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Strategic analyses on the South African grid supply and consumption inefficiencies by market segments

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ABSTRACT

The surging energy demand from residential and industrial sectors necessitates effective performance from the energy sector. The efficiency of energy generation, supply, and distribution is a crucial global agenda, as energy drives socio-economic development. Thus, strategically analyzing the efficiency of both supply services and consumer behavior in various energy markets is indispensable. This paper examines the performance of the distribution chain within the South African power grid system and the consumption intensity by regional segments. It assesses the sustainability of both the distribution chain and consumption patterns to inform long-term planning through critical intervention strategies. A two-tier approach is employed to analyze inefficiencies by examining supply and consumption in selected urban and rural residential markets. The indicators from the Energy Trilemma Index guided the empirical research, which was conducted through a quantitative survey. Supply performance was analyzed in socio-economic terms, while consumption behavior was examined through appliance usage. Descriptive statistics and exploratory factor analysis were jointly used to analyze the different data sets. Findings indicate that households in less affluent rural regions such as Soweto, Extension 39, Ikageng, and Soshanguve generally earn below 15,000 ZAR (77%) and spend less on electricity (<200 ZAR by 36% and < 300 ZAR by 40% monthly). Conversely, households in more affluent rural and urban settings typically earn between 25,001 -34,000 ZAR (37%) and 34,001 -46,000 ZAR (39%), spending over 300 ZAR monthly on electricity (80%). Significant differences also exist between regions (NWP and GP) in terms of supply consistency, supply security, use of alternative energy, and energy savings. Most households use a high number of appliances daily, except for air conditioners and pool pumps. In less affluent settings, fridges, electric geysers, and stoves older than five years are common, whereas more affluent settings have newer appliances. The intensity of air conditioner and pool pump usage is low during winter, while space heating is less intense during summer. This segmentation study assists the national government in understanding current market dynamics and the diverse needs and preferences of consumers. Analyzing multiple regional settings provides a comprehensive understanding of unique behaviors and preferences across different target consumer markets, paving the way for eradicating energy poverty and achieving sustainable communities.

KEYWORDS
Electricity supply; distribution service; appliance intensity; supply sustainability

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1. Introduction

Power grids, also known as electric grids, are intricate networks comprising power generation, transmission, and distribution systems that deliver electricity to homes, businesses, and other organizations. The primary goal of power grids is to ensure a reliable, affordable, and accessible electricity supply to end-users. This reliability is crucial for regional economic development, as energy is a key component for local economic growth, contributing significantly to a country's Gross Domestic Product (GDP) (Zahedi et al. 2022). Inefficiencies in the supply and consumption chains can have substantial impacts. Supply inefficiencies in the energy grid relate to the mitigation of both technical and non-technical negative impacts (Carreon and Worrell 2018). Technical aspects involve the effects on generation and transmission infrastructure, impacting the entire value chain, while non-technical aspects concern the performance characteristics of consumer markets from both the supply side (energy services) and demand side (consumer behavior). To ensure the sustainability of the supply and consumption chain, a comprehensive strategic analysis of the entire system at various network levels is required. Analyzing the supply service and consumer behaviors critically is crucial for maintaining a sustainable energy flow ecosystem. Optimal energy use can enhance the residential energy ecosystem by reducing secondary waste. Literature indicates that researchers (Marti and Puertas 2022; Song et al. 2023) who have conducted strategic analyses on energy systems at different levels have utilized the World Energy Trilemma (WET) Indicators, developed by the World Energy Council (WEC), to measure performance across various domains. Additionally, the United Nations (UN) emphasizes the importance of affordable, reliable, and sustainable energy access for all consumer market categories, as reflected in the UN Sustainable Development Goals (SDGs) framework (Lee et al. 2022).

A proper strategic analysis is essential to examine and address supply inefficiencies in fundamental aspects of the electricity market, such as rising prices, environmental costs, and generation capacity. This analysis provides policymakers with insights to inform state restructuring and the establishment of effective regulatory responses to market challenges (Borenstein, Bushnell, and Wolak 2002). Given South Africa's current inefficient energy performance issues, there is considerable interest among policymakers to gain insights into setbacks faced by different consumer groups. This knowledge is vital for understanding the priorities of various market segments and for better positioning the energy system. Sarkodie and Adams (2020) stress that meeting basic energy needs is a crucial pathway out of poverty, as energy is a vital development tool for local communities. Analyzing the efficiency of the supply service and consumer chain of energy activities, especially in the residential sector, through a range of factors, is essential for success (Palmer and Truong 2017). Therefore, it is necessary to examine how socio-economic distributions in rural and urban areas impact market inefficiencies. This study is particularly timely for South Africa, given the ongoing rural and urban disparities and the crippling electricity grid crisis. Sampling cities and settlements with different dwelling formations allows for identifying unique interventions for various market segments. It also enables the establishment of an equitable, sustainable energy pathway and the eradication of energy poverty within these market structures.

2. Background

2.1. Strategic analysis of energy supply service and use efficiency in residential buildings

Murgatroyd et al. (2022) agree that strategic analysis is an effective method for assessing residential services like water and other metabolic activities of a city. Their study on the resilience of water supply systems in England applied the World Energy Trilemma (WET) concept to explore the affordability, resilience, availability, reliability, and vulnerability of municipal water supply and distribution flows. They assessed how demand reduction could restore water resources and reserves, aiming for a sustainable residential water supply and demand ecosystem. Empirical findings revealed that services were below standard, and effective steps to reduce water demand were necessary to stabilize supply.

For energy, the WET framework has been proposed as a generic taxonomy for strategic analysis. Liu and Matsushima (2019) argue that since energy inefficiency affects service quality, strategic analysis is crucial for understanding how energy degradation impacts society. Energy efficiency can be measured using various scenarios involving different forms of energy, energy utility and exergy, energy return on investment, the ratio of energy, and other relevant metrics. These measures help analyze energy availability in society. Studies have examined strategic analysis of energy quality from both social science and natural science perspectives. From a natural science perspective, energy efficiency involves the transformation processes that energy and material undergo within the energy flow network through heat or work to deliver required energy to city residents. In contrast, the social science perspective views the city as an ecosystem dependent on energy to function.

2.1.1. Energy efficiency as a conversion chain (natural science perspective)

Evola, Costanzo, and Marletta (2018) highlight that the most applicable description of energy efficiency as a process is found in thermodynamics. The first law of thermodynamics, or the law of conservation of energy, states that efficiency is the relationship between the amount of useful energy output and the total energy input into a system. This law applies to all energy forms, irrespective of their taxonomy. Thus, energy can be quantified in terms of reliability of energy losses during the regeneration process, mass per unit of power stored or delivered, volumes per unit of energy stored, longevity and consistency of energy stored or delivered, and the cost per unit of energy stored or delivered (Michaelides 2021). This concept practically implies the efficiency of the energy grid to supply residential consumers with the required energy in buildings. The second law of thermodynamics, or the law of exergy, involves the strategic analysis of the quality of an energy system flow or source (Evola, Costanzo, and Marletta 2018). This approach is mostly considered when dealing with the performance of energy systems in buildings. Carreon and Worrell (2018) note that the energy source significantly influences energy efficiency, determining the quality of the energy service and the energy flows in the residential sector. The structure of the residential building is a key component of this approach, as different buildings have different nominal energy requirements (Sartor and Dewallef 2017). Sartor and Dewallef (2017) investigated various buildings in Belgium to determine the best heating infrastructure. They used variables such as fuel characteristics, building type, boiler heating system, heat pump, and electricity for heating and temperature. Electric heating was found to be the simplest and cheapest. Residential energy infrastructure also influences this approach. For instance, Western European countries have reliable natural gas grids powering over 90% of residential buildings, while in some Central and Eastern EU countries, natural gas development is limited by piping infrastructure inflexibilities.

2.1.2. Energy efficiency as a service (social science perspective)

Carreon and Worrell (2018) argue that understanding the term “service” is essential for identifying relevant determinants for measuring energy efficiency as a service. Energy service can be considered at different levels of the grid network (transmission, distribution, and consumption) and the support it provides to drive economic activities such as exploration, production, transportation, and the service industry. Residential, commercial, industrial, and transport sectors are the four recognized energy market categories in urban, rural, or city contexts. Each market demands energy for different activities: residential for daily household needs, commercial and industrial for production, and transport for various mobility modes, including electric vehicles (Carreon and Worrell 2018). Alternatively, Blok and Nieuwlaar (2020) define energy service as the ability to perform human activities and satisfy human needs using energy. In this context, energy service refers to the benefits of having access to energy for purposes like lighting, heating, cooking, mobility, and other comforts such as entertainment. After reviewing 173 articles, Fell (2017) concludes that energy service is significantly defined by its services for lighting, cooking, space heating, water heating, and refrigeration. Energy service emphasizes that society desires the services energy delivers, not just the energy itself (Kalt et al. 2019). Studies like Lee et al. (2022) have measured the service reliability of 34 African countries through grid connection, access, reliability of supply, and alternative energy sources. Social norms, demographics, economic, and political factors are direct drivers of energy service and efficiency (Carreon and Worrell 2018; Molajou et al. 2021). Urban settings typically rely on grid electricity, while rural areas may use off-grid connections like solar and wind power or traditional fuels. Due to the complex nature of current energy services, isolating an exact definition is challenging. Oshiro et al. (2021) highlight the importance of regulating residential consumer behavior in cities through appliances and other energy-related activities. Their study used a Low Energy Demand (LED) scenario for Japan (LoDem) to recommend measures for changing consumers' high-energy consumption patterns. They found that multifunctional home appliances like space and water heaters, air conditioners, lighting, cooking stoves, and televisions significantly influence residential demand. They also analyzed resident behavior in energy used for transportation, revealing high-energy use that requires a modal shift toward reduced trip frequency, public transport adoption, non-motorized mobility, supply chain localization to reduce freight transport, and industrial dematerialization toward a digital and circular economy. Gaur et al. (2022) used a similar LED scenario for Ireland (ILED) to show how transforming energy service demands can help meet decarbonization goals. They analyzed freight, passenger transport, residential dwellings, urban density, existing built-area use, space heating, water heating, refrigeration, cooking, cloth washing, drying, and dishwashing. They concluded that urban activities have high energy intensity. Gaur et al. (2022) emphasize that achieving energy efficiency through energy service or conversion chain approaches is viable but requires technological transition and socio-economic drivers. Both approaches should focus on maintaining energy efficiency for sustainable development. Therefore, strategic analysis should cross-compare the effects of different scenarios and approaches to measure energy efficiency effectively.

2.2. The South African electricity supply industry

The South African electricity grid is vertically integrated, providing electricity within the national territory and to neighboring countries in the Southern African Power Pool (SAPP). SAPP member states include South Africa, Lesotho, Zimbabwe, Zambia, Namibia, Mozambique, Eswatini, and Botswana. Eskom imports energy fuels from Lesotho, Mozambique, Zambia, and Zimbabwe, and exports to Zimbabwe, Namibia, Zambia, Botswana, Eswatini, Mozambique, and Lesotho (Department of Mineral Resources & Energy (DMRE 2019). The South African supply industry comprises Eskom, licensed municipalities, municipal energy entities (like City Power), and private distributors (responsible for Renewable Energy development programs) (National Energy Regulators South Africa (NERSA National Energy Regulators South Africa 2020). However, Eskom is the main custodian of the electricity grid, handling generation, transmission, and distribution under NERSA regulation. NERSA's primary mandate, as set out in the NERSA Act of 2004, is to ensure efficient, effective, sustainable, and orderly development and operation of electricity supply within the territory through licensing, pricing, and overall regulation (NERSA National Energy Regulators South Africa 2020). Traditionally, grid consumers receive electricity directly from Eskom or through Eskom-operated municipal generators, depending on the distribution arrangement with local authorities. Eskom supplies electricity in bulk to municipalities, which then redistribute it to consumers (Halsey et al. 2017). However, both Eskom and municipalities have failed to meet their mandates in recent decades, with the grid in distress and severe power cuts occurring since 2007 to counter the industry's inability to meet consumer demand (Sehlapelo and Inglesi-Lotz 2022). Ateba and Prinsloo (2019) note that Eskom once had a well-functioning grid with a healthy electricity supply before mismanagement led to the current crisis. Figure 1 reflects the supply industry structure in the reform industry set-up.

2.3. Supply and consumer grid inefficiencies in residential markets

Oyewo et al. (2019) state that the endemic crisis in South Africa's water and energy services has created significant socio-economic challenges for consumers in various residential market segments.

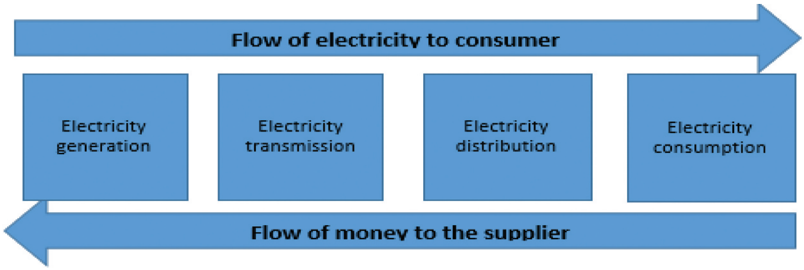


Figure 1. The supply industry structure in the reform industry set-up (DPE Department of Public Enterprises 2019, 11).

Donnenfeld, Crookes, and Hedden (2018) highlight that the 2014–2016 drought revealed existing water vulnerabilities and vulnerable areas in South Africa. The situation is worse with electricity supply, as the service has deteriorated due to endemic outages. Eskom struggles to supply the winter demand of 32,000 -34,000 megawatts (MW) and the summer demand of 26,000 -28,000 MW. Electricity prices have increased by 175% in the last decade (NERSA National Energy Regulators South Africa 2021). Nkosi and Dikgang (2018) observe that households across different regions and market segments have been severely affected by these inefficiencies. South Africa's residential electricity market is influenced by income, with high-income segments using butane gas appliances for cooking, while low-income segments rely on paraffin stoves (Nkosi and Dikgang 2018). Economic power allows larger metros to significantly influence electricity tariffs, creating challenges for rural municipal suppliers with predominantly low-income consumers (Baker and Phillips 2019). The disparity between urban and rural areas exacerbates inequalities in electricity distribution and access. Rural areas lag behind urban areas in grid connections, with only 45% of the rural population living in grid-connected zones compared to 94% in urban areas (Lee et al. 2022). End-user efficiency is critical to overcoming grid capacity shortages in South Africa (StTholen et al. 2015). Ye, Koch, and Zhang (2018) note that South African households lacked awareness of energy-saving actions. Efforts to establish appliance efficiency programs began in 2005 with the South African National Standards (SANS 941) for appliance labeling and efficiency. Despite significant steps, lack of information, knowledge, and evaluation remains a barrier (Götz, Tholen, and Adisorn 2016). Sustainable and efficient electricity delivery and consumption remain major challenges in South Africa (Bah and Azam 2017).

3. The selected regions for the survey

According to Baker and Phillips (2019), the affluent provinces in South Africa are the Western Cape and Gauteng Province (GP), which are metropolitan regions with thriving municipalities and cities. In contrast, provinces such as the Eastern Cape and all former "homeland" territories, including the North-West Province (NWP), experience sluggish economic performance. These former homelands were areas set aside primarily for Black South Africans under the 1913 Land Act. The disparities in economic performance are also reflected in the provincial household electrification statistics, as shown in Table 1.

3.1. Adapted from Sehlapelo & Inglesi-Lotz (2022)

The selection of Gauteng Province (GP) and the North-West Province (NWP) for this research stems from their contrasting yet illustrative provincial statistics regarding household electrification and socio-economic characteristics. Gauteng, the largest energy market in South Africa, boasts over 3,538,879 electrified households, accounting for 26.81% of the total electricity generated and available for supply. Conversely, the North-West Province has one of the lowest household electrification rates

Table 1. Important provincial household electrification statistics.

Provinces	Houses un-electrified	Houses electrified	Access per province	Electricity generated & available for distribution	Electricity generated and available for distribution %
Eastern Cape	323, 411	1,539,598	82.64%	8930	3.94%
Free State	123, 589	785,418	86.40%	11,674	5.15%
Gauteng	776, 997	3,538,879	82.00%	60, 839	26.81%
KwaZulu Natal	485, 472	2,318,263	82.68%	41,307	18.21%
Mpumalanga	88, 320	1,099,106	92.56%	32, 849	14.48%
Northern Cape	44, 196	288,579	86.72%	6257	2.76%
Limpopo	22, 723	1,542,976	98.55%	20,617	9.09%
North West	158,795	1,013,755	86.46%	22,119	9.75%
West Cape	185, 394	1,618,674	89.72%	22,304	9.83%
Total	**2,208,898**	**13,745,248**	**86.15%**	**226,896**	**100%**

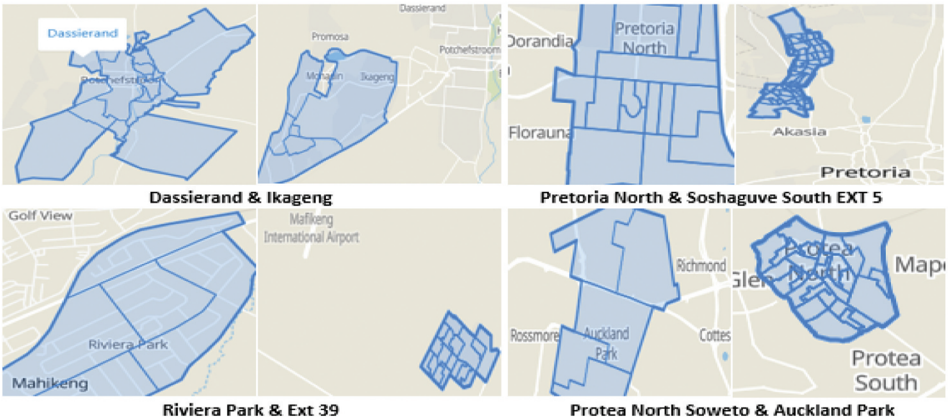
with 1,013,755 electrified households. This disparity underscores the varying degrees of development and access to essential services across different regions.

Gauteng Province (GP): Gauteng is characterized by a high degree of urbanization and includes major metropolitan areas such as Johannesburg and Pretoria. These cities are economic hubs with high-income urbanized settlements alongside "townships," which exhibit rural characteristics marked by low-income, informal communities. These townships often face higher levels of poverty and unemployment, with many residents relying on government social support programs for survival. The socio-economic divide within Gauteng provides a nuanced context for examining the relationship between electrification and development.

North-West Province (NWP): In contrast, the North-West Province, while having a lower overall electrification rate, encompasses areas that were previously designated as "homeland" territories under the 1913 Land Act. These areas typically exhibit slower economic performance and development. The targeted municipalities in the NWP for this study include Mafikeng (EXT 39 & Riviera Park) and the JB Marks Municipality (Dassierand & Ikageng). These municipalities provide a view into regions where socio-economic challenges and lower electrification rates persist. Moussa and Cosgroves-Davies (2019) and Sarkodie and Adams (2020) have examined the urban-rural divide in electricity access, noting a significant disparity linked to income levels and social factors. Their findings indicate that urban areas, typically characterized by higher incomes, have better access to electricity compared to rural areas. This disparity is mirrored in the South African context, where historical and socio-economic factors exacerbate the inequality in electricity distribution. South Africa is strikingly different from other SSA countries and the ratio between urban-rural accesses to electricity is about 3.5 times. In the NWP, Mafikeng (EXT 39 & Riviera Park) and the JB Marks (Dassierand & Ikageng) were target segments, while the City of Tswana (Pretoria North & Soshanguve South) and the City of Johannesburg (Protea North Soweto & Auckland Park Region B) were target segments for the Gauteng province. The sample settlements are further described in Figure 2.

4. Methodology

The empirical research capitalizes on the energy Trilemma framework, which is based on three pillars: energy security, energy equity, and environmental sustainability (Marti and Puertas 2022). This study focuses on the energy security pillar, which encompasses meeting future energy demands through efficiency, reliability, and resilience to supply disruptions. The background on the pillar is underlined as follows; **Energy Security**: Ensuring future energy demands are met efficiently and reliably, with resilience to supply disruptions; **Energy Equity**: Providing affordable access to energy; and **Environmental Sustainability**: Promoting environmental stewardship through sustainable energy practices. Marti and Puertas (2022) used the energy Trilemma index to analyze the linkage between income levels and the potential to achieve these pillars, highlighting how neighborhood dwelling is



Dassie: Population – 2,252, Households – 953; Main Ethnicity: White – 70%, Black Africans- 25%, Main Languages: Afrikaans – 71%, Setswana – 11%
Ikageng EXT 2: Population- 4,656, Households – 1,257; Main Ethnicity: Black Africans- 99%; Main Languages: Setswana-50%, IsiXhosa – 20%, & Sesotho – 20%
Pretoria North: Population – 12,972, Household – 3,951; Main ethnicity: White 70%, Black Africans – 26%; Main languages: Afrikaans – 69%, English – 9%, Setswana – 5%, & Sepedi – 5%
Soshanguve South EXT 5: Population – 10,240, Household – 3,348; Main ethnicity: Black Africans – 98%; Main languages: Sepedi – 26%, Xitsonga – 20%, Setswana-16%, & IsiZulu -10%
Auckland Park Region B: Population – 3,276, Households – 1,661; Main ethnicity: Black Africans – 32%, White – 30%, Asians 13%, Main languages: English 43%, Afrikaans – 17%, IsiZulu – 9%, & Setswana – 7%
Soweto Protea North: Population – 13,513, Households – 3,667; Main ethnicity: Black Africans 100%; Main languages: IsiZulu – 33%, Sesotho – 18%, Setswana – 14% & Xitsonga – 8%
EXT 39: Population - 7,522, Households – 2,837; Main ethnicity: Black Africans – 99%; Setswana – 75%
Riviera Park: Population – 2,741, Households – 787; Main ethnicity: Black Africans – 66%, Whites – 18%, & Asians - 8%; Main languages: Setswana – 47%, English – 22%, & Afrikaans – 20%

Figure 2. A description of the sample settlements.

parallel to household income. The descriptive analysis confirmed the parallel relationship between households' monthly income and monthly electricity spending in the selected settlements. Consequently, a quantitative research design was chosen to handle the study's complexity. The research employs a quantitative design with Exploratory Factor Analysis (EFA) to identify underlying factors from questionnaire items, given the conceptual nature of the investigation parameters (Auerswald and Moshagen 2019). The research aims to: *Analyze supplier inefficiencies in urban and rural residential electricity markets in South Africa*; assess consumer behavioral tendencies toward the use of home appliances; and Recommend practical implications the viability of different market

The study population includes all grid-connected households in Gauteng Province (GP) and the North-West Province (NWP), totaling 4,552,634 households. Using the central limit theorem at a 95% confidence level and a 5% margin of error, a sample size of 346 households was determined to be sufficient. However, 400 questionnaires were distributed to ensure adequate representation, with 50 households sampled from each target market segment. According to Field (2014:915), surveys with different sampling quotas should include 100 respondents from main groups (cities) and 20 to 50 respondents per subgroup (settlements) to ensure fair representation and avoid biases. This approach aligns with current quantitative survey methodologies, which recommend 50 observations per group. The field investigation involved self-administered questionnaires distributed through convenience sampling. The questionnaire focused on two main themes: supply service quality and end-user tendencies. It included dichotomous questions (yes or no) and Likert scale questions (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree). A screening question ensured respondents were 18 years or older. Only the patriarchs, matriarchs, eldest adults, or primary breadwinners were allowed to respond on behalf of their households. To manage the extensive data collection, field workers were employed. These field workers were postgraduate students with a background in social science empirical research data collection. Training sessions were conducted to instruct field workers

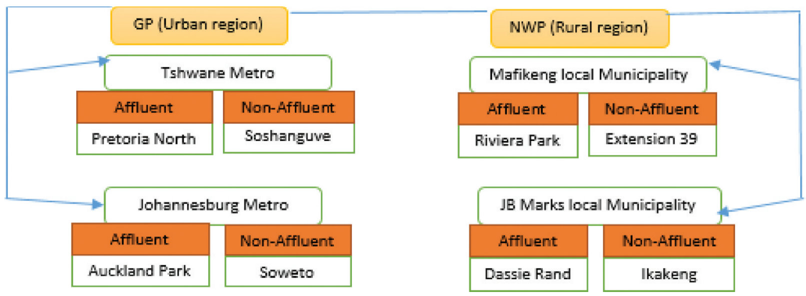


Figure 3. Population sampling of target settings.

on data collection requirements and relevant measures for gathering accurate data. The structure of the target population and sampling methodology is illustrated in Figure 3. The structured approach, coupled with trained field workers, ensured the collection of reliable and relevant data from various market segments.

5. Results

The analyses conducted encompassed a spectrum of statistical methods, including descriptive statistics to delineate dimensions, inferential statistics to elucidate underlying factors, and color notations denoting consumers' usage intensity on a color chart for sampled appliances. Descriptive statistics, employing Means (M) and Standard Deviations (SD), elucidated the central tendency and dispersion of variables, respectively. The inferential statistical arsenal comprised Independent t-tests, ANOVA, and exploratory factor analysis, facilitating a comparative analysis of the sampled groups. The Independent t-test gauged practical differences between mean scores of distinct settlements, discerning effect sizes and potential idiosyncratic traits. Effect sizes exceeding 0.2, 0.5, and 0.8 were construed as indicative of small, medium, and large differences, respectively. While Levene's p-values, signifying variance equality, were reported for completeness, their interpretation was eschewed due to the utilization of random sampling. To ensure robust factor analysis estimations, guidelines delineated by Yong and Pearce (2013) was adhered to. As elucidated by Schlomer (2009), the independent samples t-test was deployed to juxtapose two groups whose means were mutually independent.

5.1. General descriptive results for constructs

Table 2 illustrates the distribution of responses across the sampled groups, delineating the percentage of responses received from each. Out of the total questionnaires distributed, 323 participants responded. Notably, GP, encompassing the City of Johannesburg and City of Tshwane municipalities, constituted 60% of the overall sample, while NWP, comprising JB Marks and Mafikeng municipalities,

Table 2. Description of the participation for each market segment.

Settlements	Groups	Frequency	Percentage
Protea North Soweto	Low-income	49	15.2%
Extension 39 Mafikeng	Low-income	50	15.5%
Ikageng	Low-income	9	2.8%
Soshanguve	Low-income	50	15.5%
Riviera Park	High-income	49	15.2%
Dassierand Potch	High-income	15	4.6%
Auckland Park	High-income	50	15.5%
Pretoria North	High-income	51	15.8%

Table 3. Adequacy of supply.

Statements	M	SD
1. The supply of electricity is sufficient	2,48	1,02
2. The supply of electricity allows households to perform basic household activities	2,89	1,13
3. Electricity supply volumes meet the required household demand	2,48	0,94
4. Multiple electric appliances (e.g. stove, geyser & kettle) can be used simultaneously in your house	3,85	1,21

Table 4. Reliability of supply.

Statements	M	SD
1. The supply of electricity is without interruptions (blackouts)	2,33	1,01
2. Future electricity supply will be without interruptions	2,4	0,96
3. The supply of electricity is consistent(low voltage)	2,55	1,00
4. There is announced load shedding	3,93	1,13
5. Load shedding negatively affects household functioning & family comfort (e.g. study time for school children)	3,95	1,08

comprised 40%. Each settlement boasted a representation surpassing the 15% threshold, with the exception of Ikageng (2.8%) and Dassierand Potch (4.6%).

Table 3 presents descriptive statistics concerning the adequacy of supply. The findings indicate a general tendency among participants to disagree with certain statements, namely: Statement 1 (M = 2.48, SD = 1.02), Statement 2 (M = 2.89, SD = 1.13), and Statement 3 (M = 2.48, SD = 0.94). Conversely, participants tended toward agreement with Statement 4 (M = 3.85, SD = 1.21).

Table 4 reflects descriptive statistics pertaining to the reliability of supply. Overall, respondents exhibited a tendency to disagree with certain statements: Statement 1 (M = 2.33, SD = 1.01), Statement 2 (M = 2.4, SD = 0,96), and Statement 3 (M = 2.55, SD = 1.00). Conversely, households leaned toward agreement with other statements: Statement 4 (M = 3.93, SD = 1.13), and Statement 5 (M = 3.95, SD = 1.08).

Table 5 presents descriptive statistics pertaining to health risks. Overall, respondents expressed agreement with the provided statements, suggesting that alternative sources of energy pose health problems (M = 4.00, SD = 1,05), contribute to hazardous consequences (M = 4.00, SD = 1.00), and the utilization of unclean energy sources leads to environmental pollution (M = 4.21, SD = 1.07).

Table 6 provides descriptive statistics regarding cost reliability. In general, respondents predominantly concurred with the presented statements. The findings reveal that: Electricity price increases are not adjusted to accommodate households' disposable income (M = 3.88, SD = 0.99). Escalating electricity fees affect the purchasing ability of domestic electricity (M = 3.92, SD = 0.81). Future electricity price increments pose a threat to domestic electricity purchasing ability (M = 3.75, SD = 1.15). There

Table 5. Descriptive statistics for the use of alternative sources.

Statements	M	SD
1. Alternative sources for lighting, heating, and cooking are been used	4,00	1,05
2. Renewable alternative sources of energy are been used (e.g. solar lamps and butane gas)	4,00	1,00
3. Alternative energy sources with CO2 components are been used (e.g paraffin, coal & fire-wood)	4,21	1,07

Table 6. Cost affordability.

Statements	M	SD
1. Electricity price increases are relatively higher than increases in your household's disposbale income	3,88	0,99
2. Increased electricity fees impact domestic electricity purchasing ability	3,92	0,81
3. The current cost of electricity is acceptable	2,48	1,15
4. Future electricity price increases are a threat to electricity service purchase	3,75	1,15

Table 7. Description of the income and monthly electricity spending profile by settlements.

Descriptions		Brackets (ZAR/month)				
Groups	Total Participation	>15 000	15001-25 000	25 001–34 000	34 001–46 000	>46 000
Soweto	49	38	5	6	0	0
Extension 39	50	43	7	0	0	0
Ikageng Potch	9	7	3	0	0	0
Soshanguve South	50	33	8	9	0	0
Riviera Park	49	0	11	33	5	0
Dassierand-Potch	15	0	3	6	6	0
Auckland Park	50	0	0	8	24	18
Pretoria North	51	0	0	14	29	8
Descriptions		Monthly electricity spending				
Groups	Total Participation	<200	<300	>300		
Soweto	49	15	17	17		
Extension 39	50	23	21	6		
Ikageng	9	2	5	2		
Soshanguve South	50	17	19	14		
Riviera Park	49	4	11	34		
Dassierand-Potch	15	2	3	10		
Auckland Park	50	1	7	42		
Pretoria North	51	1	4	46		

exists a neutral sentiment regarding the reliance on alternative energy sources due to the escalating cost of electricity ($M = 3.41$, SD = 1.28). Participants disagreed that the current cost of electricity is deemed acceptable ($M = 2.48$, SD = 1.15).

Table 7 provides insights into the responses received from each sampled group concerning income brackets and average household monthly spending on energy. The findings underscore that households residing in less affluent settings, particularly townships in rural areas such as Soweto, extension 39, Ikageng, and Soshanguve, typically earn below 15,000 ZAR (77%) and allocate lesser funds for electricity, with less than 200 ZAR (36%) and less than 300 ZAR (40%) being the norm monthly. Conversely, households in more affluent settings, encompassing both rural and urban locales, generally earn between 25,001 -34,000 ZAR (37%) and 34,001 46,000 ZAR (39%), allocating more than 300 ZAR for electricity monthly (80%).

5.2. Inferential statistics

Table 8 reflects Cronbach alpha values for all factors. Results show that Cronbach's alpha values for all factors were 0.70 and above and thus, the factors are deemed reliable.

Table 9 delineates the factor analysis outcomes concerning supply performance. Notably, all tests conformed to guideline values, ensuring the robustness of the analysis. Communalities for this analysis closely approximated the guideline threshold of 0.3. Furthermore, the results indicate that 59.8% of the variance is explicated by the extracted factor. The Determinants, KMO, and Bartlett statistics stand at 0.62, 0.849, and ≤ 0.0001, respectively, underscoring the adequacy of the data for factor analysis. It's

Table 8. Reliability test.

Constructs	Alphas
Supply sufficiency	0,86
Supply security	0,71
Health risk	0,84
Cost reliability	0,7
Energy saving	0,72

Table 9. Factor analysis results for supply performance.

	Determinant	0,037
	KMO	0,75
	Bartlett test Sig.	≤0,0001
	Total variance	59,80%
Factors and statements	*Com*	*Pattern matrix for factors*
Adequacy of supply (Factor 1)		
The supply of electricity is sufficient	0,31	0,75
The supply of electricity allows households to perform basic household activities	0,61	0,36
Electricity supply volumes meet the required households' demand	0,51	0,48
Multiple electric appliances (e.g. stove, geyser & kettle) can be used simultaneously in your house	0,17	0,33
Reliability of supply (Factor 2)		
The supply of electricity is without interruptions (blackouts)	0,46	0,23
Future electricity supply will be without interruptions	0,26	0,41
The supply of electricity is consistent (low voltage)	0,6	0,59
There is unannounced load-shedding	0,53	0,57
Load-shedding negatively affect households, functioning &family comfort (study time & watching TV)	0,04	0,76
Alternative energy (factor 3)		
Alternative sources for lighting, heating and cooking are been used	0,64	0,83
Renewable alternative sources of energy are been used (e.g. solar lamps & butane gas)	0,77	0,46
Alternative energy sources with CO2 components are been used	0,49	0,51
Cost reliability (factor 4)		
Electricity price increases are relatively higher than increases in your household's disposable income	0,61	0,76
Increased electricity fees impact domestic electricity purchasing ability	0,52	0,70
The current cost of electricity is acceptable	0,11	0,28
Future electricity price increases are a threat to domestic electricity purchase ability	0,34	0,30

Table 10. Results of T-test between provinces.

Factors	Provinces	M	SD	L P V	Effect size
Adequacy	GP	2,83	0,78	<0,001	0,75
	NWP	2,24	0,68		
Reliability	GP	2,93	0,64	<0,001	0,62
	NWP	2,46	0,64		
Alternative energy	GP	4,05	1,01	0,01	0,07
	NWP	4,12	0,79		
Electricity cost	GP	3,96	0,67	0,04	0,02
	NWP	4,01	0,62		

noteworthy that the negative sign accompanying certain statements stemmed from the context of the questions posed.

Table 10 compiles the consolidated findings from the independent test (T-test), juxtaposing regional market urban metros (GP) against local municipalities (NWP). The results unveil notable effect size differences, categorized as medium and large, between the urban and rural regions concerning adequacy (0.75) and reliability (0.62). Specifically, rural regions exhibited a tendency to disagree, while urban regions leaned toward neutrality on these dimensions. However, no significant disparities were observed in responses regarding alternative energy and electricity cost. Both regions tended to agree that alternative energy is being utilized and that electricity costs are inefficient.

Table 11. T-test for affluent and non-affluent segments for rural and urban regions.

Factors	Regional setting	Market segment	M	SD	P Values	Effect size of groups
Adequacy of Supply	Auckland	High-income	3,03	0,85	<0,001	0,61
	Soweto	Low-income	2,17	0,76		
Reliability of Supply	Auckland	High-income	3,99	0,68	<0,001	0,92
	Soweto	Low-income	3,18	0,64		
Alternative energy	Auckland	High-income	3,54	1,13	0,11	0,18
	Soweto	Low-income	3,87	0,84		
Cost reliability	Auckland	High-income	3,49	0,85	0,84	0,04
	Soweto	Low-income	3,46	0,7		
Adequacy supply	Pretoria North	High-income	2,67	0,51	0,003	0,51
	Soshanguve	Low-income	2,27	0,77		
Reliability of supply	Pretoria North	High-income	2,95	0,55	<0,001	0,00
	Soshanguve	Low-income	2,47	0,65		
Alternative energy	Pretoria North	High-income	4,43	1,04	0, 2	0,28
	Soshanguve	Low-income	4,14	0,82		
Cost reliability	Pretoria North	High-income	3,89	0,6	0,57	0,11
	Soshanguve	Low-income	3,63	0,55		
Adequacy of supply	Dassierand	High-income	3,13	0,5	<0,001	0,86
	Ikageng	Low-income	1,71	0,55		
Reliability of security	Dassierand	High-income	2,97	0,43	0,01	0,61
	Ikageng	Low-income	2,85	0,85		
Alternative energy	Dassierand	High-income	4,1	0,51	0,02	0,19
	Ikageng	Low-income	3,91	0,7		
Cost reliability	Dassierand	High-income	3,38	0,49	0,17	0,12
	Ikageng	Low-income	3,26	0,6		
Adequacy of supply	Riviera	High-income	2,70	0,64	0,02	0,36
	Extension 39	Low-income	2,37	0,46		
Reliability of security	Riviera	High-income	2,54	0,51	0,05	0,39
	Extension 39	Low-income	2.27	0.56		
Alternative energy	Riviera	High-income	4,31	0,69	0,4	0,19
	Extension 39	Low-income	4,2	0,68		
Cost reliability	Riviera	High-income	3,84	0,53	0,33	0,09
	Extension 39	Low-income	3,73	0,54		

Table 11 presents the T-test outcomes for each regional city, highlighting the disparity between low-income (non-affluent) and high-income (affluent) market segments. A prevailing trend emerges wherein non-affluent market segments in both urban and rural regions tend to express disagreement regarding the adequacy and reliability of supply. Conversely, affluent market segments from both urban and rural regions tend to either disagree or adopt a neutral stance on these dimensions. The results indicate a consensus among both urban and rural market segments regarding the utilization of alternative energy and the inefficiency of electricity costs. Significant effect sizes are evident for certain markets concerning supply adequacy and reliability. Notable instances include adequacy for Auckland and Soweto (0.61), Pretoria North and Soshanguve (0.51), and Dassie Rand and Ikageng (0.61). Similarly, for reliability, significant effect sizes are observed for Auckland and Soweto (0.92), and Dassie Rand and Ikageng (0.86).

5.3. Results on consumers' usage intensity on sampled appliances

Participants were tasked with responding to pivotal dichotomous inquiries regarding the utilization of various appliances to gauge the intensity of consumer usage. Household consumption patterns were scrutinized across a spectrum of home appliances, including Refrigerator, Electricity, Washing Machine, Microwave Oven, Air-conditioner (AC), Electric Stove, Pool Pump, Electric Heater, Clothing Iron, and Kettle. A sequential color scheme analysis, as detailed in Appendix A, was employed to assess appliance intensity in terms of daily usage hours, thereby estimating the energy intensity of these appliances. Statement 1, probing the appliances in use within households, revealed a Very High Intensity (VHI) utilization for the Refrigerator, Electric Geyser, Cooking Stove, Clothing Iron, Water Heater, and Microwave Oven across all settlements. Notably, Air Conditioners and Pool Pumps were not utilized by low-income households (Very Low (VL) intensity). High-income settlements from both provinces exhibited a High Intensity (HI) usage of Pool Pumps and Washing Machines. Washing Machines were predominantly characterized by Low Intensity (LI) and Medium Intensity (MI) usage, with instances of VHI usage in high-income settlements. Space Heaters were predominantly utilized at VHI and HI in high-income settlements, while urban low-income settlements demonstrated HI usage, and low-income non-urban settlements indicated MI and LI usage. Statement 2, addressing energy-efficient appliance usage during peak periods, indicated that most appliances were predominantly used even during peak hours (VHI). Interestingly, some high-income settlements exhibited MI and HI usage of Electric Geysers during peak periods, contrasting with VHI usage among low-income settlements.

Statement 3, focusing on daily appliance demand, showcased VHI usage across most appliances for both low-income and high-income settlements, except for Electric Space Heaters, Pool Pumps, and Washing Machines, which exhibited VLI usage. Notably, Auckland Park and Pretoria-North demonstrated VHI and MI usage of Air Conditioners. Statement 4, delving into the utilization of appliances older than 5 years, indicated that Air Conditioners, Electric Space Heaters, Clothing Irons, and Washing Machines predominantly featured relatively recent models, with results predominantly showing LI and VLI intensity levels. Similar representation of intensity levels was observed across other appliances as depicted in the chart. Statement 5, focusing on appliance usage during warmer summer months, highlighted Microwave Ovens, Hot Water Kettles, Clothing Irons, Cooking Stoves, and Refrigerators as the most intensively used (VHI). Notably, Electric Geysers exhibited VHI usage across all high-income settlements, except for Dassie Rand (HI), while Electric Space Heaters predominantly exhibited VHL usage across most settlements. Statement 6, examining appliance usage during colder winter months, illustrated Refrigerators, Electric Geysers, Electric Stoves, Hot Water Kettles, and Microwave Ovens as predominantly utilized (VHI). Clothing Irons exhibited predominantly VHI and HI usage, while Air Conditioners and Pool Pumps were utilized at VHI intensity levels. The detail comprehensive description of the results is reflected in Appendix A.

6. Empirical findings and policy implications

6.1. Regulatory reforms and policy interventions to address energy poverty

The findings highlight stark socio-economic disparities across market segments, with households in less affluent areas, such as townships like Soweto, Extension 39, Ikageng, and Soshanguve, typically earning below 15,000 ZAR (77%) and spending less than 200 ZAR (36%) or less than 300 ZAR (40%) on electricity monthly. Conversely, more affluent settings, both rural and urban, tend to earn between 25,001 -34,000 ZAR (37%) and 34,001 46,000 ZAR (39%), allocating over 300 ZAR for electricity monthly (80%). Noteworthy is the observation that a majority of affluent households in rural regions earn between 25,001 -34,000 ZAR, while the majority in urban regions earn between 34,001 46,000 ZAR. These disparities contribute to South Africa's position as one of the most unequal societies globally in terms of income distribution and access to basic services, with a mean income distribution gap of 60% between rural and urban populations.

In light of these disparities, strategic analysis suggests that policymakers must take into account the socio-economic landscape across various market segments and its implications for access, and expenditure for electricity. It's imperative to scrutinize income distribution and the affordability of electricity across different segments, particularly comparing less affluent townships to more affluent urban and rural areas. Policy frameworks should also assess the effectiveness of social welfare programs in mitigating economic inequalities that hinder equal access to essential services, including electricity. Tailoring electricity tariffs based on location and offering rebates to township consumers could promote equitable access. While the are initiatives like the Free Basic Electricity (FBE) scheme aim to support low-income households, their implementation has faced challenges. There is a critical need to reform the FBE parameters to align with contemporary market dynamics, ensuring effective targeting of the most vulnerable households based on income and spending patterns across market segments. Furthermore, evaluating market dynamics, competition, and barriers to entry could foster efficiency and attract potential service providers to cater to the diverse needs of segments with tailored products and services.

6.2. Supplier inefficiencies

A comprehensive analysis of regional markets reveals substantial disparities in household responses between urban (GP) and rural (NWP) regions concerning supply reliability, availability, and cost. Rural market segments (NWP) predominantly express disagreement regarding the adequacy and reliability of supply, while concurrently acknowledging the utilization of alternative energy and the inefficiency of electricity costs. Conversely, urban market segments (GP) adopt a more neutral stance on supply adequacy and reliability, alongside an agreement regarding the usage of alternative energy and the inefficiency of electricity costs. This pattern persists when comparing market segments from regional settings. A notable aspect of this study lies in its examination of supply inefficiencies across different market segments, particularly contrasting less affluent townships with more affluent urban and rural areas. This novel approach sheds light on the unique socio-economic constraints impacting market supply and access, a dimension largely overlooked in previous studies.

Government investments should prioritize electrification projects in rural and township areas to enhance access and reliability of electricity supply, especially through the integration of renewable energy sources like wind, solar, hydro, and thermal sources. Additionally, policy initiatives could introduce recreational and community programs offering alternatives to high-energy activities. This not only addresses energy poverty but also fosters sustainable energy usage across diverse market segments. Innovative solutions such as energy storage, micro-grids, and distributed energy resources (DERs) can bolster grid flexibility and reliability for underserved segments. Continuous evaluation of generation capacity is imperative to meet current and future electricity demands, accounting for population growth and economic development trajectories. This multifaceted approach is essential for fostering equitable and sustainable energy access across varied market segments while addressing socio-economic disparities.

6.3. Consumer inefficiencies

The fundamental household appliances exhibit a Very High Intensity (VHI) (red) usage across all regional market segments, including the Fridge, Electric Geyser, Electric Stove, Air Conditioner (AC), Clothing Iron, Kettle, and Microwave Oven. Moreover, these appliances are heavily utilized during peak periods (VHI) by all regional market segments. Notably, some appliances older than 5 years are still in use by both low-income (non-affluent) and high-income (affluent) market segments, such as Electric Stoves and Kettles for the latter, and Fridges and Electric Stoves for the former. Conversely, certain appliances like Pool Pumps and ACs are not utilized by low-income market segments, while Washing Machines exhibit average usage within this segment. During winter, Air Conditioners and Pool Pumps experience low intensity, whereas space heating reflects low intensity during summer. This analysis of consumption tendencies provides valuable insights for the national government to comprehend current market dynamics and the diverse needs and preferences of consumers in various environments. By understanding unique consumer behaviors and preferences related to multiple appliance usage across different market segments, policymakers can identify high-consumption areas and motivations to achieve lower consumption, setting a trajectory for eradicating consumer inefficiencies and promoting sustainable communities. To optimize consumer efficiency, South African policymakers and electricity grid planners could consider the following approaches:

Consumer Education and Awareness: Implementing educational programs and awareness campaigns about energy-saving practices. The benefits of energy-efficient technologies can empower consumers to make informed choices and reduce consumption.

Modernization of Supply and Distribution Infrastructures: Upgrading grid transmission and distribution infrastructures in both rural and urban areas can enhance reliability, efficiency, and accommodate renewable energy integration. Advanced metering infrastructure and smart metering can enable modern grid analytics, predictive maintenance, and demand response programs to optimize grid performance and efficiency while improving billing accuracy and reducing losses.

Appliance Efficiency Programs: Implementing energy efficiency initiatives such as appliance labeling, subsidies for efficient appliances, and energy audits can help consumers reduce consumption. Demand response programs incentivizing consumers to reduce electricity usage during peak times are also vital. Government incentives for trading or recycling outdated appliances can promote the adoption of efficient appliances, particularly among less affluent market segments and rural areas where inefficient practices contribute to higher electricity consumption.

7. Conclusion

Through a strategic lens, this study has delved into the efficiency of both supply services and consumer behavior within the South African power grid system, offering valuable insights to inform long-term planning and intervention strategies. The investigation meticulously analyzed inefficiencies in both supply and consumption across selected urban and rural residential markets. Guided by indicators from the Energy Trilemma Index, the empirical research, deployed a quantitative survey to provide a comprehensive understanding of supply performance in socio-economic terms and consumption behavior through appliance usage. The findings reveal stark disparities in household income and electricity spending across different regions. While households in less affluent rural areas tend to earn and spend significantly less on electricity, their counterparts in more affluent settings allocate larger sums for electricity expenses. Furthermore, significant regional differences were observed in terms of supply adequacy, reliability, alternative energy usage, and electricity cost. A deeper dive into consumption patterns highlighted the prevalence of high appliance usage among most households. This segmentation study offers invaluable insights for national policymakers, enabling a nuanced understanding of current market dynamics and consumer needs, and have laid the groundwork for eradicating energy poverty and fostering sustainable communities.

Disclosure statement

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