutions are there which affect or influence your use and management of water, energy and food production in your household/community? **(Please list)**

Numbering	**WEF sector**	**Institutions**
	Energy	

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b) In your opinion what changes need to be made to improve the roles of the institutions in supporting your effective and sustainable use and management of water, energy and food production in your household/community? (**Please list**)

Numbering	**Suggested changes to improve the roles of the institutions WEF Nexus Elements**		
	Water	**Energy**	**Food production**
2.2.1.2			

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2.2.2: Rules, regulations, and laws

a) What rules, regulations, and laws* are there which affect or influence your use and management of water, energy and food production in your household/community? (**Please list)**

Numbering	**WEF sector**	**Rules**	**laws**	**Regulations**
2.2.2.1	Water	1. 2. 3.		
2.2.2.2	Energy	1. 2. 3.		
2.2.2.3	Food	1. 2. 3.		

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b) **In your opinion what changes need to be made to improve the roles of the rules, regulations, and laws in supporting your effective and sustainable use and management of water, energy and food production in your household/community? (Please list)**

Numbering	Changes need to be made to improve the roles of the rules, regulations, and laws in supporting WEF nexus elements		
	Water	**Energy**	**Food production**
2.2.2.4			

2.2.3: Policies

a) What policies are there which affect or influence your use and management of water, energy, and food production in your household/community? (**Please list)**

Numbering	WEF sector	Current policy	Explain how does each of the listed to the left affect use or management of water.
2.2.3.1	Water		
2.2.3.2	Energy		
2.2.3.3	Food production		

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b) In your opinion what changes need to be made to improve the roles of the policies in supporting your effective and sustainable use and management of water, energy, and food production in your household/community? (**Please list**)

Numbering	**Changes need to be made to improve the roles of the policies in supporting WEF nexus elements**		
	Water	**Energy**	**Food**
2.2.3.4			

SECTION 3: FINANCIAL SUPPORT, EXTENSION AND ADOPTION

Section 3.1: WEF financing

Have you received any financing towards any of the following?

Numbering	**WEF**	**Credit source**	**Yes/No**	**Specific Purpose on which credit was utilised**	**Any comment**
3.1.1	Water development	Cooperative Bank			

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		Microcredit Family Local saving group Grant (specify)			
3.1.2	Energy development	Cooperative Bank Microcredit Family Local saving group Grant (specify)			

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Section 3.2: Communication channels and extension services on WEF technologies

For each of the information sources provide the frequency you have had in the last one year

Numbering	Source of information for each WEF	Source of information	Yes/ No	How frequent do you receive the information (for each source)
3.2.1	Energy smart technologies	Public extension Private extension Radio Newspaper Online Peers Scientific publication Autonomous (own effort)		Daily Weekly Monthly Quarterly Biannually Annually

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Section 3.3: Players in WEF technology promotion and adoption

Numbering	Smart technology	Specific WEF smart innovation	Who promotes	Constraints	Rank the constraints named (Use 1 for the most pressing)
3.3.1	Energy	Solar Energy saving Wind Any Other	Public extension Private Extension NGO/ CSO/ CBO Research Organisation Government agency International organisation Autonomous (own effort)	Initial investment cost Maintenance costs Lack of market Lack of knowhow High Cost of alternatives Lack Access to alternatives Any other	

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Section 3.4: Factors influencing adoption of smart WEF technologies

What has influenced or likely to influence you adopt smart technologies?

Numbering	WEF Technology	Factor	Already influenced you? Yes/ no	Rank the influencer (Use 1 to n with 1 as the most important
3.4.1	Energy smart technologies	Knowledge/ education Finance Value for environment Social network Peers Family spillovers Market access Grant High returns Cost saving Reliability		

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Section 3.5: Barriers to WEF smart technologies

Numbering	WEF resource	Barrier	Yes / No	Rank the barriers (Use 1 to n with 1 as the most important)
3.5.1	Energy smart technologies	Initial cost		
		Technical Knowhow		
		Government regulation and policies		
		Lack of information		
		Lack of capital/ credit		
		Lack of alternatives		
		High cost of alternatives		
		Any other		

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Appendix ii: Effect of cost saving on energy smart innovations

Effect of Cost saving on adoption of energy smart technology	B	Std. Error	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp(B)	
							Lower Bound	Upper Bound
Intercept	15.022	2.861	27.576	1	<.001			
Age of the respondent in yrs	.115	.225	.261	1	.609	1.122	.722	1.742
[gender of the respondent =1]	.862	.503	2.938	1	.086	2.368	.884	6.346
[gender of the respondent =2]	0[b]	.	.	0	.	.	.	.
[Highest level of education attained=1]	1.184	1.559	.577	1	.448	3.266	.154	69.291
[Highest level of education attained=2]	1.836	1.340	1.877	1	.171	6.268	.454	86.631
[Highest level of education attained=3]	1.037	1.183	.769	1	.381	2.821	.278	28.669
[Highest level of education attained=4]	.804	1.378	.340	1	.560	2.234	.150	33.270
[Highest level of education attained=5]	0[b]	.	.	0	.	.	.	.
[Employment status=1]	-1.640	1.443	1.291	1	.256	.194	.011	3.284
[Employment status=2]	-.417	1.480	.080	1	.778	.659	.036	11.985

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[Employment status=3]	-1.650	1.380	1.429	1	.232	.192	.013	2.872
[Employment status=4]	0[b]	.	.	0	.	.	.	.
[Mains Electricity as Energy mix=0]	18.245	3147.503	.000	1	.995	83859029.326	.000	.[c]
[Mains Electricity as Energy mix=1]	0[b]	.	.	0	.	.	.	.
[Biomass as energy mix at Household=0]	.565	.653	.751	1	.386	1.760	.490	6.326
[Biomass as energy mix at Household=1]	0[b]	.	.	0	.	.	.	.
[Solar as energy mix at Household=0]	1.824	1.474	1.532	1	.216	6.199	.345	111.402
[Solar as energy mix at Household=1]	0[b]	.	.	0	.	.	.	.
[LPG as Energy Mix at Household=0]	1.936	1.459	1.759	1	.185	6.928	.397	120.983
[LPG as Energy Mix at Household=1]	0[b]	.	.	0	.	.	.	.
[Paraffin as Energy Mix at Household=0]	-18.018	.000	.	1	.	1.496E-8	1.496E-8	1.496E-8
[Paraffin as Energy Mix at Household=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for heating=0]	1.058	.658	2.587	1	.108	2.882	.794	10.463
[Uses Energy for heating=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for Lighting=0]	-1.730	1.177	2.158	1	.142	.177	.018	1.783
[Uses Energy for Lighting=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for cooking=0]	-.281	1.845	.023	1	.879	.755	.020	28.070

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[Uses Energy for cooking=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for Cooling =0]	-1.325	.866	2.343	1	.126	.266	.049	1.450
[Uses Energy for Cooling =1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for refrigeration/Freezer=0]	-1.193	.562	4.500	1	.034	.303	.101	.913
[Uses Energy for refrigeration/Freezer=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy to run TV/Radio=0]	.833	.819	1.035	1	.309	2.301	.462	11.454
[Uses Energy to run TV/Radio=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for Appliances =0]	.520	1.166	.199	1	.656	1.682	.171	16.519
[Uses Energy for Appliances =1]	0[b]	.	.	0	.	.	.	.

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Appendix iii: Effect of finance on smart energy

Effect of finance on adoption of energy smart technology	B	Std. Error	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp(B)	
							Lower Bound	Upper Bound
Intercept	14.574	1582.554	.000	1	.993			
Age of the respondent in yrs	-.032	.198	.026	1	.872	.968	.656	1.429
[gender of the respondent =1]	.389	.479	.658	1	.417	1.475	.577	3.776
[gender of the respondent =2]	0[b]	.	.	0	.	.	.	.
[Highest level of education attained=1]	.797	1.556	.262	1	.609	2.219	.105	46.879
[Highest level of education attained=2]	2.563	1.401	3.346	1	.067	12.973	.833	202.134
[Highest level of education attained=3]	1.729	1.264	1.873	1	.171	5.637	.474	67.095
[Highest level of education attained=4]	3.078	1.496	4.231	1	.040	21.707	1.156	407.526
[Highest level of education attained=5]	0[b]	.	.	0	.	.	.	.

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[Employment status=1]	2.273	1.494	2.314	1	.128	9.709	.519	181.540
[Employment status=2]	2.464	1.563	2.487	1	.115	11.756	.550	251.362
[Employment status=3]	1.910	1.485	1.654	1	.198	6.756	.368	124.202
[Employment status=4]	0[b]	.	.	0	.	.	.	.
[Mains Electricity as Energy mix=0]	-1.749	1.671	1.095	1	.295	.174	.007	4.602
[Mains Electricity as Energy mix=1]	0[b]	.	.	0	.	.	.	.
[Biomass as energy mix at Household=0]	1.148	.619	3.436	1	.064	3.151	.936	10.604
[Biomass as energy mix at Household=1]	0[b]	.	.	0	.	.	.	.
[Solar as energy mix at House-hold=0]	16.550	1582.552	.000	1	.992	15397751.679	.000	.[c]
[Solar as energy mix at House-hold=1]	0[b]	.	.	0	.	.	.	.
[LPG as Energy Mix at House-hold=0]	1.196	1.558	.589	1	.443	3.308	.156	70.175
[LPG as Energy Mix at House-hold=1]	0[b]	.	.	0	.	.	.	.
[Paraffin as Energy Mix at Household=0]	-34.993	.000	.	1	.	6.350E-16	6.350E-16	6.350E-16

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[Paraffin as Energy Mix at Household=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for heating=0]	-1.521	.600	6.422	1	.011	.218	.067	.708
[Uses Energy for heating=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for Lighting=0]	-.241	1.079	.050	1	.823	.786	.095	6.519
[Uses Energy for Lighting=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for cooking=0]	33.321	2989.958	.000	1	.991	295E6	.000	.[c]
[Uses Energy for cooking=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for Cooling =0]	-1.112	.784	2.013	1	.156	.329	.071	1.528
[Uses Energy for Cooling =1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for refrigeration/Freezer=0]	-.179	.536	.111	1	.739	.836	.293	2.390
[Uses Energy for refrigeration/Freezer=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy to run TV/Radio=0]	.521	.673	.599	1	.439	1.684	.450	6.300
[Uses Energy to run TV/Radio=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for Appliances =0]	.203	1.079	.035	1	.851	1.225	.148	10.162
[Uses Energy for Appliances =1]	0[b]	.	.	0	.	.	.	.

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Appendix iv: Effect of knowledge on adoption of smart energy innovations

Effect of Knowledge on adoption of energy smart technology	B	SE	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp(B)	
							Lower Bound	Upper Bound
Intercept	174.532	129.903	1.805	1	.179			
Age of the respondent in yrs	.280	1.028	.074	1	.786	1.323	.176	9.919
[gender of the respondent =1]	.977	2.535	.149	1	.700	2.658	.018	382.031
[gender of the respondent =2]	0[b]	.	.	0	.	.	.	.
[Highest level of education attained=1]	-.217	10.523	.000	1	.984	.805	8.881E-10	729248052.181
[Highest level of education attained=2]	-2.308	8.705	.070	1	.791	.099	3.872E-9	2555861.294
[Highest level of education attained=3]	1.620	8.607	.035	1	.851	5.055	2.384E-7	107200203.330
[Highest level of education attained=4]	.258	9.401	.001	1	.978	1.294	1.288E-8	129996334.086
[Highest level of education attained=5]	0[b]	.	.	0	.	.	.	.
[Employment status=1]	-187.862	5.046	1385.853	1	<.001	2.585E-82	1.309E-86	5.104E-78
[Employment status=2]	-190.964	3.952	2334.921	1	<.001	1.163E-83	5.030E-87	2.688E-80

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[Employment status=3]	-191.108	1.447	17433.511	1	<.001	1.006E-83	5.897E-85	1.717E-82
[Employment status=4]	0[b]	.	.	0	.	.	.	.
[Mains Electricity as Energy mix=0]	-.882	14.167	.004	1	.950	.414	3.614E-13	473792885443.493
[Mains Electricity as Energy mix=1]	0[b]	.	.	0	.	.	.	.
[Biomass as energy mix at House-hold=0]	2.047	3.358	.372	1	.542	7.748	.011	5587.640
[Biomass as energy mix at House-hold=1]	0[b]	.	.	0	.	.	.	.
[Solar as energy mix at House-hold=0]	.087	8.612	.000	1	.992	1.091	5.099E-8	23351437.667
[Solar as energy mix at House-hold=1]	0[b]	.	.	0	.	.	.	.
[LPG as Energy Mix at House-hold=0]	17.027	128.840	.017	1	.895	24808279.002	5.314E-103	1.158E+117
[LPG as Energy Mix at House-hold=1]	0[b]	.	.	0	.	.	.	.
[Paraffin as Energy Mix at House-hold=0]	-.538	13.195	.002	1	.967	.584	3.423E-12	99542378501.128
[Paraffin as Energy Mix at House-hold=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for Heating=0]	-1.746	3.214	.295	1	.587	.174	.000	94.934
[Uses Energy for Heating=1]	0[b]	.	.	0	.	.	.	.

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[Uses Energy for Lighting=0]	-.153	6.910	.000	1	.982	.858	1.127E-6	653508.574
[Uses Energy for Lighting=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for Cooking=0]	-2.710	8.242	.108	1	.742	.067	6.422E-9	689296.818
[Uses Energy for Cooking=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for Cooling =0]	1.463	2.792	.275	1	.600	4.319	.018	1028.502
[Uses Energy for Cooling =1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for refrigeration/Freezer=0]	.943	3.275	.083	1	.773	2.568	.004	1576.733
[Uses Energy for refrigeration/Freezer=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy to run TV/Radio=0]	.605	4.308	.020	1	.888	1.831	.000	8512.730
[Uses Energy to run TV/Radio=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for Appliances =0]	1.165	8.008	.021	1	.884	3.204	4.886E-7	21015366.925
[Uses Energy for Appliances =1]	0[b]	.	.	0	.	.	.	.

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Appendix v: Effect of reliability on adoption of smart energy technology

Effect of reliability on adoption of smart energy technology	B	Std. Error	Wald	df	Sig.	Exp(B)		
							Lower Bound	Upper Bound
Intercept	17.916	1761.790	.000	1	.992			
Age of the respondent in yrs	-.403	.204	3.901	1	.048	.668	.448	.997
[gender of the respondent =1]	.391	.479	.667	1	.414	1.479	.578	3.781
[gender=2]	0[b]	.	.	0	.	.	.	.
[Highest level of education attained=1]	-1.309	1.587	.680	1	.409	.270	.012	6.060
[Highest level of education attained=2]	-1.838	1.392	1.744	1	.187	.159	.010	2.436
[Highest level of education attained=3]	-1.520	1.263	1.448	1	.229	.219	.018	2.601
[Highest level of education attained=4]	-2.166	1.457	2.209	1	.137	.115	.007	1.995
[Highest level of education attained=5]	0[b]	.	.	0	.	.	.	.
[Employment status=1]	-.660	1.150	.329	1	.566	.517	.054	4.923
[Employment status=2]	-1.741	1.217	2.047	1	.152	.175	.016	1.904

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[Employment status=3]	-1.715	1.121	2.343	1	.126	.180	.020	1.618
[Employment status=4]	0[b]	.	.	0	.	.	.	.
[Mains Electricity as Energy mix=0]	16.654	2620.869	.000	1	.995	17094592.079	.000	.[c]
[Mains Electricity as Energy mix=1]	0[b]	.	.	0	.	.	.	.
[Biomass as energy mix at Household=0]	1.521	.614	6.137	1	.013	4.575	1.374	15.238
[Biomass as energy mix at Household=1]	0[b]	.	.	0	.	.	.	.
[Solar as energy mix at House-hold=0]	17.157	1761.789	.000	1	.992	28269698.773	.000	.[c]
[Solar as energy mix at House-hold=1]	0[b]	.	.	0	.	.	.	.
[LPG as Energy Mix at House-hold=0]	4.570	1.599	8.169	1	.004	96.541	4.204	2216.811
[LPG as Energy Mix at House-hold=1]	0[b]	.	.	0	.	.	.	.
[Paraffin as Energy Mix at Household=0]	-34.435	.000	.	1	.	1.109E-15	1.109E-15	1.109E-15
[Paraffin as Energy Mix at Household=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for heating=0]	-.172	.573	.090	1	.764	.842	.274	2.589

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[Uses Energy for heating=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for Lighting=0]	-1.262	1.161	1.182	1	.277	.283	.029	2.754
[Uses Energy for Lighting=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for cooking=0]	-68.654	3715.069	.000	1	.985	1.527E-30	.000	.[c]
[Uses Energy for cooking=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for Cooling =0]	-.657	.737	.794	1	.373	.518	.122	2.199
[Uses Energy for Cooling =1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for refrigeration/Freezer=0]	-.230	.531	.188	1	.664	.794	.281	2.247
[Uses Energy for refrigeration/Freezer=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy to run TV/Radio=0]	.620	.699	.787	1	.375	1.859	.472	7.316
[Uses Energy to run TV/Radio=1]	0[b]	.	.	0	.	.	.	.
[Uses Energy for Appliances =0]	.643	1.144	.316	1	.574	1.903	.202	17.909
[Uses Energy for Appliances =1]	0[b]	.	.	0	.	.	.	.

a. The reference category is: yes. Nag .399; sig 0.001

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Appendix vi: Discounted Net cash flows data on Solar WEF Innovations

Time (Yrs)	innovation	description	Netcasflow5%	Netcasflow10%	Netcasflow 15%	Netcashflow 20%	
1	large panels with water pump	LPWW	-128272	-134380	-140489	-146597	
2	large panels with water pump	LPWW	-99683	-111149	-161562	-175916	
3	large panels with water pump	LPWW	-69664.4	-85594.1	-185796	-211099	
4	large panels with water pump	LPWW	-38144.8	-57483.9	-213666	-253319	
5	large panels with water pump	LPWW	-5049.22	-26562.7	-245715	-303983	
6	large panels with water pump	LPWW	29701.12	7450.597	-282573	-364780	
7	large panels with water pump	LPWW	66188.98	44865.26	-324959	-437736	
8	large panels with water pump	LPWW	104501.2	86021.38	-373702	-525283	
9	large panels with water pump	LPWW	144729.1	131293.1	-429758	-630339	
10	large panels with water pump	LPWW	186968.3	181092	-494222	-756407	
11	large panels with water pump	LPWW	231319.6	235870.8	-568355	-907689	
12	large panels with water pump	LPWW	277888.3	296127.5	-653608	-1089226	
13	large panels with water pump	LPWW	326785.6	362409.9	-751649	-1307072	
14	large panels with water pump	LPWW	378127.6	435320.5	-864397	-1568486	
15	large panels with water pump	LPWW	432036.8	515522.1	-994056	-1882183	
16	large panels with water pump	LPWW	488641.5	603743.9	-1143164	-2258620	
17	large panels with water pump	LPWW	548076.3	700787.9	-1314639	-2710344	
18	large panels with water pump	LPWW	610482.9	807536.3	-1511835	-3252413	
19	large panels with water pump	LPWW	676009.9	924959.5	-1738610	-3902895	
20	large panels with water pump	LPWW	744813.2	1054125	-1999402	-4683475	
1	large panels without water pump	LPWTW	-102022	-106880	-111739	-116597	
2	large panels without water pump	LPWTW	-72120.5	-80898.8	-90163	-99913	
3	large panels without water pump	LPWTW	-40723.7	-52319.1	-65351	-79892.4	

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4	large panels without water pump	LPWTW	-7757.12	-20881.4	-36817.3	-55867.6	
5	large panels without water pump	LPWTW	26857.82	13700.02	-4003.49	-27037.9	
6	large panels without water pump	LPWTW	63203.51	51739.62	33732.39	7557.664	
7	large panels without water pump	LPWTW	101366.5	93583.18	77128.65	49072.4	
8	large panels without water pump	LPWTW	141437.6	139611.1	127034.3	98890.08	
9	large panels without water pump	LPWTW	183512.3	190241.8	184425.9	158671.3	
10	large panels without water pump	LPWTW	227690.7	245935.6	250426.2	230408.7	
11	large panels without water pump	LPWTW	274078	307198.8	326326.5	316493.7	
12	large panels without water pump	LPWTW	322784.7	374588.2	413611.9	419795.6	
13	large panels without water pump	LPWTW	373926.8	448716.7	513990.1	543758	
14	large panels without water pump	LPWTW	427625.9	530257.9	629425	692512.8	
15	large panels without water pump	LPWTW	484010	619953.3	762175.1	871018.5	
16	large panels without water pump	LPWTW	543213.3	718618.2	914837.8	1085225	
17	large panels without water pump	LPWTW	605376.8	827149.7	1090400	1342274	
18	large panels without water pump	LPWTW	670648.4	946534.2	1292296	1650732	
19	large panels without water pump	LPWTW	739183.6	1077857	1524477	2020881	
20	large panels without water pump	LPWTW	811145.6	1222313	1791485	2465061	
1	small pannels with water pump	SPWW	-33373.2	-34962.4	-36551.6	-38140.8	
2	small pannels with water pump	SPWW	-30090.1	-33271	-36610.9	-45769	
3	small pannels with water pump	SPWW	-26642.8	-31410.5	-36679.2	-54922.8	
4	small pannels with water pump	SPWW	-23023.1	-29364	-36757.7	-65907.3	
5	small pannels with water pump	SPWW	-19222.5	-27112.8	-36847.9	-79088.8	
6	small pannels with water pump	SPWW	-15231.8	-24636.5	-36951.7	-94906.5	
7	small pannels with water pump	SPWW	-11041.6	-21912.5	-37071	-113888	
8	small pannels with water pump	SPWW	-6641.85	-18916.2	-37208.3	-136665	
9	small pannels with water pump	SPWW	-2022.14	-15620.2	-37366.1	-163998	
10	small pannels with water pump	SPWW	2828.554	-11994.6	-37547.7	-196798	
11	small pannels with water pump	SPWW	7921.782	-8006.48	-37756.4	-236158	
12	small pannels with water pump	SPWW	13269.67	-3619.53	-37996.5	-283389	

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13	small pannels with water pump	SPWW	18884.95	1206.122	-38272.6	-340067	
14	small pannels with water pump	SPWW	24781	6514.334	-38590	-408081	
15	small pannels with water pump	SPWW	30971.85	12353.37	-38955.1	-489697	
16	small pannels with water pump	SPWW	37472.25	18776.3	-39375	-587636	
17	small pannels with water pump	SPWW	44297.66	25841.54	-39857.9	-705163	
18	small pannels with water pump	SPWW	51464.34	33613.29	-40413.2	-846196	
19	small pannels with water pump	SPWW	58989.36	42162.22	-41051.7	-1015435	
20	small pannels with water pump	SPWW	66890.63	51566.04	-41786.1	-1218522	
1	small panels without water pump	SPWTW	-29549.1	-30956.2	-32363.3	-33770.4	
2	small panels without water pump	SPWTW	-28550.7	-31458	-34506.1	-37694.9	
3	small panels without water pump	SPWTW	-27502.3	-32010	-36970.3	-42404.3	
4	small panels without water pump	SPWTW	-26401.5	-32617.2	-39804.2	-48055.5	
5	small panels without water pump	SPWTW	-25245.7	-33285.1	-43063.1	-54837	
6	small panels without water pump	SPWTW	-24032.1	-34019.9	-46810.8	-62974.8	
7	small panels without water pump	SPWTW	-22757.8	-34828	-51120.8	-72740.2	
8	small panels without water pump	SPWTW	-21419.8	-35717.1	-56077.2	-84458.6	
9	small panels without water pump	SPWTW	-20014.8	-36695	-61777.1	-98520.7	
10	small panels without water pump	SPWTW	-18539.7	-37770.7	-68331.9	-115395	
11	small panels without water pump	SPWTW	-16990.8	-38953.9	-75870	-135645	
12	small panels without water pump	SPWTW	-15364.4	-40255.5	-84538.8	-159944	
13	small panels without water pump	SPWTW	-13656.7	-41687.3	-94507.9	-189103	
14	small panels without water pump	SPWTW	-11863.7	-43262.2	-105972	-224094	
15	small panels without water pump	SPWTW	-9980.94	-44994.6	-119157	-266084	
16	small panels without water pump	SPWTW	-8004.09	-46900.3	-134318	-316471	
17	small panels without water pump	SPWTW	-5928.4	-48996.5	-151754	-376935	
18	small panels without water pump	SPWTW	-3748.92	-51302.3	-171806	-449493	
19	small panels without water pump	SPWTW	-1460.46	-53838.8	-194865	-536562	
20	small panels without water pump	SPWTW	942.4158	-56628.9	-221383	-641044	

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Appendix vii: BCR of various WEF solar innovations

Innovation	description	Time (Yrs)	BCR 5%	BCR 10%	BCR 15%	BCR 20%
large panels with water pump	LPWW	1	0.214379421	0.214379	0.214379	0.2143794
large panels with water pump	LPWW	2	0.418550299	0.40927	0.400796	0.3930289
large panels with water pump	LPWW	3	0.612998753	0.586443	0.562898	0.5419035
large panels with water pump	LPWW	4	0.798187758	0.747509	0.703856	0.6659657
large panels with water pump	LPWW	5	0.974558238	0.893933	0.826428	0.7693508
large panels with water pump	LPWW	6	1.142530124	1.027046	0.933012	0.8555051
large panels with water pump	LPWW	7	1.302503349	1.148058	1.025695	0.9273004
large panels with water pump	LPWW	8	1.454858801	1.258068	1.106288	0.9871297
large panels with water pump	LPWW	9	1.599959232	1.358078	1.176369	1.0369875
large panels with water pump	LPWW	10	1.738150118	1.448996	1.237309	1.0785357
large panels with water pump	LPWW	11	1.869760486	1.531648	1.2903	1.1131592
large panels with water pump	LPWW	12	1.995103694	1.606787	1.33638	1.1420121
large panels with water pump	LPWW	13	2.114478177	1.675095	1.376449	1.1660561
large panels with water pump	LPWW	14	2.228168161	1.737193	1.411291	1.1860929
large panels with water pump	LPWW	15	2.336444337	1.793646	1.441589	1.2027901
large panels with water pump	LPWW	16	2.439564504	1.844966	1.467935	1.2167045
large panels with water pump	LPWW	17	2.537774187	1.891622	1.490845	1.2282999
large panels with water pump	LPWW	18	2.631307218	1.934035	1.510766	1.2379626
large panels with water pump	LPWW	19	2.720386295	1.972593	1.528089	1.246015
large panels with water pump	LPWW	20	2.805223512	2.007646	1.543153	1.2527252
large panels without water pump	LPWTW	1	0.255448276	0.255448	0.255448	0.2554483
large panels without water pump	LPWTW	2	0.523668966	0.487674	0.477577	0.4683218
large panels without water pump	LPWTW	3	0.766953038	0.698788	0.670733	0.6457165

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large panels without water pump	LPWTW	4	0.998652154	0.89071	0.838694	0.7935453
large panels without water pump	LPWTW	5	1.21931798	1.065185	0.984748	0.9167361
large panels without water pump	LPWTW	6	1.429475908	1.223798	1.111751	1.019395
large panels without water pump	LPWTW	7	1.629626316	1.367992	1.222188	1.1049441
large panels without water pump	LPWTW	8	1.820245752	1.499077	1.31822	1.176235
large panels without water pump	LPWTW	9	2.001788074	1.618246	1.401727	1.2356441
large panels without water pump	LPWTW	10	2.174685521	1.726581	1.474341	1.2851517
large panels without water pump	LPWTW	11	2.339349758	1.825067	1.537484	1.326408
large panels without water pump	LPWTW	12	2.49617284	1.9146	1.592391	1.3607883
large panels without water pump	LPWTW	13	2.645528157	1.995994	1.640136	1.3894385
large panels without water pump	LPWTW	14	2.787771314	2.069988	1.681654	1.4133137
large panels without water pump	LPWTW	15	2.92324099	2.137256	1.717756	1.4332097
large panels without water pump	LPWTW	16	3.052259727	2.198408	1.749149	1.4497897
large panels without water pump	LPWTW	17	3.175134715	2.254001	1.776447	1.4636064
large panels without water pump	LPWTW	18	3.292158514	2.30454	1.800185	1.4751202
large panels without water pump	LPWTW	19	3.40360975	2.350485	1.820827	1.4847151
large panels without water pump	LPWTW	20	8.446640965	2.392253	1.838776	1.4927109
small pannels with water pump	SPWW	1	0.129205479	0.129205	0.129205	0.1292055
small pannels with water pump	SPWW	2	0.252258317	0.246665	0.241558	0.2368767
small pannels with water pump	SPWW	3	0.369451496	0.353446	0.339256	0.3266027
small pannels with water pump	SPWW	4	0.481064047	0.45052	0.424211	0.4013744
small pannels with water pump	SPWW	5	0.587361714	0.538769	0.498084	0.4636842
small pannels with water pump	SPWW	6	0.688597588	0.618996	0.562322	0.515609
small pannels with water pump	SPWW	7	0.785012707	0.691929	0.618181	0.5588796
small pannels with water pump	SPWW	8	0.876836629	0.758232	0.666755	0.5949385
small pannels with water pump	SPWW	9	0.964287983	0.818507	0.708992	0.6249876
small pannels with water pump	SPWW	10	1.047574987	0.873303	0.74572	0.6500284
small pannels with water pump	SPWW	11	1.126895943	0.923117	0.777658	0.6708958
small pannels with water pump	SPWW	12	1.202439711	0.968403	0.80543	0.6882854

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small pannels with water pump	SPWW	13	1.274386157	1.009572	0.829579	0.7027766
small pannels with water pump	SPWW	14	1.342906581	1.046998	0.850579	0.7148527
small pannels with water pump	SPWW	15	1.408164128	1.081022	0.868839	0.724916
small pannels with water pump	SPWW	16	1.470314173	1.111953	0.884718	0.7333022
small pannels with water pump	SPWW	17	1.529504692	1.140072	0.898525	0.7402906
small pannels with water pump	SPWW	18	1.585876614	1.165634	0.910532	0.7461143
small pannels with water pump	SPWW	19	1.63956416	1.188873	0.920972	0.7509674
small pannels with water pump	SPWW	20	1.690695156	1.209999	0.930051	0.7550117
small panels without water pump	SPWTW	1	0.077311475	0.077311	0.077311	0.0773115
small panels without water pump	SPWTW	2	0.150941452	0.147595	0.144539	0.1417377
small panels without water pump	SPWTW	3	0.221065239	0.211488	0.202997	0.1954262
small panels without water pump	SPWTW	4	0.287849799	0.269574	0.253831	0.2401667
small panels without water pump	SPWTW	5	0.35145414	0.322378	0.298034	0.2774504
small panels without water pump	SPWTW	6	0.412029705	0.370383	0.336472	0.3085201
small panels without water pump	SPWTW	7	0.469720718	0.414023	0.369895	0.3344116
small panels without water pump	SPWTW	8	0.52466454	0.453696	0.39896	0.3559878
small panels without water pump	SPWTW	9	0.57699199	0.489762	0.424233	0.373968
small panels without water pump	SPWTW	10	0.626827657	0.52255	0.44621	0.3889514
small panels without water pump	SPWTW	11	0.674290195	0.552357	0.46532	0.4014377
small panels without water pump	SPWTW	12	0.719492614	0.579454	0.481937	0.4118429
small panels without water pump	SPWTW	13	0.762542537	0.604088	0.496388	0.4205139
small panels without water pump	SPWTW	14	0.803542462	0.626482	0.508953	0.4277397
small panels without water pump	SPWTW	15	0.842590011	0.646841	0.519879	0.4337612
small panels without water pump	SPWTW	16	0.879778153	0.665349	0.52938	0.4387792
small panels without water pump	SPWTW	17	0.915195431	0.682174	0.537642	0.4429608
small panels without water pump	SPWTW	18	0.948926171	0.69747	0.544826	0.4464455
small panels without water pump	SPWTW	19	0.981050686	0.711375	0.551074	0.4493494
small panels without water pump	SPWTW	20	1.011645462	0.724016	0.556506	0.4517693

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Appendix viii: Proof reading letter



To whom it may concern

Dear Sir/Madam

This is to authenticate that I, Zitha Innocent, have proofread and edited a dissertation for a Master of Science in the Department of Earth Sciences in the Faculty of Science, Engineering and Agriculture at the University of Venda entitled **Use and management of energy resources from Water, Energy, and Food (WEF) nexus perspective: The case of Vhembe District Municipality (VDM), Limpopo Province**

By

Mudau, M

Student No: 16008470

I have meticulously and comprehensively inspected this dissertation for consistency, coherence, and correctness of language use, ensuring proper register usage and citations. I have suggested several amendments, which were communicated to the student for consideration and implementation. The student has undertaken to effect these amendments before this dissertation is finally submitted.

Date: **21/02/2025**

BA Hons (English), MA (English), PhD (current studies), Lecturer (English) @ North-West University

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Appendix ix: Ethics approval certificate

ETHICS APPROVAL CERTIFICATE

ETHICS APPROVAL CERTIFICATE

FACULTY OF SCIENCE, ENGINEERING AND AGRICULTURE
RESEARCH ETHICS COMMITTEE

NAME OF RESEARCHER/INVESTIGATOR: M MUDAU

STAFF/STUDENT NO: 16008470

PROJECT TITLE: Assessment of use and management of energy resources in relation to water, energy, and food nexus in selected areas in the Vhembe district municipality, Limpopo Province.

ETHICAL CLEARENCE NO: FSEA/23/ES/11

SUPERVISORS/ CO-RESEARCHERS/ CO-INVESTIGATORS

NAME	INSTITUTION & DEPARTMENT	ROLE
Prof R Makungo	University of Venda, Earth Sciences	Supervisor

Type: **Student research**

Risk: **Minimal risk to humans, animals, or environment (Category 1)**

Approval Period: **January 2024 – January 2026**

The Faculty Research Ethics Committee (FREC) of the Faculty of Science, Engineering and Agriculture hereby approves your project as indicated above.

University of Venda

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General Conditions

While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, please note the following.

- **The project leader (principal investigator) must report in the prescribed format to the REC:**
  - **Annually (or as otherwise requested) on the progress of the project, and upon completion of the project**
  - **Within 48hrs in case of any adverse event (or any matter that interrupts sound ethical principles) during the project.**
  - **Annually, research projects may be randomly selected for auditing.**
- **The approval applies strictly to the protocol as stipulated in the application form. Should a change to the protocol be deemed necessary during the project, the project leader must apply for approval of these changes before their implementation. Should there be a deviation from the study protocol, without the necessary approval for the change, the ethics approval is automatically forfeited.**
- **The date of approval indicates the earliest date that the project may begin. Should the project have to continue after the expiry date; a new application must be made, and a new approval received before or on the expiry date.**
- **In the interest of ethical responsibility, the FREC retains the right to:**
  - **Request access to any information or data at any time during the course or after completion of the project,**
  - **To ask further questions; Seek additional information; Require further modification or monitor the conduct of your research or the informed consent process.**
  - **withdraw or postpone approval if:**
  - **Any unethical principles or practices of the project are revealed or suspected.**
  - **It becomes apparent that relevant information was withheld from the REC or that information has been false or misrepresented.**
  - **The required annual report and reporting of adverse events was not done timely and accurately,**
  - **New institutional rules, national legislation or international conventions deem it necessary**

ISSUED BY:
FACULTY OF SCIENCE, ENGINEERING AND AGRICULTURE RESEARCH ETHICS COMMITTEE



Chairperson: Prof. L.C Murulana

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