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Original research article

Multidimensional energy poverty and food insecurity nexus in Gauteng and Western cape provinces of South Africa

Adrino Mazenda *

Faculty of Economic and Management Sciences, School of Public Management and Administration, University of Pretoria, Hatfield, South Africa

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ABSTRACT

Energy poverty and food insecurity are interconnected challenges that disproportionately affect vulnerable populations in low and middle-income countries. The paper utilised the Tobit regression model to examine the relationship between household food insecurity and various socioeconomic factors, and the Structural Equation Modelling (SEM) to examine the complex interactions between multidimensional energy poverty (MEP), (measured by the MEP fuzzy score) and food insecurity, measured by the Household Food Insecurity Access Scale (HFIAS), mediated by various socioeconomic factors. A total of 6484 households were analysed, categorised by region and gender, in both metropolitan and non-metropolitan areas of the Gauteng and Western Cape provinces of South Africa, using data from the 2021–2022 South African General Household Survey. The Tobit regression findings showed that higher household income consistently reduces food insecurity. A larger household size and increased MEP contribute to higher levels of food insecurity, with the effect of MEP being significant in the Western Cape. Social grant recipients remained more food insecure, suggesting persistent vulnerability. Spatial differences emerged, with higher food insecurity in metropolitan areas of the Western Cape but lower in Gauteng. The SEM analysis revealed that energy poverty has a direct and significant impact on food insecurity, with household income serving as the strongest mediating factor. Education, employment, and household size contributed modest indirect effects, while other socio-economic variables showed weak or inconsistent mediation. The paper highlights the importance of adopting integrated policy approaches that simultaneously address energy access and food security, with a focus on gender and spatial inequalities.

1. Introduction

Understanding the factors that influence household energy security is crucial for developing evidence-based policies and financial strategies to effectively address energy poverty [1]. The paper examines the relationship between energy poverty and food insecurity from a gender perspective in metropolitan and non-metropolitan areas of Gauteng and the Western Cape provinces in South Africa [1,2]. Additionally, the paper analyses how various socio-economic factors, such as the education level of the household head, household size, income, employment status, business ownership, and access to social support grants, affect the relationship between energy poverty and food insecurity in these households.

Energy poverty and food insecurity are significant challenges faced by many households, particularly in developing regions. Understanding how socioeconomic factors mediate these issues is crucial for creating effective policies and financial strategies to combat energy poverty [2]. Key determinants of energy poverty include household characteristics, such as living space, income, and education, as well as regional elements, including urbanisation [3]. Vulnerable households often require trust in stakeholders and perceive health benefits as significant motivators; deep-energy retrofits can serve as a vital resource to alleviate their circumstances [4]. Addressing energy inadequacies requires considering financial factors, such as potential energy savings and access to free retrofitting options. Government regulations, particularly in social housing, play a crucial role in the process [5]. Therefore, it is essential to understand the multifaceted nature of energy poverty across different contexts for effective and integrated solutions [6].

Energy access is foundational in addressing numerous global development challenges like poverty, inequality, climate change, food insecurity, health, and education [7]. With about 25 % of the global population relying on traditional biofuels due to limited access to modern energy services, adverse health and economic repercussions arise [8]. This energy significantly hinders development efforts,

* Corresponding author.
E-mail address: adrino.mazenda@up.ac.za.

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particularly in sub-Saharan Africa and developing Asia [9]. Renewable energy offers a promising pathway to alleviate poverty and combat climate change, with systems like mini-grids potentially bridging inequality gaps and achieving Sustainable Development Goals [10].

Households experiencing energy poverty often face increased food insecurity and related health issues [11]. Access to clean cooking energy and electricity is positively linked to improved food security, particularly in sub-Saharan Africa [12]. The connections between energy and food systems require attention because reliance on traditional biomass fuels can worsen food insecurity and contribute to environmental degradation [13]. Investing in alternative energy sources can help to alleviate both food and energy crises while promoting environmental preservation and public health [14].

In South Africa, energy poverty and food insecurity are significant issues that greatly affect communities already facing socio-economic inequalities [15]. The lack of affordable and clean energy sources perpetuates energy poverty, limiting households' ability to reliably prepare and store food. This situation is not just a local problem; it also aligns with the Sustainable Development Goals, notably Goals 1, 2, 7, and 10, which focus on eradicating poverty and hunger, ensuring access to affordable energy, and reducing inequalities [16]. Furthermore, this study supports the principles of the *Sustainable Livelihoods Approach (SLA),* which advocates for multi-dimensional interventions that consider human, social, financial, and physical capital to alleviate energy poverty and food insecurity [17].

The SLA, introduced by the Department for International Development (DFID) in the early 1990s, has evolved to address the complex interconnections among poverty reduction, food security, and sustainable development. It emphasises the importance of considering the diverse assets and capabilities that individuals and households depend on for their well-being [18].

A key aspect of the SLA is its emphasis on the interplay between human, social, physical, financial, and natural capital, all of which contribute to resilience in the face of shocks [20]. This integrated perspective supports multi-dimensional poverty assessments, including evaluations of food security, and helps analyse the influence of social networks and institutions on vulnerable groups [22]. Studies that employ the SLA often uncover the connection between energy poverty and food security. Some of these studies advocate for urban safety nets that incorporate diverse livelihood strategies, emphasising that access to energy is crucial for enhancing food security [23]. Additionally, the SLA also highlights how individuals manage food security while addressing economic vulnerability [24].

Understanding the gender dynamics within household structures is crucial for comprehending the complexities of these relationships. Male-headed households often have different access to resources and opportunities compared to female-headed households, who may encounter additional challenges such as discrimination or limited access to financial services [25]. Therefore, interventions that do not take gender differences into account risk reinforcing existing inequalities. A gender-sensitive analysis is necessary not only to identify the specific needs and capabilities of male- and female-headed households but also to design equitable and effective development strategies that promote and ensure inclusive access to food, energy, and sustainable livelihoods. This study adds to the existing body of knowledge by emphasising the multidimensional gendered aspects of energy poverty and its systemic links to food insecurity. It highlights the need for integrated policy interventions that address both energy and food access within a socio-economic framework.

While existing global literature suggests a general link between energy poverty and food insecurity, the specific dynamics of this relationship, especially within the South African context, across different regions (metropolitan vs. non-metropolitan), remain underexplored [26]. Most global studies assess energy poverty and food insecurity separately, rather than employing an integrated nexus approach to analyse causal connections between the two [27,28]. Similarly, some studies have employed the gender element in their analysis but have not investigated how energy poverty disproportionately affects women's roles in food provisioning responsibilities, their nutritional choices, and their household coping strategies. [29].

This paper aims to investigate the impact of energy poverty on food insecurity, considering key socio-economic factors such as education, employment, and access to social grants. By utilising the Multidimensional Energy Poverty Index (MEPI), the Household Food Insecurity Access Scale (HFIAS), Structural Equation Modelling (SEM) and Probit modelling techniques, this paper seeks to go beyond general assumptions and provide empirical evidence on the complex relationships between energy poverty and food insecurity. This focused analysis addresses a significant area and offers valuable insights for more targeted policy interventions.

The focus on Gauteng and the Western Cape was guided by both theoretical and practical reasons. These two provinces represent different urban contexts in South Africa, characterised by relatively high levels of economic development, infrastructure availability, and service delivery. However, they also include significant deprivation, especially in non-metropolitan and peri-urban areas. This contrast creates a unique opportunity to explore the dynamics of energy poverty.

The paper is structured as follows: After the introduction, the subsequent sections outline the study area, materials and methods, results, discussion, conclusion, and limitations of the study.

2. Study area

Gauteng and the Western Cape are two of South Africa's most significant provinces, both in terms of geography and economy. Gauteng is in the north-eastern part of the country, and although it is the smallest province in terms of area, it has the largest population. This province serves as South Africa's economic powerhouse. Rapid urban development has been observed, particularly in major cities such as Johannesburg and Pretoria. The growth of these urban areas is closely linked to socio-economic factors, including significant income inequality and high migration rates [30]. Gauteng primarily consists of high-altitude grasslands and is centrally located, enabling easy connectivity to other provinces [31].

The Western Cape, located in the southwestern region of South Africa, is renowned for its tourism and vibrant cultural heritage. This province experiences diverse climatic conditions, ranging from a Mediterranean climate along the coast to a semi-arid climate further inland. These varying conditions significantly impact both its agriculture and biodiversity [32]. The approximately 1200-km distance between Gauteng and the Western Cape creates significant logistical and economic separation [33]. Unlike Gauteng's emphasis on finance and industry, the Western Cape is renowned for its wine production and tourism, underscoring its distinctive economic profile [34]. The map of the study area is shown in Fig. 1:

3. Materials and methods

This section outlines the materials and methods used in the study. It describes the data sources and sampling procedures, the measurement of food insecurity and multidimensional energy poverty, and the analytical approaches employed. Specifically, it details the application of the Tobit regression model and the SEM with path analysis to examine both direct and mediated relationships among the key variables.

3.1. Data and sampling

This study utilised data from the General Household Survey (GHS) for the years 2021 to 2022. The survey encompasses a range of socio-economic variables, including demographic factors, social development, housing, health, education, livelihoods, access to water, sanitation, energy, transportation, communication, economic activities, and

Fig. 1. Provinces of South Africa.
(Source: Authors)

agricultural and food security.

The study population included all households in the Western Cape and Gauteng. The sample consisted of 722 male-headed and 433 female-headed households in Western Cape metropolitan areas, 362 male-headed and 255 female-headed households in Western Cape non-metropolitan areas, 2556 male-headed and 1389 female-headed households in Gauteng metropolitan areas, and 501 male-headed and 268 female-headed households in Gauteng non-metropolitan areas. Sampling weights were applied to produce weighted household estimates of 830,857 and 527,847 (Western Cape metro), 406,042 and 314,525 (Western Cape non-metro), 3,161,565 and 1,734,050 (Gauteng metro), and 451,511 and 239,468 (Gauteng non-metro), respectively.

3.2. Food insecurity assessment

Food security and insecurity can be assessed through various attributes using different metrics. Common tools for evaluation include the Food Consumption Score (FCS), the Household Food Insecurity Access Scale (HFIAS), and the Household Dietary Diversity Score (HDDS). In this paper, the HFIAS was utilised based on the available data [35]. The analysis followed the methodology outlined in the Food and Nutrition Technical Assistance III Project (FANTA) guidelines [36]. In this study, we adapted the HFIAS approach to better fit the data. We developed a set of 14 food security indicators that capture various dimensions of food insecurity, including anxiety about accessing food, inadequate food quality, and reductions in food quantity. These indicators were transformed into binary variables, where a response of "yes" was coded as 1 and "no" as 0.

The indicators included concerns about food, the inability to consume nutritious food, eating a limited variety of foods, skipping meals, reducing portion sizes, running out of food, going to sleep hungry, and going an entire day without eating. Some variables also took into account the frequency of these experiences.

We then summed the 14 binary variables to create a composite food insecurity score for each household. This score ranges from 0, indicating no experience of food insecurity, to 14, indicating that the household has experienced all measured conditions of food insecurity.

3.3. Energy poverty assessment

This study utilised the multidimensional energy poverty index (MEPI) methodology to assess energy poverty [37]. The MEPI was specifically applied to evaluate energy security for rural households in the Melani and Hamburg communities in the Eastern Cape, South Africa. Other studies have similarly explored multidimensional energy poverty by examining both energy affordability and energy accessibility, where the poverty outcomes can be a combination of both [38].

The energy poverty (EP) cutoff of 0.33 used in this study is based on the MEPI fuzzy approach applied in previous studies in the South African context. [39]. This cutoff has become increasingly common in national-level studies that aim to capture more severe or conservative levels of deprivation, identifying households as energy poor if they are deprived in at least one-third of the weighted indicators. The MEPI approach broadens the analysis to include non-monetary indicators of living standards [40]. The MEPI takes into account various dimensions and indicators, such as access to electricity, modern cooking, lighting, and heating fuel, indoor pollution, and energy services provided using household appliances like refrigerators, radios, televisions, and telecommunication means (landline or mobile phones). By focusing on energy services, this approach highlights what matters to people and how it impacts their lives [41].

In the assessment of multidimensional poverty, the fuzzy approach has gained increased attention. Common steps for undertaking this assessment include identifying the deprivation in terms of analysis, which may involve exploration and confirmatory factor analysis or personal judgment to determine the relevant dimensions [42]. Additionally, it includes determining the weights that will be used to calculate the fuzzy score. Overall, this paper adopts the multidimensional poverty fuzzy approach previously employed by other researchers [43]. The functional form of the multidimensional poverty ratio $\mu_B(a_i)$ for the fuzzy approach is shown in equation (i) [44].

$$\mu_B(a_i) = \sum_{j=1}^{m} X_{ij} w_j \Big/ \sum_{j=1}^{m} w_j \quad \text{(i)}$$

The weight w_j is the inverse function of the deprivation extent, for example, when there are more households that are deprived in an attribute, the weight is smaller and vice versa.

The rationale behind the weighting of MEPI indicators is to reflect the relative significance of different dimensions of energy poverty, such as cooking fuel, lighting, appliance ownership, and energy affordability, based on prior literature and expert consensus. Each indicator is assigned a specific weight that captures its contribution to overall energy poverty, ensuring that critical deprivations are appropriately emphasised. Aggregation is conducted by summing the weighted indicators for each household, generating a composite score that identifies households experiencing multidimensional energy poverty based on a predetermined cutoff threshold.

3.4. Tobit regression model

The Tobit regression model was employed to examine the relationship between household food insecurity and various socio-economic factors, including multidimensional energy poverty [45].

$$y_i^* = x_i\beta + \varepsilon_i \quad \text{(ii)}$$

The dependant variable was the HFIAS score (log), the independent variables were: education, employment (yes = 1, no = 0), business (yes = 1, no = 0), grant recipient (yes = 1, no = 0), income (log equalized), household size, female headed household ((yes = 1, no = 0), metropolitan location (yes = 1, no = 0), MEPI fuzzy score.

3.5. Structural equation modelling (SEM) and path analysis

To understand the relationship between energy poverty and food insecurity, correlation analysis using the Spearman correlation coefficient was first applied. The variables were evaluated at the household level, with energy poverty represented by the weighted MEPI deprivation count, while food insecurity is represented by the HFIAS score. This helps to determine the strength and direction of the relationship between energy poverty and food insecurity; a positive correlation would suggest that as energy poverty increases, food insecurity also increases.

The SEM was applied to analyse the relationship between energy poverty and food insecurity, mediated by socio-economic factors such as education, employment, business ownership, grants, income, and household size [46]. Fig. 2 illustrates the path analysis model, which shows the relationships between the variables.

The mediators used in this study included education, employment, business ownership, grants, income, and household size. The study analysed direct effects to determine how the independent variable, energy poverty, impacts the dependent variable, food insecurity. Additionally, covariances were established among several variables to account for their interrelationships.

The model applied in this research utilised Full Information Maximum Likelihood (FIML) to manage missing data, while also considering sampling weights to ensure representativeness. The Maximum Likelihood with Robust Standard Errors (MLR) estimator was employed to account for non-normality and heteroscedasticity in the data. Separate models were run for each group to capture regional and gender-specific variations, providing insights into how socio-economic conditions influence the relationship between energy and food insecurity.

The data was disaggregated into two provinces, Gauteng and Western Cape, each divided into metropolitan and non-metropolitan areas. These areas were further classified by male-headed and female-headed households, allowing for a detailed analysis of regional and gender-based differences in the relationship between energy and food insecurity. Consequently, models for each subgroup were run simultaneously.

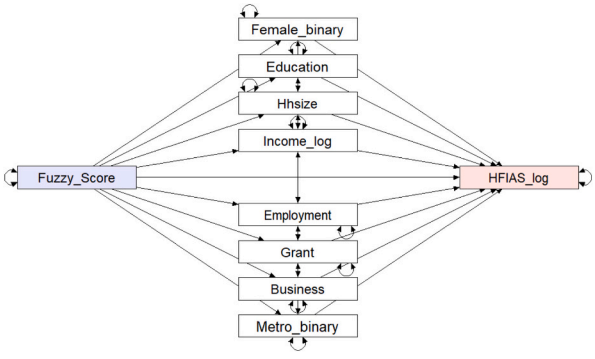

Fig. 2. The path analysis model showing the relationship between the variables.
(Source: Authors)

The data processing and analysis were performed using R statistical software (R Core Team, 2024, version 4.4.0). The haven package was utilised for data import and manipulation [47]. Mardia's test for multivariate normality was conducted with the MVN package. The data analysis for the Tobit regression model was done in R using the AER package. SEM was carried out using the lavaan packageand the semPlot was employed to create graphical representations [48].

4. Results

This section presents the results of the study. It begins with descriptive statistics on the demographic and socio-economic characteristics of households, levels of food insecurity, and multidimensional energy poverty. This is followed by the correlation analysis between energy poverty and food insecurity, the Tobit regression results, and finally, the structural equation modelling outcomes.

4.1.1. Demographics and socio-economic factors

Table 1 shows the descriptive statistics for demographics and socio-economic factors.

The socio-economic conditions of households in Gauteng and the Western Cape reveal significant gender and regional disparities, particularly in household size, education, employment, business ownership, grant dependence, and income distribution. These factors highlight the challenges male- and female-headed households face across metropolitan and non-metropolitan areas.

On household size, female-headed households tend to have larger families. In Gauteng's metropolitan areas, the average household size for female-headed households is 3.3 members, compared to 2.8 members for male-headed households. A similar trend can be observed in non-metropolitan areas. In the Western Cape, the pattern remains consistent, with female-headed households in metropolitan areas averaging 3.4 members, while male-headed households average 3.2. This suggests that female-headed households tend to be larger, particularly in non-metropolitan regions.

Education levels also vary by gender and region. In Gauteng, a larger proportion of household heads in metropolitan areas have completed Grade 12, with 32 % of female-headed households and 34 % of male-headed households achieving this level. However, female-headed households in both Gauteng and the Western Cape typically achieve lower educational outcomes than their male counterparts, with fewer reaching vocational or post-secondary qualifications, such as NTC Level 1. This educational gap is evident in both metropolitan and non-metropolitan areas.

In assessing income, we consider total household income per month (in Rands) and log equivalised income. In Gauteng, metropolitan households headed by males reported the highest average income at R16,477, followed by female-headed households in metropolitan areas, which averaged R10,766. In non-metropolitan areas of Gauteng, male-headed households also earned more, with an average income of R10,672 compared to R6,016 for female-headed households. In the Western Cape, male-headed metropolitan households had the highest income at R23,653, while female-headed households earned R15,676. In non-metropolitan areas of the Western Cape, male-headed households reported an average income of R14,701, compared to R11,811 for female-headed households.

When adjusting for household size using log equivalised income, the gaps in income by gender and across metropolitan areas persist but are reduced. In both Gauteng and the Western Cape, male-headed households in metropolitan areas report slightly higher log equivalised incomes: R8.1 versus R7.6 in Gauteng and R8.5 versus R8 in the Western

Table 1
Demographics and Socio-economic factors.

	Gauteng				Western Cape			
	Metropolitan		Non-metropolitan		Metropolitan		Non-metropolitan	
Variable	Female	Male	Female	Male	Female	Male	Female	Male
Total households	433	722	255	362	1389	2556	268	501
Weighted frequency	527,847	830,857	314,525	406,042	1,734,050	3,161,565	239,468	451,511
Percentage per metro type	39 %	61 %	44 %	56 %	35 %	65 %	35 %	65 %
Household size	3.3	2.8	3.3	2.9	3.4	3.2	3.1	3.1
Highest education level in household	11.3	11.2	10.8	10.6	11.3	11.4	10.8	11.2
Education level of household head	10.5	10.9	9.4	10	10.5	10.9	9.9	10.3
Household income	10,766	16,477	6016	10,672	15,676	23,653	11,811	14,701
Income (log equivalised)	7.6	8.1	7.2	7.2	8	8.5	8	8
Employment	40 %	28 %	49 %	32 %	32 %	26 %	32 %	21 %
	60 %	72 %	52 %	68 %	68 %	75 %	68 %	79 %
Business	86 %	78 %	91 %	85 %	87 %	79 %	93 %	84 %
	14 %	22 %	9 %	16 %	13 %	21 %	7 %	16 %
Grant	50 %	70 %	40 %	69 %	54 %	72 %	49 %	66 %
	50 %	30 %	60 %	31 %	46 %	28 %	51 %	34 %

Source: Authors.

Cape. However, in non-metropolitan areas, both male and female-headed households have similar log equivalised income values: R7.2 in Gauteng and R8 in the Western Cape.

Employment rates reflect a significant gender gap, with male-headed households consistently exhibiting higher employment levels across both provinces. In Gauteng's metropolitan areas, 72 % of male-headed households are employed compared to 60 % of female-headed households. Similarly, the Western Cape indicates that male-headed households in metropolitan areas have a higher employment rate (75 %) compared to female-headed households (68 %). This gender disparity is particularly stark in non-metropolitan regions, where male-headed households have higher employment rates than female-headed ones.

Business ownership also follows gendered trends, with male-headed households more likely to own businesses. In Gauteng's metropolitan areas, 22 % of male-headed households are involved in business ownership, compared to 14 % of female-headed households. The gap is similarly present in the Western Cape, with 21 % of male-headed households owning businesses in metropolitan areas, compared to only 13 % of female-headed households. This trend highlights the challenges faced by female-headed households in achieving business success and entrepreneurship.

Grant reliance is another key area of disparity, with female-headed

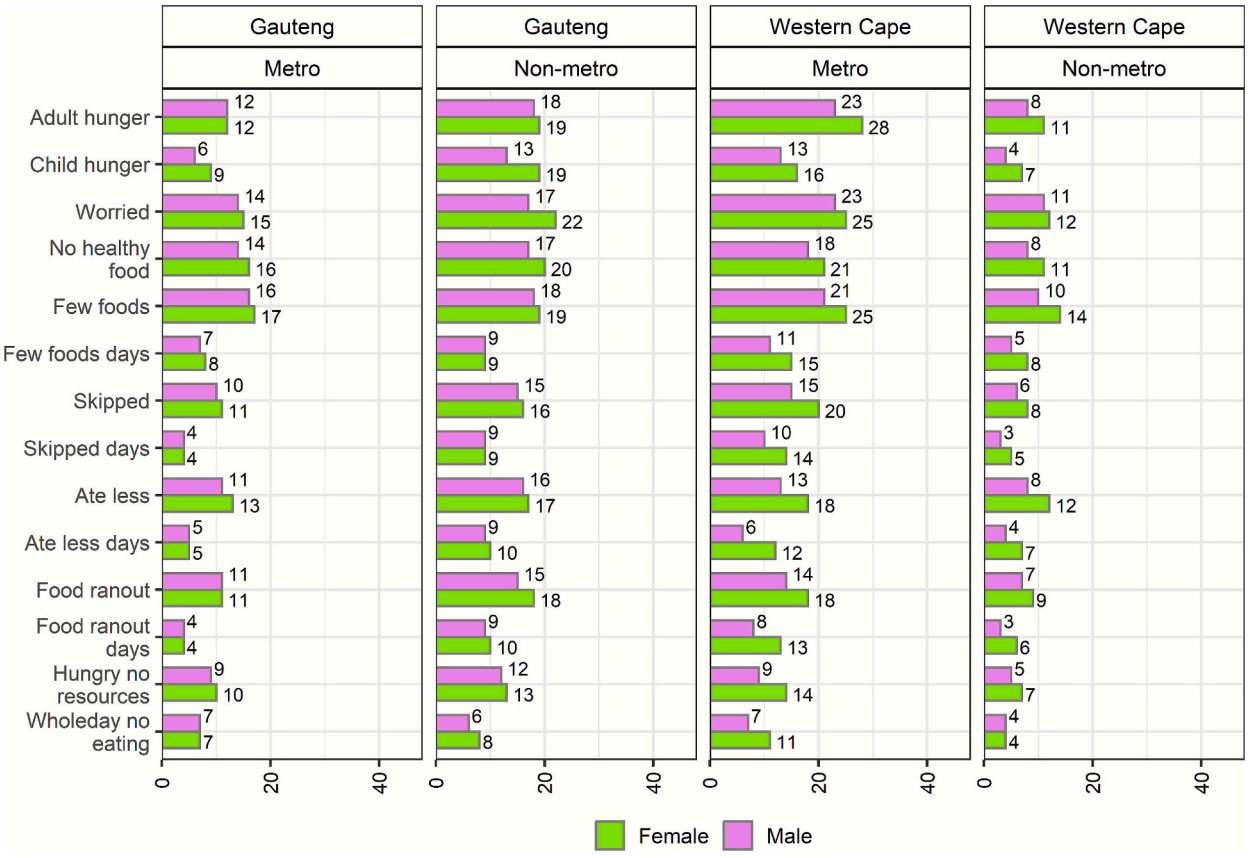

Fig. 3. Food insecurity prevalence.
(Source: Authors)

households generally more dependent on government assistance. In Gauteng's metropolitan areas, 50 % of female-headed households rely on grants, compared to 30 % of male-headed households. This dependency is even more pronounced in non-metropolitan areas, where 60 % of female-headed households rely on grants, compared to 31 % of male-headed households. In the Western Cape, a similar pattern is observed, with female-headed households being more likely to receive grants, particularly in non-metropolitan areas.

4.1.2. Food insecurity

Based on the formulated HFIAS, the data reveal significant food insecurity across various demographics in Gauteng and Western Cape provinces. Fig. 3 shows the food insecurity prevalence scale.

In Fig. 3, it is shown that women experience higher levels of food insecurity compared to men, particularly in the Gauteng non-metro area, where the rates of adult hunger are 18 % for women and 13 % for men. In the Western Cape metro area, the disparity is even more pronounced, with adult hunger rates of 28 % for women and 23 % for men, as well as 20 % of women skipping meals compared to 15 % of men. Conversely, the non-metro region of the Western Cape reports lower rates of adult hunger at 11 % for women and 8 % for men; however, women still face disadvantages across all indicators of the HFIAS.

Fig. 4 shows the average HFIAS score.

In reference to Fig. 4, non-metropolitan areas in Gauteng exhibit higher levels of food insecurity compared to metropolitan areas. Female-headed households in non-metropolitan Gauteng have the highest mean score in the province (2.11), followed by male-headed households in the same areas (1.84). Within metropolitan areas of Gauteng, food insecurity levels are relatively lower, with female-headed households having a slightly higher mean score (1.41) than their male counterparts (1.31). In the Western Cape, a different pattern emerges. Metropolitan areas show higher levels of food insecurity compared to non-metropolitan areas. Female-headed households in metropolitan Western Cape report the highest mean HFIAS score among all groups (2.52). In non-metropolitan areas of the Western Cape, food insecurity is notably lower, with female-headed households at 1.2 and male-headed households at 0.86. Across all groups, female-headed households consistently report higher HFIAS scores than male-headed households. These findings underscore the need for targeted interventions to address food insecurity, particularly among vulnerable female-headed households in various regions.

4.1.3. Multidimensional energy poverty indicators

Fig. 5 shows deprivation in energy indicators.

The data reveal key disparities in energy poverty across different groups and areas. The analysis across Gauteng and Western Cape reveals clear and contrasting patterns between basic energy services and asset ownership. Across both provinces, and in both metropolitan and non-metropolitan areas, there is generally low deprivation in terms of access to basic energy services, specifically electricity, modern cooking fuels, modern lighting fuels, and modern water heating fuels. In most cases, less than 15 % of households reported deprivation in these indicators, suggesting that basic energy access is relatively widespread. However, a notable exception to this pattern is the consistently high levels of deprivation related to modern space heating fuels. Across both provinces, deprivation in this dimension was substantially higher than for other energy-related services, with many groups reporting deprivation levels exceeding 20 %, and in some cases, surpassing 50 %.

In contrast to the relatively low levels of deprivation in basic energy services, ownership of household assets shows a more worrying picture. Deprivation levels for items such as televisions, radios, pay television services, computers, home security systems, and geysers are consistently high across both provinces and all household types. In many cases, over half of the households reported deprivation in these assets, with particularly high rates of deprivation in computers, home security systems, and radios. The radio shows relatively high levels of deprivation compared to expectations. This finding should be interpreted with caution, as it may reflect changing technology use patterns toward multifunctional devices rather than standalone radios.

Fig. 6 shows the mean MEPI fuzzy scores.

The mean multidimensional energy poverty index (MEPI) fuzzy score results reveal notable differences across geographic and demographic groups (Fig. 6). In Gauteng, male-headed households consistently exhibit higher MEPI fuzzy scores compared to female-headed households in both metro and non-metro areas, suggesting higher levels of energy poverty among male-headed households in this province. Specifically, male-headed households in non-metro areas of Gauteng recorded the highest score (0.180), followed by male-headed households in metro areas (0.152). In contrast, Western Cape households exhibit relatively lower MEPI fuzzy scores overall, with female-headed metro households reporting the lowest score (0.115), closely followed by male-headed metro households (0.108). In the Western Cape, non-metro male-headed households reported slightly higher scores (0.126) than their female counterparts (0.121), though the differences are marginal. Overall, Gauteng shows higher energy poverty levels compared to the Western Cape, with non-metro areas experiencing greater deprivation than metro areas in both provinces.

Fig. 7 shows the Percentage distribution of fuzzy MEPI.

The majority of households across all areas fall in the low deprivation category (<0.25). However, there are notable geographic and gendered variations. In Gauteng, both metropolitan and non-metropolitan areas show high shares in the low deprivation category, though slightly lower than in the Western Cape. In the Gauteng metro, 83 % of male-headed and 89 % of female-headed households fall below the 0.25 threshold. Non-metropolitan Gauteng similarly shows 81 % of male-headed and 87

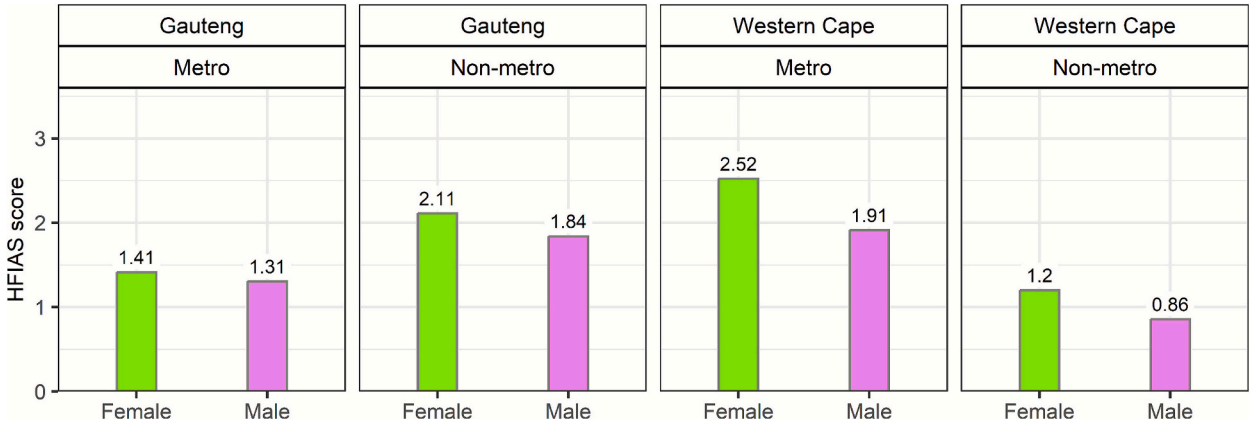

Fig. 4. Average HFIAS scores.
(Source: Authors)

Fig. 5. Deprivation in energy indicators.
(Source: Authors)

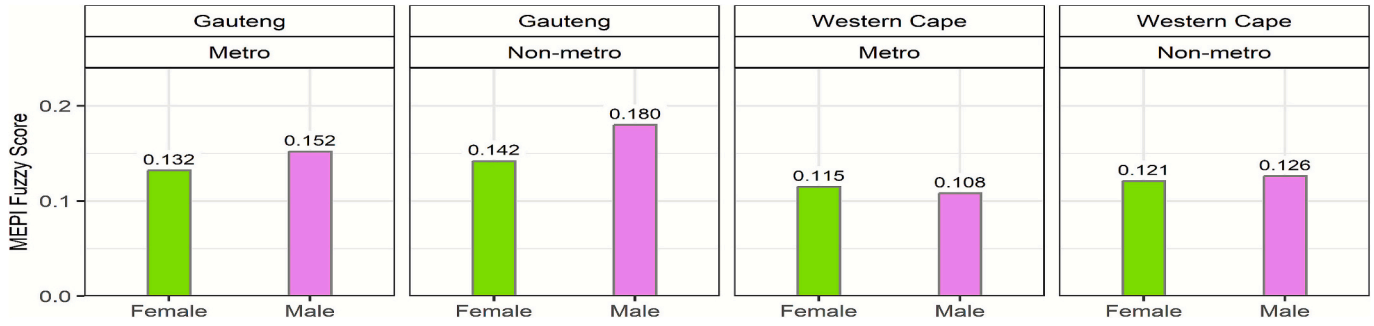

Fig. 6. Mean MEPI fuzzy scores.
(Source: Authors)

% of female-headed households in this category. The Western Cape exhibits even lower levels of deprivation. In metropolitan areas, 93 % of male-headed and 94 % of female-headed households fall into the low deprivation category. In the non-metro Western Cape, 88 % of female-headed households and 93 % of male-headed households are in the low deprivation category (<0.25). Higher deprivation categories (≥0.75) are slightly more common in Gauteng than in the Western Cape.

4.1.4. Correlation between energy poverty and food insecurity

The correlation between energy poverty and food insecurity was assessed at the household level, as measured by the MEPI fuzzy score and the HFIAS score.

Table 2 shows the correlation between the MEPI fuzzy score and HFIAS.

The correlation analysis shows that across all subgroups, the correlation between energy poverty and food insecurity is positive and statistically significant at the 1 % level ($p < 0.01$). This implies that households experiencing higher levels of energy poverty also tend to report higher levels of food insecurity. In the Western Cape, the relationship seems to be slightly stronger than in Gauteng.

4.1.5. Tobit regression analysis

The Tobit regression analysis examined the determinants of food insecurity, measured using the log of the HFIAS score, across the

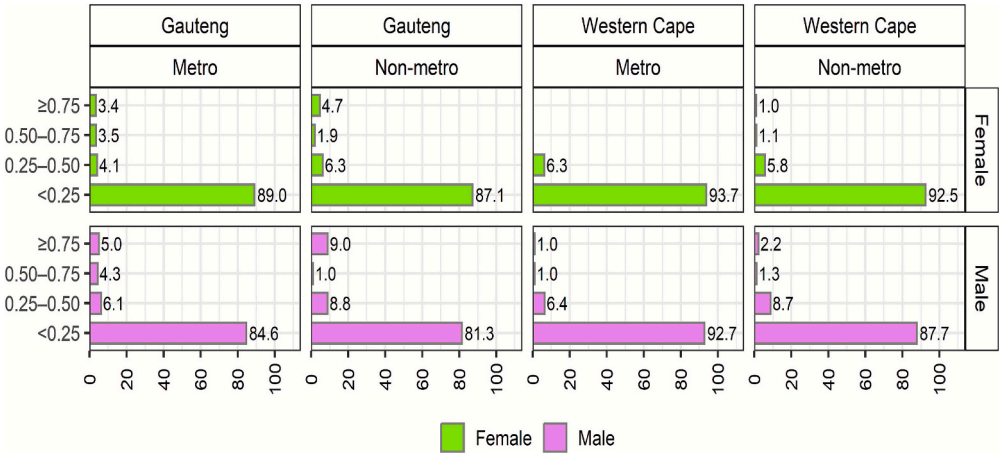

Fig. 7. Percentage distribution of fuzzy MEPI.
(Source: Authors)

Table 2
Correlation between energy poverty: (MEPI fuzzy score) and (HFIAS score).

Area	Location	Household type	Correlation Estimate	*P* value
Gauteng	Metro	Male	0.246	0.000***
		Female	0.243	0.000***
	Non-metro	Male	0.285	0.000***
		Female	0.291	0.000***
Western Cape	Metro	Male	0.370	0.000***
		Female	0.393	0.000***
	Non-metro	Male	0.338	0.000***
		Female	0.303	0.000***

Significance levels: *** 1 %, ** 5 %, * 10 %.
Source: Authors.

Western Cape, Gauteng, and the combined sample.

Table 3 shows the Tobit regression analysis.

The Tobit regression analysis revealed good model performance across all samples, as evidenced by substantial improvements in log-likelihood from initial to final model iterations. The log-likelihood improved by 217 units in the Western Cape (from −1278 to −1062), 232 units in Gauteng (from −2783 to −2551), and 339 units in the combined sample (from −4083 to −3744). Significant Wald test statistics were observed across the models: 89 in the Western Cape, 109 in Gauteng, and 183 in the combined model, demonstrating the relevance of the included predictors. The censoring patterns show a high proportion of households fall into the left-censored category (households reporting the lowest food insecurity scores): 68.6 % (1128 of 1645) in the Western Cape, 75.9 % (3271 of 4311) in Gauteng, and 73.8 % (4399 of 5956) in the combined sample. However, there were also notable numbers of households at the upper end of the food insecurity scale (right-censored cases), particularly in Gauteng (906 cases) and the combined sample (1324 cases).

Table 3
Tobit regression analysis.

Variable	Western Cape	Gauteng	Combined
(Intercept)	5.793***	14.001***	9.778***
Education	−0.048	−0.083	−0.111**
Employment	0.038	−0.424	−0.286
Business	0.151	−0.722	−0.501
Grant	0.853**	0.775	0.753**
Income (log)	−1.571***	−2.633***	−2.072***
Household size	0.318***	0.514***	0.501***
Female-headed (binary)	0.108	0.037	0.152
Metropolitan area (binary)	4.125***	−1.156**	1.139***
MEPI fuzzy score	11.484***	5.777***	5.367***

Significance levels: *** 1 %, ** 5 %, * 10 %.
Source: Authors.

Several notable patterns emerged from the results, revealing both shared and distinct drivers of food insecurity across these contexts. Income, measured as log-transformed household income, was an important predictor of reduced food insecurity in all three models. Higher household income was associated with significantly lower levels of food insecurity in the Western Cape, Gauteng, and the combined sample. This highlights the crucial role of household income in mitigating food insecurity, regardless of regional context. Similarly, household size was found to be a consistent positive predictor of food insecurity across all models. Larger households were more likely to experience higher levels of food insecurity, indicating that the number of household members is a significant vulnerability factor.

MEPI, as measured by the fuzzy score, also emerged as a strong and significant driver of food insecurity. The strongest association was observed in the Western Cape (11.5), where households with higher energy poverty scores faced substantially higher food insecurity. In Gauteng, it was 5.8, and in the combined model, it was 5.4. The receipt of social grants showed a significant positive association with food insecurity in the Western Cape and the combined sample, but not in Gauteng. This suggests that grant recipients remain vulnerable to food insecurity, likely because these programs are targeted toward households already facing economic hardship. The findings imply that while grants provide some support, they may not be sufficient to lift households out of food insecurity.

There were interesting contrasts in the effects of metropolitan residence across the two provinces. In the Western Cape, living in a metropolitan area was associated with significantly higher food insecurity, whereas in Gauteng, metropolitan households experienced lower food insecurity. This highlights important regional differences in the spatial distribution of food insecurity, suggesting that urban food insecurity may be more prevalent in the Western Cape, whereas in Gauteng, it may be more concentrated in non-metropolitan areas.

Other socio-economic factors, such as education, employment, and business ownership, showed weaker and more inconsistent effects. Education had a small but significant negative association with food insecurity in the combined sample, suggesting a modest protective effect. Employment and business ownership generally showed negative but non-significant effects, except for some weak associations in Gauteng and the combined model. Female-headed households did not show significant associations with food insecurity in any model, suggesting that the sex of the household head was not a key factor once other socio-economic variables were accounted for.

4.1.6. Structural equation modelling results

The section presents the diagnostic tests for the SEM analysis results in multidimensional energy poverty and food insecurity in Gauteng and the Western Cape, as well as the combined sample, which includes both provinces.

All models estimated 53 parameters with corresponding degrees of freedom fixed at 10. The Comparative Fit Index (CFI) values were above 0.95 in all models, specifically 0.989 for the Western Cape, 0.982 for Gauteng, and 0.988 for the combined sample, indicating excellent fit. Similarly, the Tucker-Lewis Index (TLI) values also suggested a good fit, with the Western Cape achieving a value of 0.951, Gauteng 0.917, and the combined sample 0.947, all exceeding the 0.90 threshold for an acceptable fit. The RMSEA was below 0.05 in all models (0.041 in the Western Cape, 0.047 in Gauteng, and 0.038 in the combined model), indicating close model fit. Moreover, the *p*-values for the null hypothesis of RMSEA $\leq$0.05 were all non-significant ($p = 0.835$ for the Western Cape, $p = 0.714$ for Gauteng, and $p = 0.998$ for the combined sample), further confirming good fit. The tests for poor fit (RMSEA $\geq$0.08) were significant ($p < 0.001$) across models, indicating that poor fit can be confidently rejected. In addition, the Standardised Root Mean Square Residual (SRMR) values were well below the 0.08 cutoff, suggesting a good fit in terms of standardised residuals.

Table 4
SEM Analysis.

		Western Cape	Gauteng	Combined
HFIAS (log) ~ MEPI (fuzzy score)	C	1.72***	0.54***	0.64***
Education ~ MEPI (fuzzy score)	a1	−6.49***	−2.37***	−2.76***
Employment ~ MEPI (fuzzy score)	a2	−0.39***	−0.27***	−0.29***
Business ~ MEPI (fuzzy score)	a3	−0.19**	−0.10***	−0.10***
Grant ~ MEPI (fuzzy score)	a4	0.56***	−0.00	0.06*
Income (log) ~ MEPI (fuzzy score)	a5	−4.39***	−1.99***	−2.29***
Household size ~ MEPI (fuzzy score)	a6	−0.94**	−1.68***	−1.63***
Female (binary) ~ MEPI (fuzzy score)	a7	−0.27**	−0.25***	−0.26***
Metro (binary) ~ MEPI (fuzzy score)	a8	−0.08	−0.02	0.02
HFIAS (log) ~ Education	b1	−0.00	−0.02***	−0.02***
HFIAS (log) ~ Employment	b2	−0.15***	−0.10***	−0.11***
HFIAS (log) ~ Business	b3	−0.01	−0.08***	−0.07***
HFIAS (log) ~ Grant	b4	0.08	0.01	0.02
HFIAS (log) ~ Income (log)	b5	−0.18***	−0.15***	−0.15***
HFIAS (log) ~ Household size	b6	0.06***	0.03***	0.04***
HFIAS (log) ~ Female (binary)	b7	0.00	−0.04*	−0.03
HFIAS (log) ~ Metro (binary)	b8	0.40***	−0.05	0.08***
Indirect effect: Education	a1* b1	0.02	0.04***	0.05***
Indirect effect: Employment	a2* b2	0.06**	0.03***	0.03***
Indirect effect: Business	a3* b3	0.00	0.01**	0.01**
Indirect effect: Grant	a4* b4	0.05	−0.00	0.00
Indirect effect: Income	a5* b5	0.79***	0.30***	0.36***
Indirect effect: Household size	a6* b6	−0.06**	−0.05***	−0.07***
Indirect effect: Female (binary)	a7* b7	−0.00	0.01	0.01
Indirect effect: Metro (binary)	a8* b8	−0.03	0.00	0.00
Total effect		2.56***	0.87***	1.03***

Source: Authors.
*** Significance levels: 1 %
** 5 %
* 10 %.

Table 4 presents the standardised estimates for the mediation effects of socio-economic variables on energy poverty and food insecurity.

The SEM analysis highlights the complex interactions between energy poverty (measured by the MEPI fuzzy score) and food insecurity (measured by the HFIAS score), which are mediated by various socio-economic factors. The mediation analysis revealed that household income plays a central role in explaining the link between energy poverty and food insecurity. Income exhibited the strongest and most significant indirect effects across all models, with coefficients of 0.79 in the Western Cape, 0.30 in Gauteng, and 0.36 in the combined sample. Employment also contributed modestly to the mediation pathway, with indirect effects ranging from 0.03 to 0.06. Other socio-economic factors displayed varying degrees of mediation. Education exhibited weak but statistically significant indirect effects in Gauteng and the combined sample, although the effect was negligible in the Western Cape. Business ownership exhibited small but significant mediating effects in Gauteng and the combined sample, suggesting a minor role in the pathway between energy poverty and food insecurity. Household size demonstrated negative indirect effects across all models. Some variables, such as grant receipt and female-headed households, showed limited or non-significant mediation effects in most models. Similarly, the metro/non-metro status of households did not emerge as a significant mediator in the relationship between energy poverty and food insecurity. Overall, the total effects combining both direct and indirect pathways remained significant in all models. The Western Cape again showed the largest total effect (2.56), followed by the combined sample (1.03) and Gauteng (0.87). These results emphasise that energy poverty has both a strong direct effect on food insecurity and additional indirect effects operating primarily through income and employment.

5. Discussion

Energy poverty is a pervasive and multifaceted issue that disproportionately affects vulnerable populations across South Africa, exacerbating food insecurity and deepening socio-economic inequalities. The findings from the MEPI, HFIAS, and SEM on the impact of energy poverty on food insecurity among female and male-headed households in metropolitan and non-metropolitan areas of the Western Cape and Gauteng provide compelling evidence that energy poverty in South Africa is particularly acute in non-metropolitan areas and among female-headed households. The relationship between energy poverty and food insecurity is a complex one. It highlights the urgent need for a holistic approach integrating energy access with broader social policies targeting education, income, employment, and gender equality. Addressing energy poverty in South Africa requires improving access to energy and tackling the root causes of inequality, which disproportionately affect marginalised communities, particularly in non-metropolitan regions.

The MEPI analysis results underscore the stark regional disparities in energy poverty across South Africa. Non-metropolitan areas, where access to energy infrastructure is often limited, are significantly more affected by energy poverty than urban areas, particularly in provinces such as Gauteng and the Western Cape. The situation is compounded by high levels of deprivation among female-headed households in rural regions. Energy poverty in these areas limits access to basic cooking, heating, and lighting services and compounds food security challenges [49].

This pattern aligns with global trends, where rural areas tend to be more vulnerable to energy poverty due to the lack of energy infrastructure, lower income levels, and limited access to modern energy sources [50]. Additionally, the gendered nature of energy poverty in non-metropolitan areas calls for targeted interventions that specifically address the unique challenges faced by women, particularly in rural areas. In many developing countries, women are disproportionately responsible for managing household energy needs, making them more vulnerable to the impacts of energy poverty [51]. This gender disparity further complicates efforts to address energy poverty and food insecurity

in South Africa.

The SEM analysis emphasises the significant role that energy poverty plays in exacerbating food insecurity, particularly in non-metropolitan regions. Energy poverty often leads to limited income opportunities, reducing households' capacity to purchase sufficient and nutritious food [52]. This relationship is not unique to South Africa; global studies consistently show that energy poverty is a critical driver of food insecurity. In countries with high levels of energy poverty, households are forced to spend a disproportionate share of their income on energy, leaving them with less for food and other essential necessities [53]. Furthermore, energy poverty limits households' ability to engage in income-generating activities, thereby reducing access to food and other essential resources [54]. The link between energy access and economic outcomes has been well-documented globally, with energy poverty often acting as a barrier to economic development, particularly for marginalised communities [55]. Therefore, addressing energy poverty in South Africa must be accompanied by broader economic policies that create job opportunities, increase household income, and promote sustainable livelihoods.

A key argument in the analysis is the mediating role of education, income, and employment in the relationship between energy poverty and food insecurity. Education, while a powerful tool for mitigating the effects of energy poverty, is often inadequate in non-metropolitan regions where access to quality education is limited. The SEM analysis shows that lower education levels, particularly in non-metropolitan areas, exacerbate food insecurity, as education plays a crucial role in improving household resilience to economic shocks [56]. Moreover, the indirect effect of education on food insecurity is particularly significant in Gauteng's metropolitan areas, highlighting the importance of investing in education to break the cycle of poverty and food insecurity [57]. However, the effect is less pronounced in non-metropolitan areas, where limited access to quality education makes it harder for households to escape the grip of energy poverty and food insecurity.

Income and employment also play a critical role in mediating the impact of energy poverty on food security. In South Africa, the SEM analysis reveals a strong negative relationship between energy poverty and income, with the effects being most severe in the Western Cape. Lower income exacerbates food insecurity, as households with limited financial resources struggle to access adequate and nutritious food. The impact of energy poverty on income has been widely documented, with studies showing that energy poverty limits income-generating opportunities, particularly in rural areas [58]. This reinforces the argument that improving energy access is essential for improving economic outcomes and reducing food insecurity. Employment also significantly reduces food insecurity, with the analysis indicating that energy poverty leads to reduced employment opportunities, particularly for female-headed households in the Western Cape. Employment acts as a buffer against food insecurity, increasing household income, which can be used to access food and other necessities [59].

Despite the importance of income and employment, the SEM analysis reveals that grants and business ownership have weaker mediating effects on energy poverty and food insecurity. While energy poverty does impact household access to grants and business opportunities, the indirect effects on food insecurity are less significant. This suggests that social safety nets and business ownership alone may not be sufficient to alleviate the effects of energy poverty. A more comprehensive approach is needed, one that not only improves energy access but also addresses the structural factors that contribute to poverty and inequality. In South Africa, income from social grants tends to exacerbate energy poverty, as beneficiaries are unlikely to prioritise spending on clean energy sources; additionally, social grant recipients are identified based on specific indicators of welfare deprivation, including unemployment, disability, and low income. [60]. Critics may argue that South Africa's energy challenges are primarily technical, focusing on expanding energy supply and improving infrastructure. While these are important goals, they do not address the underlying socio-economic factors that drive energy poverty and food insecurity [61]. Increasing energy access without addressing the root causes of inequality, such as education, employment, and income disparities, will not lead to sustainable improvements in living conditions, particularly in non-urban or rural areas. Such an approach risks entrenching existing inequalities, as energy poverty in these regions is often linked to broader socio-economic exclusion [62]. To effectively combat energy poverty and its impacts on food insecurity, South Africa must adopt a more integrated, multi-sectoral approach that addresses the socio-economic vulnerabilities faced by its most marginalised populations.

6. Conclusions

The paper examined the impact of multidimensional energy poverty on household food insecurity in both metropolitan and non-metropolitan areas of Gauteng and the Western Cape, two of South Africa's most economically diverse provinces. Moreover, the paper examines how socio-economic factors, including education, the gender of the household head, household size, income, employment, business ownership, access to grants, and geographic location, mediate this relationship. The paper makes a novel contribution to the growing discourse on the intersection between energy poverty and food insecurity by introducing a gendered spatial perspective within the South African context. While previous research has primarily treated energy poverty and food insecurity as separate or unidirectional challenges, this study demonstrates, through the integration of SEM and Tobit regression, how energy poverty directly and indirectly affects food insecurity through socio-economic mediators, including income, education, and employment. The incorporation of gender and urban–rural (metropolitan vs. non-metropolitan) dynamics provides fresh empirical evidence of the multi-layered vulnerabilities faced by female-headed households, particularly outside metropolitan areas. By revealing that household income serves as the most critical mediating factor linking energy deprivation to food insecurity, the study extends the understanding of energy poverty beyond access and affordability, situating it as a core determinant of household wellbeing and resilience.

The Tobit regression revealed that Household income consistently reduced food insecurity, while larger household size increased it across all models. MEPI was a strong positive predictor of food insecurity, with the effect strongest in the Western Cape. Social grant recipients remained more food insecure, particularly in the Western Cape, indicating persistent vulnerability. Spatial patterns differed, with higher food insecurity in metropolitan areas in the Western Cape but lower in Gauteng, while other socio-economic factors showed weak or inconsistent effects.

The SEM analysis reveals that energy poverty has a profound and direct impact on food insecurity across both the Gauteng and Western Cape provinces, with notable variations between metropolitan and non-metropolitan areas, as well as gender differences among household heads.

In terms of indirect effects, household income consistently emerged as the strongest mediator of the relationship between energy poverty and food insecurity. Employment and education also contributed modest but significant indirect effects. H**ousehold size** had a **significant negative indirect effect**, meaning that larger households, while directly associated with increased food insecurity, also played a role in **mediating** the relationship between energy poverty and food insecurity. In contrast, variables such as business ownership, grant receipt, sex of household head, and metro/non-metro residence showed limited or inconsistent mediation effects, with some effects being negligible or non-significant across regions.

Interventions addressing energy poverty could significantly reduce food insecurity, particularly in non-metropolitan areas and for female-headed households. Improving access to energy and providing support in education, employment, and income could mitigate the indirect pathways through which energy poverty exacerbates food insecurity.

Strengthening income-generating opportunities, particularly for female-headed households, will help address the broader socio-economic disparities that underpin food insecurity.

These interventions should prioritise improving access to affordable and reliable energy, particularly in non-metropolitan areas and for female-headed households. This could include subsidies for low-income households, the expansion of renewable energy sources in rural areas, and programs to reduce the cost of energy for vulnerable groups.

Programs that target adult education and vocational training for both men and women, particularly in rural and disadvantaged communities, would provide individuals with the skills necessary to secure stable employment, thereby reducing the negative effects of energy poverty on food insecurity. Finally, policies that promote family planning and resource management could help reduce the burden on larger households.

7. Limitations of the study

One limitation of the paper is that it did not include information on the reliability of electricity access. Specifically, it failed to address issues such as electricity load shedding, which has been experienced in various parts of the country. Including this information would allow the MEPI to be adapted, providing a more accurate reflection of how people experience energy poverty.

Regarding gender, the study employs a narrow definition of gender, focusing on "female-headed" households. Since gender is much broader, this is a limitation in terms of fully understanding the relationship between gender, energy poverty and household food insecurity.

CRediT authorship contribution statement

Adrino Mazenda: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Transparency declaration

The author affirms that this manuscript is an honest, accurate, and transparent account of the study being reported, that no important aspects of the study have been omitted and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

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Declaration of competing interest

The author/s declare a non-competing conflict of interest in the study.

Data availability

The data is obtained from Statistics South Africa. General Household Survey 2021 [dataset]. Version 1. Pretoria: Statistics SA [producer], 2021. Cape Town: DataFirst [distributor], 2022. doi:10.25828/7h7t-df42

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