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Spatial variation of household energy consumption across counties in Kenya

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ABSTRACT

Kenya has reported a trajectory of success towards universal access to sustainable and modern energy sources over the past years. However, the discussion on the spatial variations of energy consumption is limited especially, at the disaggregated level. The study seeks to analyse the spatial variations of energy consumption across counties. Energy consumption for clean and non-clean energy sources varies significantly across counties. The spatial variations are linked to specific county-level attributes such as the population density, urban/ rural status, energy infrastructure, fuel resources availability, and climatic factors. Therefore, the universal transition to clean energy sources will require location-specific policy interventions.

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Kenya; county; energy transition; spatial variation; energy consumption; energy sources

1. Introduction

Energy is increasingly at the center of the international debate on sustainable development, environment, disaster risk reduction, and climate change (IEA, 2020c). Consumption of clean and modern energy is a central pillar toward socio-economic transformation and a prerequisite for improved health (Andrade-Pacheco, Savory, Midekisa, Gething, Sturrock, Bennett et al., 2019; World Health Organization, 2016; International Energy Agency (IEA), 2020c). Households account for a significant share of the total energy consumption; hence, they play an important role in enhancing energy transition at the micro-level (Jiang et al., 2019; Kenya National Bureau of Statistics, 2019). Notably, Africa has made remarkable strides in access to clean and modern sources. The number of people gaining access to electricity growing from 9 million people between 2000 and 2013 to 20 million people between 2014 and 2018, outpacing population growth (IEA, 2020d).

Despite the accelerated efforts toward universal access and transition to clean and modern energy sources, nearly 860 million people have no access to electricity globally, with 600 million (one-out-of-two people) spread out in Sub-Saharan Africa (International Energy Agency (IEA,2019). Similarly, cooking fuels indicate a similar trend, with 2.4 billion people still relying on traditional biomass and inefficient cooking technologies globally, with roughly 900 million spread across Sub-Saharan Africa (IEA, 2020d). On the other hand, approximately 60 million people rely on kerosene or coal to meet their daily energy needs (IEA, 2020d). The trends indicate that universal access and transition to modern fuels will require concerted efforts by sector players.

Global statistics indicate that the absolute annual household electricity consumption stands at 3,010 Kilowatt-hours (kWh) (IEA, 2020d). Disparities show across regions, with developing countries recording an average of 6,000 kWh to a low of 1,000 kWh in South Asia and Sub-Saharan Africa (IEA, 2020d). Notably, household's electricity consumption levels in SSA are among the lowest in the world. On

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average, households in Sub-Saharan Africa consume less than 1,000 (kWh) of electricity each year, seven times less than the average household consumption in advanced economies (IEA, 2020d).

Kenya is ranked among the top 20 fastest electrifying countries globally, at a rate of 5 percentage points since the year 2010 (IEA, 2020d). The level of electricity access increased from 29% in 2012 to 73% by the end of 2018 (Kenya Power, 2018). Despite notable progress, household access levels vary significantly across the country (IEA & UNSD, 2019; KNBS 2018). The disparities are mainly attributable to limited, unpredictable disposable income, unreliable services, and inadequate grid infrastructure, among other factors (Republic of Kenya, 2018a; World Health Organization, 2018).

The limited access to clean cooking fuels and technologies remains prevalent. Consumption of clean cooking fuels in Kenya falls below the global average as Kenya ranks among the top 20 countries that are deficient in clean cooking sources (IEA, 2020d). Biomass fuels constitute the largest share of primary energy consumption among households in Kenya (Kenya National Bureau of Statistics (KNBS), 2019). Biomass accounts for roughly 69% of the total primary energy consumption and provides more than 90% of rural households (Republic of Kenya, 2018a). About 55% of biomass-derived from farmlands in the form of woody biomass, crop residue, animal waste, and the remaining 45% is from forests (Republic of Kenya, 2018a). Over-reliance on inefficient fuels has detrimental implications on human health (Makonese et al., 2018). Exposure to indoor pollution during the combustion of the inefficient fuels contributes to approximately 15,000 premature deaths each year in Kenya, disproportionately affecting women and children (World Health Organization, 2018). To overcome these adverse effects and enhance livelihoods, the transition toward cleaner and more efficient energy forms are inevitable. As such, Tesfamichael et al. (2020) emphasize that stimulation of demand and transition to clean energy sources at the household level is one of the key challenges for policymakers.

The concept of households' variations in energy use is mainly explained from the perspective of the energy ladder. The energy ladder theory postulates that households switch from non-clean energy sources (biomass) to conventional fuels such as kerosene, coal, and charcoal and finally to LPG, natural gas, or electricity in response to higher incomes (Leach, 1992; Masera et al., 2000). However, Mekonnen et al. (2009) contend that household economic status is not the principal driver of households' energy-use-behavior. As such, geographical, environmental, technological advancement, resource availability, perceptions, levels of urbanization, and living standards are also pertinent to energy use patterns and intensity of use (Mekonnen et al., 2009). Besides adopting various energy sources, the actual energy consumption level is also key in defining the household level's energy transition pathways. Blimpo and Cosgrove-Davies (2019) report that even when households have access to clean and modern energy sources, consumption levels remain low, meaning that households are limited to less intensive energy services such as lighting. As noted by Chatterton et al. (2016), the amount of energy consumed by households provides a coherent starting point in understanding energy transition pathways at the micro-level.

Mashhoodi et al. (2019) purport that the transition to clean and modern energy goes beyond demographic and household characteristics to locational factors that are critical in addressing inequalities from a spatial perspective. Therefore, energy consumption patterns are embedded in the spatial heterogeneity concept key in understanding energy consumption variations from a regional perspective (Bardia Mashhoodi et al., 2019). The inclusion of spatial models in energy research provides new insights into the comprehension of spatial heterogeneity in energy consumption.

Understanding the energy consumption patterns at sub-national levels is vital in ensuring equitable transition to clean and modern energy sources. It is one of the crucial aspects embedded in the global efforts toward universal energy access by 2030 and the central pledge to leave no one behind (UNDP, 2015a). Bardia Mashhoodi et al. (2019) points out that most studies do not consider spatial heterogeneity in household energy consumption as key in explaining the progress and pathways of energy transition. Spatial dimensions of energy use remain integral in planning specific locational interventions in transitioning to clean and modern sources (Van der Kroon et al., 2013).

This is partly due to lack of disaggregated energy data that hinder targeted interventions at the subnational levels (Andrade-Pacheco, Savory, Midekisa, Gething, Sturrock, Bennett et al., 2019).

Since the inception of devolution, not much work has investigated the spatial disparities in consumption of various energy sources to inform strategic energy transition plans among the 47 counties. Counties face challenges and opportunities in energy resource endowment, energy infrastructure development, energy services, and geographical structure. Therefore, this study fills the knowledge gap and broadens the concept of the household's energy consumption by investigating spatial variations and autocorrelation in the consumption of various energy sources at the household level among counties in Kenya. The two research questions put forward ; are there spatial disparities in access to different energy sources and, how is the spatial clustering in consumption of various energy sources at a national and county level?

The county-level empirical analysis aims at informing targeted programs, strategies, and policy interventions geared toward transitioning to clean and modern energy sources in Kenya. The spatial analysis employed in this study is also replicable for other energy deficit countries. Besides, this study is motivated by the need to cascade and propagate clean energy access plans from the national perspective to the local level subnational energy policies in line with the specific characteristics, resource endowments, and energy needs. This paper is organized as follows: Section 1.1 describes the key legislative frameworks and initiatives geared toward universal access to clean energy sources. Section 2 focuses on the relevant literature on households' access to clean energy sources. Section 3 explains the methodological approach used in this study, while section 4 discusses the research findings. Section 5 provides the conclusion and policy recommendations.

1.1. Legal and policy environment for the energy sector in Kenya

The energy sector operates under various constitutional, policy, and legal frameworks. The legal and policy environment in Kenya has advanced over the years, with significant reforms commencing with the restructuring of the energy value chain sectors. The key developments were geared toward liberalization and unbundling of the electricity sub-sector by separating regulatory function, commercial activities, generation function, and transmission and distribution (Electric Power Act 1996; Energy Act, 2006). The recent reforms in the energy sector are embedded in constitution of Kenya which establishes the 47 county governments. The constitution set out National and County governments' functions for developing the energy sector, such as policy development and development of energy plans, respectively.

Access to competitively priced, reliable, quality, safe, and sustainable energy is essential for achieving the Kenya Vision 2030. The recently enacted National energy policy 2018 sets out critical strategies on improving access to affordable, competitive, and reliable energy services. The policy objectives are geared toward ensuring the development and implementation of a comprehensive, integrated, and well-informed energy sector plan. Similarly, the Energy Act, 2019, requires the National Government to collaborate with County agencies to develop a conducive environment for promoting investments in clean energy infrastructure development, including developing guidelines on developing energy projects. The Energy Act also requires county governments and their strategic partners to develop subnational energy policies in line with the specific characteristics, resource endowments and energy need of each county.

Kenya National Electrification Strategy (KNES), 2018–22, defines the roadmap toward universal electricity access for households and businesses across the country in fast-tracking connectivity. Based on a least-cost geospatial assessment., KNES identifies the least-cost technology options (grid extension, grid intensification, mini-grids, and standalone systems) and the associated investments required for reaching the remaining population with affordable and reliable electricity.

The Kenya Electricity Sector Investment Prospectus 2018–2022 initiative by the Ministry of Energy outlines the investment and financing opportunities toward universal access to modern energy for power generation, electricity transmission, distribution, off-grid electrification, and energy efficiency.

The investment prospectus identifies the avenues for mobilization of resources and multi-stakeholder engagement to facilitate the implementation of priority projects in the electricity sector. It also advocates for increased private sector participation through the Private-Public Partnerships framework and Feed-in Tariffs and Renewable Energy Auctions. The other initiatives include the Last Mile Connectivity Project, which enabled electricity connectivity by subsidizing the connection fee by almost 50per cent in rural and peri-urban areas. The rural electrification program aims at increasing electricity access in rural areas by connecting public facilities and households within the proximity of the transformer and development of mini grids in remote and isolated regions. Despite the progress made, the energy sector is still lagging. Therefore, this study aims at identifying the critical gaps that impede the transition to clean and modern energy sources for all.

2. Review of previous work on household energy consumption

The energy discourse elucidates that the determinants of energy consumption at the household level are multifaceted. As purported, factors influencing energy consumption vary at the macro and micro-level scales. Inherently, energy studies on energy consumption are embedded within economic, technical, social domains, and along the urbanization spectrum (Nansaior et al., 2011; Tesfamichael et al., 2020). Studies analyzed at the aggregated level indicate that Gross Domestic Product, level of industrialization, population, and urbanization financial development, price, income, and trade openness play a key role in influencing energy consumption (Borozan, 2018; Kwakwa, 2018; Mawia, 2013; Aboagye, 2017). This study also acknowledges a plethora of empirical studies focusing on household energy consumption ranging from economic, socio-demographic, political economy, and physical characteristics. Burger et al. (2015) and Wallis et al. (2016) imply that education level, age group, family composition, and the number of adolescent children influence households' energy consumption. McLoughlin et al. (2012) accentuated that income, the price of electricity, and energy technology are key factors that influence energy consumption.

Similarly, Jones et al. (2015) indicates that the dwelling's physical characteristics, including; dwelling age, number of rooms, appliance ownership, and total floor area, have a significant positive effect. The political economy also plays a crucial role in advancing the transition among countries. Governance defines the role of different actors, interests, and institutions in promoting competing energy pathways and associated technologies (Newell & Phillips, 2016). Ockwell et al. (2017) point out that Key actors in the sector have the responsibility, authority, and capacity to address energy poverty and transformations toward a low carbon economy in a pro-poor way. However, vested interests and systems of political incentives that frustrate governance reform programs limit public institutions' performance and disincentivize private investment (Desai (2011). Therefore, governments can offer supportive as well as disabling roles with respect to energy transitions and transformations. This reflects differences within and between regions across several dimensions (Ockwell et al., 2017).

Scholars also apply psychology and behavioral science disciplines to predict households' perceptions, habits, and attitudes on the consumption of various energy sources (Abrahamse et al., 2005; Fell and King, 2012; Huijts et al., 2012). Maréchal (2009) alludes that the potential persistence of habits lies in substantial short-term rewards that override long-term benefits. Such approaches are vital in designing more cost-effective and mass-scalable behavioral solutions to encourage the utilization of clean energy sources (Frederiks et al., 2015). The behavioral aspects of energy consumption divert from traditional economic theory's dogmas and postulate that decision-making and energy use behavior is purely a rational choice (Simon, 1957). Whereby, a household where an objectively weighs up the costs and benefits of all energy alternatives before choosing the optimal course of action (Frederiks et al., 2015). Similarly, Fuerst et al. (2020) investigates drivers of energy consumption and reveals that household socio-economic characteristics such as; household size, annual gross household income, primary employment status, and household composition are key predictor factors.

In recent years, energy consumption patterns across rural/urban divide have received extensive attention as energy profiles, including; energy consumption, expenditure, and choice, greatly vary along the urbanization spectrum (Adkins et al., 2012; Chun-sheng et al., 2012; Lekveishvili, 2019; Miah et al., 2011). The concept of the energy transition at the household level has expanded to reflect multifaceted aspects of transition, including socio-demographic characteristics, behavioral elements, household spending priorities, among other household characteristics (Alem et al., 2016; Farsi & Filippini, 2007; Mottaleb et al., 2017, 2017; Rahut et al., 2017). Further, studies give a more in-depth breakdown of insights on urban transition inequalities in informal settlements and slums (Karekezi et al., 2008; Lesirma, 2016; Yonemitsu et al., 2004). Concerning this, studies show that people living in more urbanized areas tend to use energy sources that are more convenient, cleaner, and more efficient (Cai & Jiang, 2008). Similarly, Pohekar et al. (2005) and Dhingra et al. (2008) illustrated that households shift from fuelwood to modern types of energy due to a rapid increase in urbanization. A recent study by Osano et al. (2020) looks at energy use patterns among urban and rural communities in four different Counties in Kenya, namely Narok, Voi, Mombasa, and Bomet. The study observed that urban residents used slightly more clean and non-solid fuels for cooking, such as LPG and kerosene, while rural households heavily relied on firewood and charcoal. Other studies examine temporal variations whereby household energy consumption is presumed to vary by season (Valenzuela et al., 2014). De Almeida et al. (2011) indicated that households utilized heating or cooling appliances for thermal comfort and impacting the energy consumption level. However, seasonal variations in energy consumption may not be necessary for countries that do not experience extreme climatic conditions (Valenzuela et al., 2014).

Besides energy consumption patterns for clean and non-clean energy sources among households, the studies also apply a spatial lens to conceptualize energy consumption. Studies are burgeoning on the international focus on the geographies of energy transitions (Calvert, 2016). Economic geography's discourse mainly inspires this by advancing spatial decision-support for energy planning (Calvert, 2016). As revealed from above, energy transition discourse needs to shift the focus on household decision-making on energy consumption to addressing inequalities from a spatial perspective. For instance, Mashhoodi et al., 2018 applied a new approach to unveil the local determinants of household gas and electricity consumption with an underlying assumption that factors influencing energy poverty are spatially heterogeneous. Bridge et al. (2013) introduced the concepts of location, landscape, territoriality, spatial differentiation, scaling, and spatial embeddedness to elaborate on the role of spaces and places in the transition to a low-carbon economy. The study indicated that overdependence on non-clean energy sources leads to low carbon transition and spatial differentiation, and uneven development. Therefore, the call for managing transitions that reduce inequalities rather than widen them emerges as a policy challenge (Bridge et al., 2013).

Mashhoodi and van Timmeren (2018) introduce the neglected spatial dimension in assessing households' homogeneity and heterogeneity of energy poverty. The study shows that the impact of energy poverty determinants could be spatially homogeneous (national-level determinants) or heterogeneous (neighborhood-specific determinants). Similarly, Ambole et al. (2019) demonstrate that household energy transitions' multi-perspective lens looks at the historical, socio-spatial political, and cultural issues that form energy geographies. Davies et al. (2018) show the spatial realities of energy transition and connection to urban governance's political dynamics in South Africa.

The effects of energy prices and transportation on household energy consumption vary across the geographical space. The concept of geographic variation also features prominently in the study by Raven (2012) by proposing the extension of transition frameworks to acknowledge the impact of spatial heterogeneity in endowments and circumstances on transitions. Further, Balta-Ozkan et al. (2015) emphasize that demographic structures are not spatially homogenous are likely to affect how receptive regions are to certain low-carbon technologies. Accessibility to energy sources influences inter-regional differences in the consumption of various sources as regional natural resource access impacts the spatial pattern of household energy consumption. Therefore, there is a need to consider differences in spatial elements and take appropriate measures when developing energy consumption transition guiding policies (Jiang et al., 2019).

Notwithstanding the plentiful empirical evidence presented, knowledge gaps remain evident on spatial dimensions of energy consumption. Previous studies attempting to explain energy consumption at the household level mainly focus on household socio-demographic characteristics, household composition, dwelling unit characteristics. They also focus on consumption patterns in the urban/rural divide with little emphasis on spatial aspects of households' energy consumption at sub-national levels (citations needed). On the other hand, Coenen et al. (2012) point out that the spatial dimension of energy consumption is mostly unexplored, and knowledge gaps exist, especially in an attempt to establish the links between household energy consumption from a regional spatial perspective (Coenen et al., 2020). Besides, the vast majority of previous studies on household energy consumption presumed that factors influencing household energy consumption are similar in each location regardless of the location-specific circumstances.

Regional and local situations can generate substantial impacts on transition pathways whereby transition analyses have often neglected where transitions take place, and the spatial configurations and dynamics of the networks within which transitions evolve (Coenen et al., 2012). Studies touching on geographical disparities of energy consumption are minimal as studies predominantly emphasize inequalities between socio-demographic and socio-economic groups. Notably, Robinson et al. (2018) dispute that spatially homogeneous factors can explain energy deprivation across all areas of a city, country, region, or continent. They affirm the importance of capturing socio-spatial indicators in examining energy poverty disparities between different geographical contexts. In the past, this has led to inappropriate or economically infeasible energy planning. It has often failed to achieve local acceptance for lack of incorporating the spatial planning aspect (Cader et al., 2018). The anticipated future demand and universal access make it essential to consider what drives electricity consumption, any observable spatial or regional consumption patterns, and the barriers to electricity access, for which residential energy use data are particularly critical (Olaniyan et al., 2018). A similar perspective is put forward by Nazmiye et al. (2015) by suggesting that a regional perspective to energy policy and research by identifying regions as the spatial unit of analysis for monitoring the progress both within and between regions.

Spatial autocorrelation was defined years back, but application was limited due to computation incapacity and software unavailability (Anselin & Rey, 1997). Even with the recent development application of spatial analysis, such as global and local Moran I test, transitioning to modern sources has remained unexploited. Previous studies implicitly presumed that geographical aspects have an unvarying impact on consumption patterns for various energy sources (Zaharia et al., 2019). This paper opens the way for a more systematic exploration of regional variations in energy consumption patterns at the household level. The study is motivated by the need to account for spatial and geographical differences as a critical aspect in the understanding the household's role in the transition and to describe how unique regional and local situations can generate substantial impacts on energy transition pathways. The knowledge gap is eminent in the current body of literature on spatial variations in household energy consumption. This study bridges this gap by investigating the location-specific effect of household energy consumption levels in Kenya.

2.1. Limitations of the study

The study appreciates the phenomenon of energy stacking, which refers to the parallel use of multiple fuels for various purposes such as cooking, lighting, and heating; hence, reported energy consumption levels were all-inclusive. However, according to the KNBS(2016) report, grid-electricity is mainly used for lighting; LPG, wood fuel, and charcoal are primarily used for cooking purposes; kerosene is used for lighting by the majority and cooking among the urban poor.

3. Material and methods

3.1. Study area

The study was carried out across counties in Kenya which comprises diverse energy and geographical representation (Figure 1). Counties are uniquely endowed with varied climatic conditions, socioeconomic development, population density, natural and indigenous energy resources, and energy consumption patterns. Oceans and mangrove forests dominate the southern part, which has

Figure 1. Map of Kenya and the 47 counties. Source: Author

a coastline on the Indian Ocean. In contrast, the mainland has broad plains and numerous hills comprised of a heterogeneous mosaic of vegetation, including grassland, scrubs, exotic plantations, and forests. The central region is generally cooler than the rest of Kenya due to its high altitude and occupied by two major forest eco-systems, namely Aberdare ranges and Mount Kenya – the country's highest point at 5,200 m above sea level. The region has other isolated forested hills and experiences equatorial rainfall due to its location within Kenya's highland zone with more precipitation levels than other areas. Mount Kenya forest is one of the major forests that has been heavily exploited for timber and firewood for domestic use over the past years. The western part has distinct physiographic features, including Mount Elgon, Kenya's second-highest mountain, and Kakamega rainforest, which experiences heavy rainfall all year round. The eastern region is endowed with various natural resources that range from natural forests, numerous bushlands, woodlands, grasslands, mountains, among other vegetation covers. The northern region consists of a series of arid-and semi-arid plains and primarily inhabited by nomadic pastoralist communities, making up 80 per cent of the population. Among the 47 Counties, Nairobi County hosts the capital city while Mombasa County hosts the second largest City and Kisumu County is the third-largest city. The Nairobi metropolitan area Counties include Kiambu, Machakos, Kajiado, and Murang' a which are comprised of a significant proportion of the urban and peri-urban population (Kenya National Bureau of Statistics (KNBS), 2019).

3.2. Data sources

The study utilized data from the Kenya Integrated Household Budget Survey (KIHBS), 2015/2016, conducted by the Kenya Bureau of statistics. This was the first periodic large-scale multipurpose cross-sectional population-based survey since the inception of County governments in Kenya. The data provided the energy data across the 47 counties and in urban and rural areas. Notably, Nairobi and Mombasa Counties, which hosts the capital city and second-largest city, were defined as entirely urban. Other Counties had a combined urban and rural populace. In this study, a household was identified as the unit of analysis for this study. It relays detailed and comprehensive data on energy consumption with relevant attribute data for spatial units of interest. Besides, data pass credibility and reliability test in capturing energy-related information and other variables of interest. Spatial data, which includes shapefiles for counties in Kenya, was sourced from openAfrica.

3.3. Data preparation

The initial step involved merging household energy consumption data and County data into a single dataset for easier management, transformation, computation, and conversion. The second step involved converting energy consumption for all sources to standard energy unit; Megajoules (MJ) represents the equivalency conversion factor for total final energy consumption. (International Energy Agency, 2020b). The conversion was as follows; electricity 3.6 MJ kWh_1, LPG, 49 MJ/kg, kerosene 36.6 MJ dm_3, wood-fuel (collected and purchased) (dry basis) 16 MJ/kg, and charcoal at 29 MJ/kg.

3.4. Data analysis

3.4.1. Spatial analysis

The initial analysis entailed deriving the attribute data for the quantities of energy consumed from various sources across the 47 counties for spatial join. The study utilized QGIS (v3.8.0) to link the attribute and spatial data to map the variations in consumption of various energy sources. Geographical Information Systems (GIS) tools for Exploratory Spatial Data Analysis (ESDA) were used to explore the spatial variations and autocorrelations in energy consumption across the 47 Counties. GeoDa (v.1.14.0) was used to conduct Global Moran's I and LISA analyses using the Spatial

Autocorrelation (Univariate Moran's I) and the Local Indicator Spatial Association (LISA) (Univariate Local Moran's I) respectively.

The spatial statistical analysis progressed through four stages as follows:.

The first step involved spatial join of energy consumption attribute data to a shapefile that contains the geographical layout of counties in Kenya followed by deriving the spatial distribution maps on the level of consumption for various energy sources across counties.

The next stage entailed spatial autocorrelation analysis, to detect the spatial dependence on the consumption of various energy sources among Counties (Getis & Ord, 2010) and Anselin, 1995). This involved.

The construction of spatial weights referred to as the connectivity matrix for all the energy sources. Spatial weights classify the geographical units (counties) based on their degree of connectivity with one another to represent information on the neighborhood structure for each county. . This study employed first order Queen Contiguity weights approach which classifies geographical units as neighbours if they share a point or line boundary (Anselin & Arribas-Bel, 2013). A value of one was assigned to neighboring counties (i.e., shared a border) and a value of zero for counties that did not have a connection.

Global Moran's I is a measure spatial autocorrelation, which depicts whether there is an autocorrelation among all spatial features, location (counties), and feature values (consumption). Therefore, Global Moran's I test determines whether the level of consumption for various energy sources show spatial dependence (the tendency of the same variables measured in locations in proximity to be related).

Global autocorrelation is a simultaneous measurement of spatial autocorrelation for all the counties. The assumption for global test for autocorrelation is that the relationship between nearby or otherwise connected observations, in this case, consumption of various energy sources, remains the same across the counties, referred to as stationarity or structural stability. In this study, Global Moran's I was used to estimate the degree of spatial dependence and heterogeneity of energy consumption.

Global Moran's I index calculation is as follows:

$$\text{Moran's I} = \frac{N}{\sum_i \sum_j wij} \cdot \frac{\sum_i \sum_j wij(X - \bar{X})(X - \bar{X})}{\sum_i (Xi - \overline{X})^2} \tag{1}$$

Where *N is the total number of observations (polygons; Counties) and i and j represents different locations; Xi and Xj* are values of the variable in the *i* th and *j* th locations and $\bar{X}$ is the mean of the variable X;*wij* is a measure of spatial proximity for pairs *I* and *j*.

Interpretation of the Global Moran's I test results.

Global Moran's I test for autocorrelation is used to measures the tendency across all data points for higher (or lower) values that correlate more closely together in space with other higher (or lower) values than would be expected if the data points were drawn from a random distribution. The Global Moran's I tool is an inferential statistic, which means that the analysis results are interpreted within the null hypothesis's context. When the p-value returned by this tool is statistically significant, we reject the null hypothesis. For this study, the null hypothesis states that consumption of a particular energy source is randomly distributed among counties in Kenya, which means that spatial processes promoting the observed pattern of energy consumption is a random chance meaning that there is complete spatial randomness. Therefore, a significant ($p < 0.05$) and positive Moran's I suggest that values in County i tend to associate with values in County j, respectively. Negative Moran's I values would indicate that high values tend to associate with low values and vice versa. Random spatial distribution is shown when Moran's I is 0 indicative of no spatial autocorrelation. This illustrates that the domain of global Moran's I range between −1.0 (perfect dispersion) to 1.0 (perfect clustered) (Cliff et al., 1981), and the higher the Moran's I value, the stronger the spatial autocorrelation (Huo et al., 2012). However, the global test does not identify specific locations on a map where the measured autocorrelation is most pronounced and does not efficiently recognize the grouping of spatial patterns hence, the need for Local Moran I test.

Local Moran I Test; Local indicators of spatial association (LISA).
Unlike the global test, which indicates the overall clustering of energy consumption at a national level, Local Moran's statistic provides more detailed insights on the presence or absence of significant spatial clusters or outliers for each location in a dataset. For this study, Local Moran I is used in determining if energy consumption in a specific County is higher or lower than would be expected based on the global average or, in other words, to identify clusters where the consumption pattern runs counter to the overall spatial autocorrelation trends. Basically, cluster mapping augments significant locations with an indication of five types of spatial associations and outliers. High values (hotspots) in a high-value neighborhood- High-High[1] (HH) indicates a County with high consumption surrounded by Counties with high consumption; Low-Low[2] (cold spots) (LL) denotes that a County with low consumption surrounded by Counties with low consumption; Low-high (outlier) (LH) denotes a County with low consumption level surrounded by Counties with high consumption; High-low (Outlier) (HL) indicates a County with high consumption surrounded by Counties with low consumption and not significant are Counties with no statistically significant spatial autocorrelation (at $p < 0.05$).

Local Moran's I is fully developed by Anselin (1995) and its formation is shown in the following equation:

$$I_i = \frac{z_i}{\sum_i z_i^2} \times \overset{\circ}{z_i} \tag{2}$$

Where expresses the observation for region for a variable as a deviation from the mean, and the $\overset{\circ}{z_i}$ is the spatial lag for location$I$ obtained as:

$$Z_I = \sum_{j=1}^{n} w_{ij} z_j \tag{3}$$

Where z_i and $z_j$are the deviations from the mean, and w_{ij} is the weight defined for each of the neighboring spatial unit j of i under a definition of neighborhood n. LISA aggregation maps were used to present the spatial distribution of clustering among Counties.

In addition, LISA significance maps analyzed show counties with a significant local statistic, with the degree of significance reflected in increasingly darker shades of green. The maps start with $p < 0.05$ and show all the categories of significance with p-value is 0.001 as the smallest.

4. Results and discussion

4.1. Spatial exploratory analysis on energy consumption among Counties

4.1.1. Electricity

Spatial variations in the consumption of various energy sources are evident among Counties, as illustrated in the spatial distribution maps (Figures 2–7). Nairobi County and the adjacent counties, including Kajiado, Machakos, Kiambu, Murang'a, and Nakuru, record relatively higher consumption levels. A similar trend is seen in counties in the central region, such as Nyeri, Kirinyaga, Laikipia, and Embu. Besides, Kisumu County and counties in the South, such as Mombasa, Kilifi, Kwale, and Lamu, also have comparatively higher consumption levels. Similarly, the western region Counties including include Uasin Gishu and, Trans Nzoia, stands out with relatively higher electricity consumption. Counties with relatively high electricity consumption levels are deemed to have high penetration of the grid network a significant proportion of households connected to the grid, a higher proportion of the urban population and high population density (KNBS, 2016).

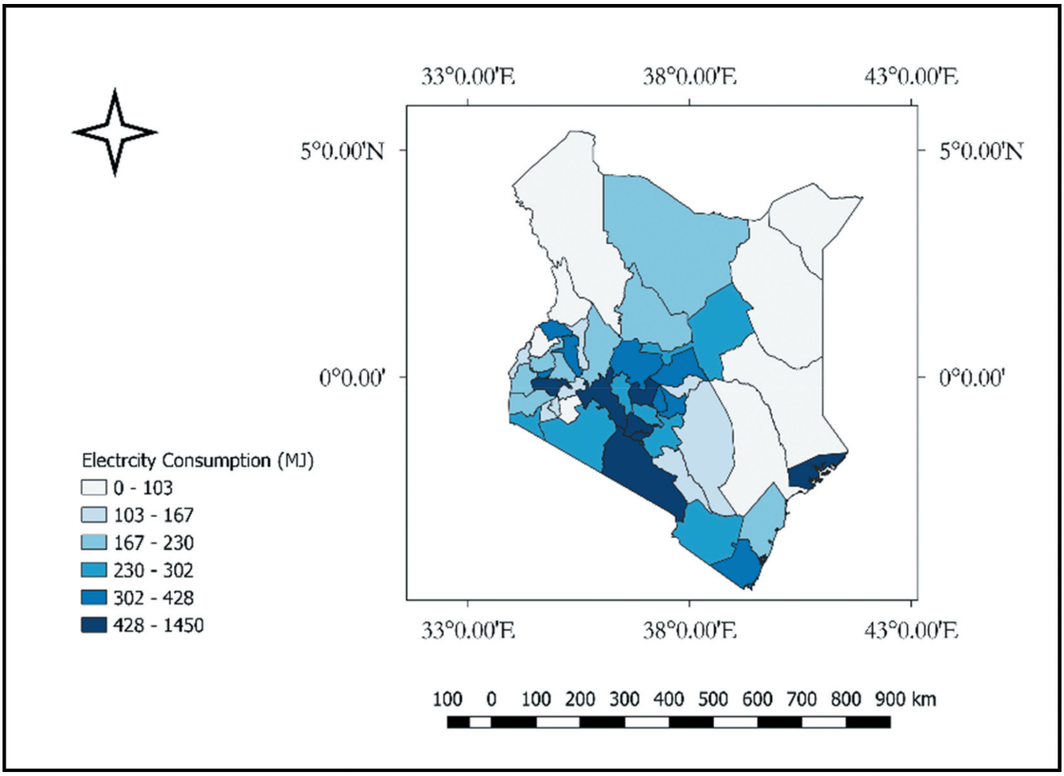

Figure 2. Spatial distribution of electricity consumption among Counties.

These observations concur with Blimpo and Cosgrove-Davies (2019) that a higher population density in urban areas reduces the per capita cost of grid electrification and increases the financial viability of the utilities due to higher demand for electricity as a result of higher incomes in cities (Taale & Kyeremeh, 2019; Zeyringer et al., 2015). Similarly, low electricity consumption levels registered in viable grid areas are attributable to financial constraints, little reverence for electricity use, and delay by power utilities in dispensing household connection services. For instance, a study conducted among 150 communities in western Kenya found that low uptake of grid electricity was among the relatively well-off households, averaging 6% for households (Lee et al., 2016).

On the contrary, Counties in the north eastern region (Marsabit, Wajir, Mandera), far northwest (Turkana, West Pokot, Elgeyo-Marakwet, Bomet), lower eastern (Tana-River) have considerably low levels of electricity consumption. In contrast, Counties in the South, which is coastal, have relatively high and moderate consumption levels. Counties with low consumption are closely linked to a high incidence of poverty and low purchase power for low-income households (KIHBS, 2015/16). The low consumption is evident in the northeast region since Counties are mainly off-grid and characterized by arid and semi-arid lands with highly dispersed populations, mostly practicing nomadic pastoralism (KIHBS, 2015/2016; ESMAP,). The sparse population and widely separated settlement clusters make grid extension infeasible. Besides grid electricification, other viable alternatives includes renewable energy mini-grids, or stand-alone systems as counties are endowed with vast energy resources, including solar and wind. According to the Kenya National Bureau of Statistics (KNBS) (2019), most households in the off-grid areas use battery lamp/torch for lighting purposes. Kenya Electricity Sector Investment Prospectus defines a clear roadmap for increasing electricity access through mini-grid and solar photovoltaic projects in these off-grid Counties referred to as ‘underserved.’ In the next few years, it is expected a greater proportion of households will have access to electricity.

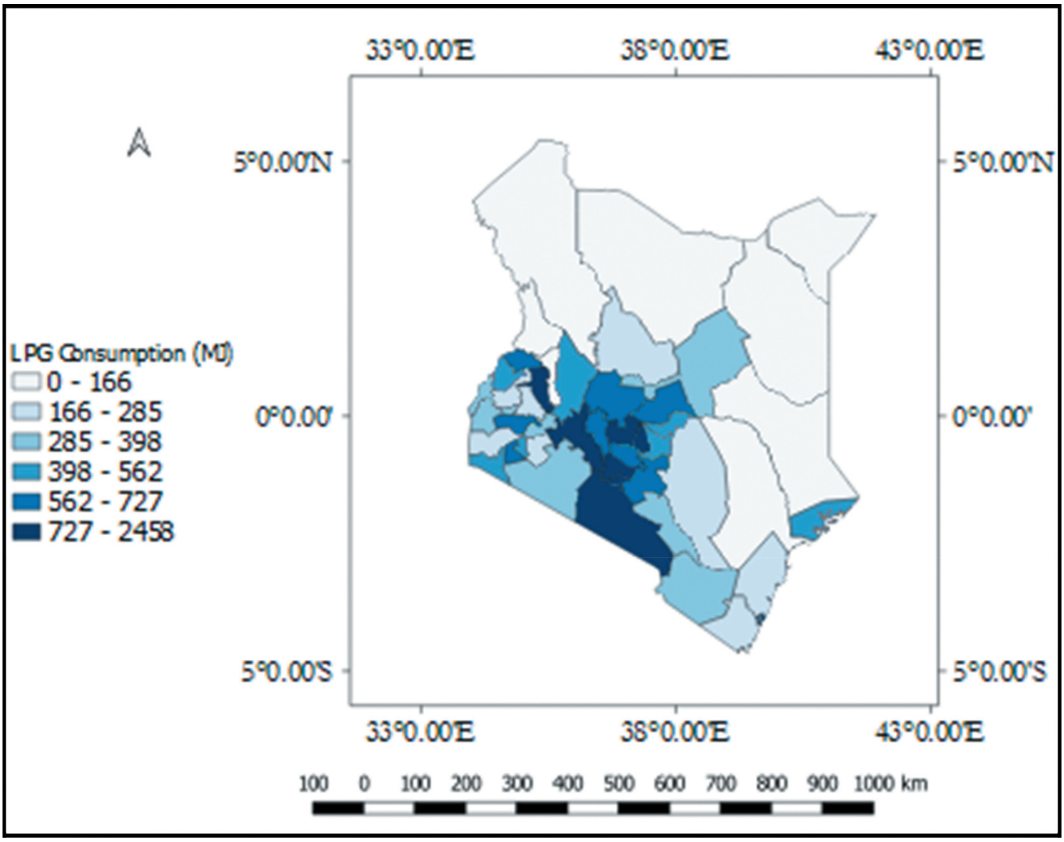

Figure 3. Spatial distribution of LPG consumption among Counties.

It is also worth noting that 83per cent of the Counties have above the specified subsistence consumption of 108 MJ (30 kWh) per month (ESMAP). More than 64% of counties are below the national average of 306 MJ, and only 8.5% were above the average monthly household electricity consumption in Sub-Saharan Africa of 720 MJ (200 kWh) (M. Blimpo et al., 2017). The low levels of consumption recorded indicate that electricity is mainly used for basic services such as lighting as opposed to productive benefits such as off-season farming, value-added agro-processing, and small businesses. Low levels of consumption also constrain the power utilities in recovering the power supply costs (Blimpo & Cosgrove-Davies, 2019). For instance, counties such as Machakos, Murang'a that have considerably high access levels (KIHBS 2015/16), consumption is reportedly below the national average. This scenario shows that uptake of electricity does not necessarily translate to high consumption or continuously used by the households. Energy access policies and strategies should also focus on improving the living standards of the people, enabling households to engage in improved or new income-generating activities, often referred to as productive use of energy, as opposed to consumptive use.

4.1.2. Liquified Petroleum Gas (LPG)

At the household level, LPG is mainly used for cooking (KNBS, 2016), and the consumption varies significantly among counties (Figure 3). Consumption is more intense in Nairobi County and the adjacent Counties, including Kajiado, Kiambu, Machakos, and Nakuru. The Counties in central (Kirinyaga, Nyandarua Laikipia and Nyeri), eastern (Meru, Embu, and Nyeri) and western (Trans-Nzoia, Kisii, and Uasin-Gishu), Kisumu and Mombasa Counties

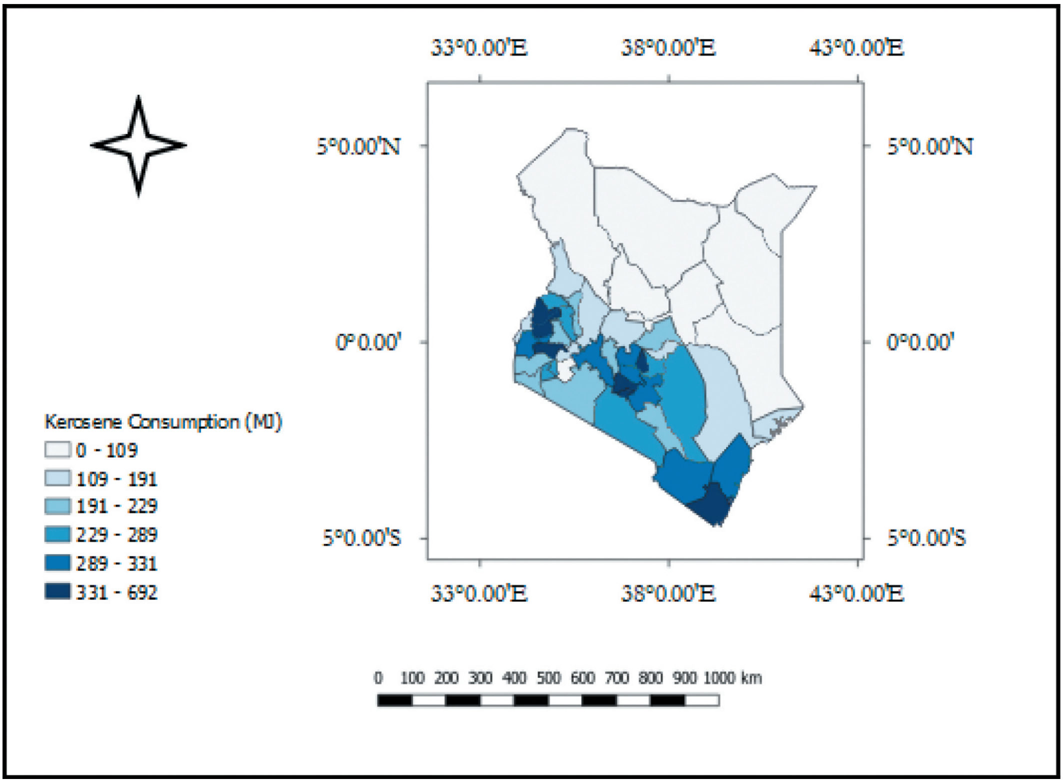

Figure 4. Spatial distribution of kerosene consumption among Counties.

have relatively high consumption which is above the national average of 542 MJ. The high levels of consumption are attributable to the predominance of a high proportion of urban and peri-urban households characterized by higher household income, proximity to the denser LPG retail networks as a result of high population density. For instance, Nairobi metropolitan Counties account for 60% of the LPG market, and the penetration rate for LPG is estimated at 40% (Ministry of Energy And Petroleum Kenya Petroleum Technical Assistance Project (KEPTAP), 2016).

In particular, Mombasa makes up 15% of the LPG market. The remaining market is distributed among major urban centers in Kenya like Nakuru, Kisumu, Eldoret, Nyeri, among others (Ministry of Energy And Petroleum Kenya Petroleum Technical Assistance Project (KEPTAP), 2016). More so, LPG storage and filling stations are concentrated in Nairobi and Mombasa, providing a lower-cost distribution foundation. On the contrary, the high cost of LPG in Kisumu and northern Counties are associated with the high cost of transporting cylinders over a long distance (Van den Berg, 2018).

The spatial patterns in the consumption of LPG are scattered across all regions. Low consumption is also in Counties characterized by a high proportion of the rural population with limited access to LPG distribution networks, especially in remote and hilly regions, and high poverty levels and availability of wood fuel resources (KIHBS 2015/16). It is worth noting that one of the major obstacles to the penetration of LPG in northern counties includes low population density, periodic migration patterns, and poor road infrastructure. The LPG distribution system's availability is crucial for enhancing LPG access, especially for households that can afford (World LPG Association (WLPGA)).

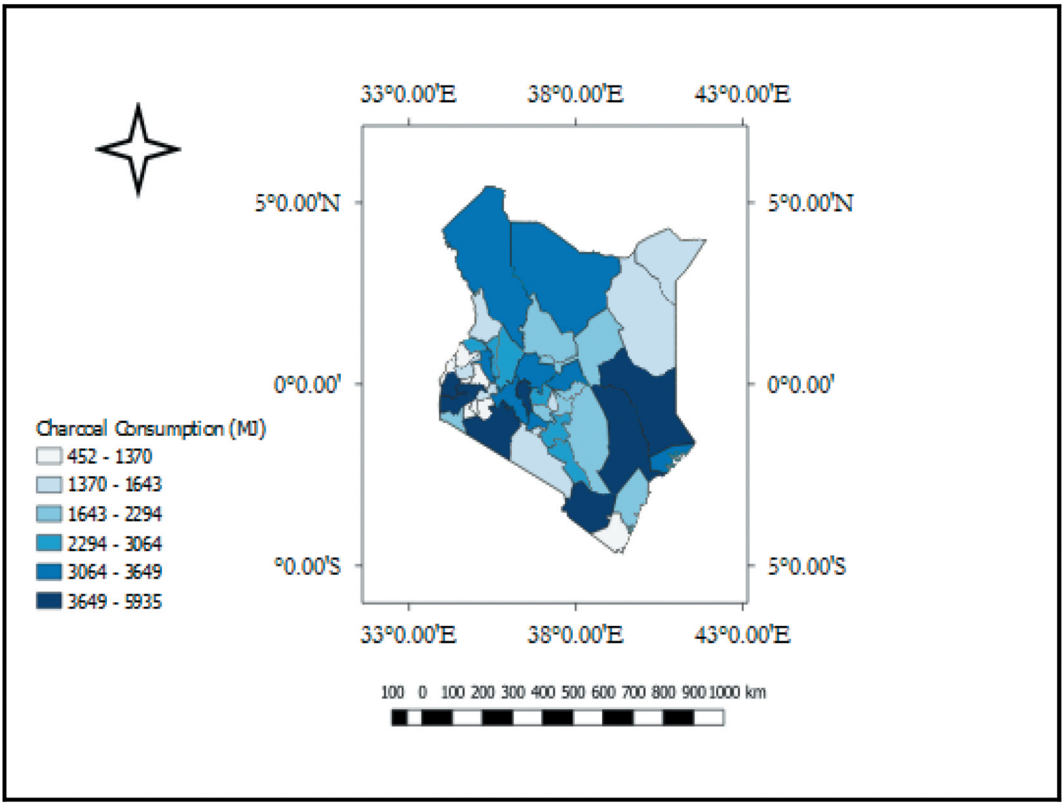

Figure 5. Spatial distribution of charcoal consumption among Counties.

Notably, low consumption is also associated with limited and scarce disposable income for the upfront cost of the cylinders and refilling. Therefore, many households use charcoal, kerosene, and fuelwood, which is acquired at a relatively lower price than LPG and available in small quantities, allowing for a degree of financial flexibility. Notably, LPG is expensive in Kenya, relative to the cost of competing fuels. For instance, LPG's annual fuel costs in Kenya are 2–3 times higher than equivalent yearly fuel costs for purchased charcoal or kerosene (Kenya National Bureau of Statistics (KNBS), 2019). Therefore, LPG's high price relative to traditional fuels reinforces some of the negative price perceptions. On the other hand, lack of consumer awareness and cultural preferences across counties hinder LPG's penetration due to safety concerns and perceived as more suitable for the wealthy. Some food tastes better when prepared using traditional fuels. (Energy Africa Renewable, 2014; Stanistreet et al., 2019; World LPG Association (WLPGA)). Evidence shows that lack of awareness of the negative impacts of smoke from solid fuels limits LPG adoption (Vigolo et al., 2018). Also, availability and no direct cost of solid fuels such as firewood and farm residue are more financially attractive for lower-income consumers.

Switching to LPG is considered a vital step in reducing the negative impacts of heavy reliance on inefficient, traditional biomass and a substitute for solid fuels and kerosene in the short term, and a promising transition fuel in the long run (Global Alliance for Clean Cookstoves, 2015). According to KIHBS, 2015/16, 13.4% of the households used LPG as the primary source for cooking, an improvement from 3.5% recorded (KIHBS 2005/06). However, only 10% of Kenya's top income quintile consume use LPG, compared with 45–85% in sub-Saharan Africa. (Van den Berg, 2018). This indicates that LPG's take-up lags the target of

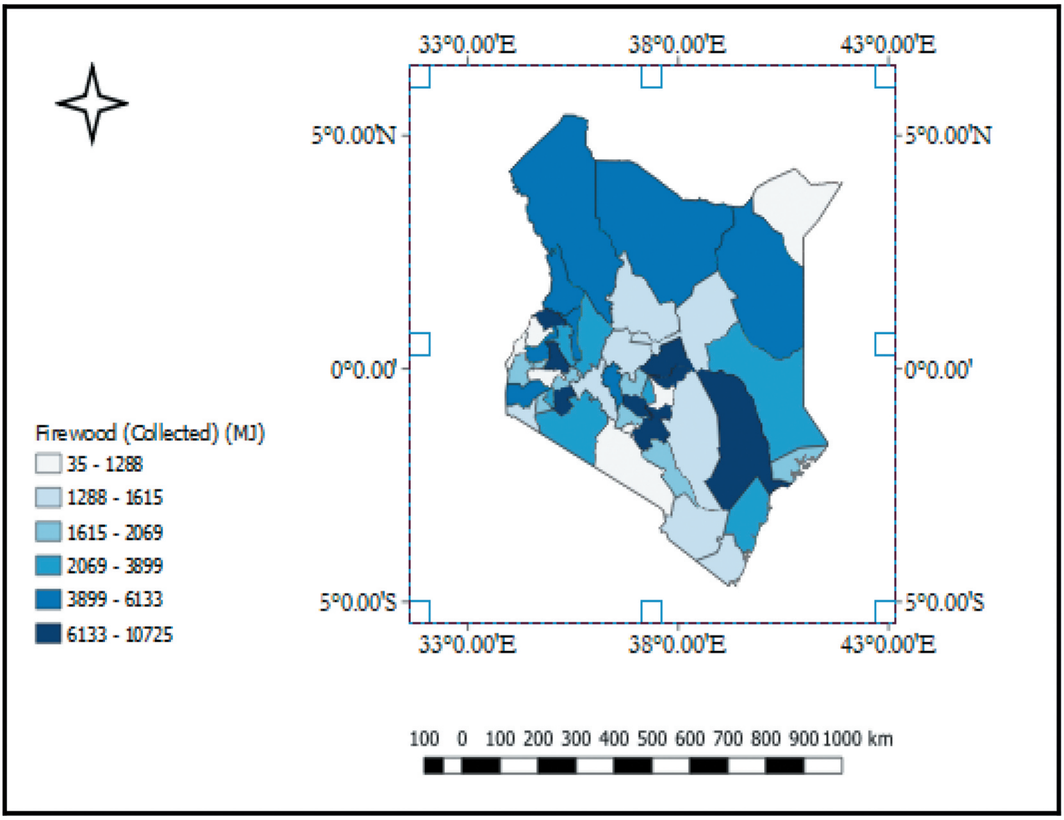

Figure 6. Spatial distribution of collected firewood consumption among Counties.

increasing penetration from 10% to 70% among the urban poor and rural households (Third Medium-Term Plan, 2018). It is worth noting that LPG's high calorific value in liquid form reduces transportation costs and makes it easier to handle than traditional fuels and coal. For instance, a 13- kilogram cylinder of LPG provides around 180 kWh of energy, and an equivalent of 25 kg of coal and 91 kg of firewood would be needed for the same amount of energy (World LPG Association (WLPGA)).

Therefore, there is a need to consider the spatial aspects that deter LPG's penetration across various Counties in Kenya. This includes; the level of development, population density, cost of transportation, socio-cultural, and literacy levels on use among Counties. Therefore, Counties need to identify the gaps in the LPG value chain LPG distribution, affordability, consumption, creating awareness and prioritizing key policy issues that are unique among the Counties.

4.1.3. Kerosene

Nairobi and the metropolitan area Counties, western and southern (coastal region) region Counties exhibit relatively higher kerosene consumption. Notably, about 21 Counties out of the 47 counties registered consumption levels above the national average of 241 MJ. Nairobi, Kakamega, Mombasa, Bungoma Kiambu, and Kisumu Counties lead in Kerosene consumption (Figure 4). On the contrary, Counties in the north, including Mandera, Marsabit, Turkana, Garissa, and Wajir, exhibit comparatively low consumption levels of below 30 MJ. This coincides with the KIHBS 2015/16 report on access patterns whereby less than

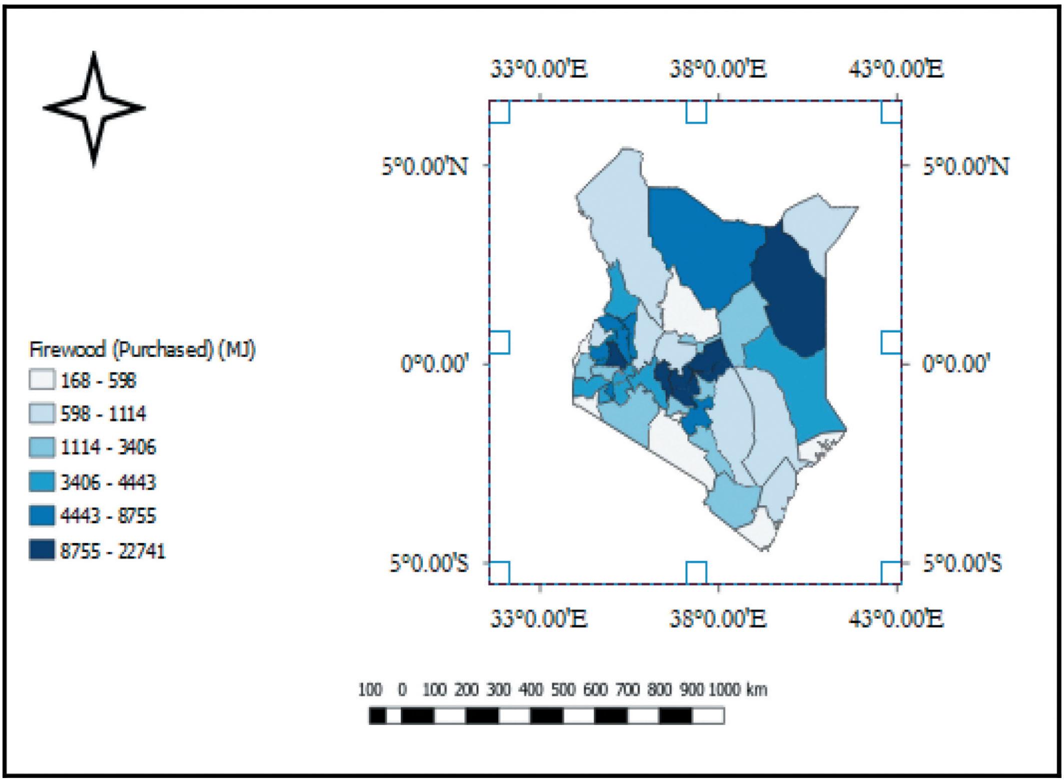

Figure 7. Spatial distribution of purchased firewood consumption across Counties.

1.0% of households in northern Counties, including Wajir, Marsabit, Mandera, Garissa, used kerosene as the primary sources for cooking and lighting.

Notably, Counties that registered high consumption of kerosene mainly comprise a high proportion of the urban population, especially among the urban poor as it is currently the lowest cost of cooking fuel in urban Kenya. Kerosene is also used by and dominant rural populace as it is widely available in most neighborhoods across Counties (Dalberg, 2018).

Kerosene is a supplementary fuel for lighting and cooking in rural areas with no electricity supply and limited LPG penetration in urban areas (World Health Organization, 2018). While kerosene is considered a modern or transitional fuel and makes a significant contribution to the household's energy mix, its use is linked to carcinogenic properties; hence deemed as harmful to human health (IEA, 2016). Evidence points out that besides safety risks such as poisoning and burns, kerosene emits health-damaging pollutants (particulate matter, carbon monoxide, and formaldehyde) that have been shown to impair lung function, increase infectious illnesses (for example, tuberculosis), and cancer risk (International Energy Agency , 2014). This is of great concern as roughly 35.2% and 14% of households use kerosene as the primary source for lighting and cooking (KIHBS, 2015/16). This indicates that kerosene has a large consumer base, leveraging as a potential market for other clean energy alternatives.

4.1.4. Charcoal

The consumption of charcoal is relatively high among Counties. Charcoal consumption is more pronounced in Garissa and Tana- River Counties, which are in the lower eastern region. In the western region, Kisumu, Siaya, and Homa Bay register high consumption. In addition, Nyandarua and Nakuru Counties led the central region and Taita-Taveta and Lamu in the coastal region (Figure 5). Charcoal is considered a non-clean energy source; however, most households rely on it for their cooking needs and act as a substitute for LPG and kerosene KIHBS, 2015/2016 and Sepp, 2014). Some of the Counties with high consumption, such as Tana-River, Lamu, and Taita-Taveta, also were purported as the most top producers and a large mass of small- and large-scale traders distributing to Counties such Malindi, Mombasa, and Nairobi among others. The high production of charcoal is partly owned by the dominance of tree species such as Prosobis and Juliflora used for burning charcoal. This indicates the type and amounts of energy consumed by households are closely associated with ease of access and the availability of a source of energy across Counties. Following the moratorium imposed on the logging of forest products in 2018, charcoal production will decrease significantly; hence, higher pricing will stand competitive to cleaner sources. Charcoal is a major poverty premium as the cost of buying charcoal in 4 kg tin is 20–30% is costly compared to buying in a 40 kg bag (Dalberg, 2018). Besides, using charcoal for cooking and heating comes at a lower upfront cost than biogas (IEA, 2020b). According to IEA (2020b), charcoal will remain essential for cooking for the next two to three decades. Therefore, as the country transitions to clean energy sources as a short-term measure, there is a need to deploy more efficient biomass-stoves in the transition process, especially among Counties dominating charcoal consumption.

4.1.5. Firewood: collected and purchased

Firewood still takes a significant share of the household energy mix in most of the Counties. Firewood consumed in Kenya is either purchased from informal vendors or collected from the forest and shrubs at no direct costs. In this context, the study considered the two means of acquiring firewood as independent in unveiling the spatial differentiation among the Counties.

Collected firewood concentrated was high in the eastern, northern, and western Counties. Meru and Tharaka-Nithi Counties are leading in the east region with consumption levels standing at 10,725.3MJ and 10,361.0 MJ, respectively (Figure 6). These Counties record-high consumption due to their proximity to forests and an abundance of planted trees making firewood freely available. This concurs with Li and Yao (2009) that natural resources in a region impact the type of energy consumed by households.

Notably, high consumption witnessed in Machakos County, which is in the Nairobi metropolitan area, is attributable to the dominant rural population and firewood availability. In the coastal region, Tana River County, Trans Nzoia, Nandi, and Bomet Counties in the western part also registered a relatively higher consumption of collected firewood collected. The use of freely acquired fuel acts as a barrier to cleaner sources as there is no associated direct cost. In this light, energy access programs should incorporate aspects of creating awareness on the benefits of transitioning to cleaner fuels among the communities and provide subsidies and incentives for cleaner fuels.

Similarly, purchased firewood significantly contributed to the household energy consumption mix, especially in the northern, eastern central, and western Counties. In the north, Wajir and Marsabit Counties in the north revealed high consumption while Nyandarua, Kirinyaga, and Murang'a Counties were leading in the central region. Nandi, Uasin Gishu, Trans-Nzoia, Kakamega, and Nyamira Counties also took the lead in the western part. The observation was also similar for Meru and Tharaka-Nithi Counties, which were also leading in the upper eastern region (Figure 7). Notably, Counties with a comparatively higher proportion of the urban households exhibit low consumption of both purchased and collected firewood. Therefore, Counties using firewood have an abundant biomass resource, useful in producing biogas as a cleaner alternative energy source.

4.1.6. Observed County-level Spatial Patterns of Household Energy Consumption

Overall, the consumption of various energy sources varies among Counties. Counties with higher consumption levels have a lower incidence of poverty dispersed populations and a high proportion of the urban population. On the other hand, high dependency on non-clean fuels tends to be more pervasive around dominant rural Counties and urban poor. Charcoal and kerosene present an asymmetric pattern with urban and rural dominated Counties exhibiting almost similar consumption levels. Overall non-clean sources, including purchased firewood, collected firewood, and charcoal registered the higher average consumption of 4,606.26MJ, 3,322.25MJ, and 2,525.22MJ, respectively. For cleaner sources, LPG and electricity stood at 5,19.44 MJ and 306.44 MJ, respectively, while kerosene was the lowest at 214.45 MJ.

4.2. Spatial autocorrelation analysis: Global Moran (1) Index

As illustrated in the previous section, substantial degree of spatial variation in consumption of various energy sources is evident across counties. However, there is a need to understand whether the observed patterns are random in nature or have a component of spatial dependency. This explains whether the consumption level observed across counties have a spatial inference. Spatial autocorrelation analysis was conducted using Global Moran' s-I and LISA. The Global Moran (I) global index values for all energy sources, as illustrated in (Table 1) are greater than zero, indicative of spatial autocorrelation among the 47 Counties. The same is validated by looking at the p values, which revealed significant positive spatial autocorrelations for all energy sources at (<0.05) significance level. This implies that the level of energy consumption in a county is associated with consumption levels of the neighboring Counties. The Moran's I index was much lower for charcoal, collected firewood, and electricity, which is indicative of a weaker clustering.

4.3. Spatial autocorrelation analysis: Local Indicators for Spatial Association (LISA)

The results of the Global Moran I index are limited to the overall spatial autocorrelation in the consumption of various energy sources among the 47 Counties. The results however do not indicate clustering patterns; hot spots, cold spots, and outliers. Therefore, the Local Moran (1) Index is used to detect clustering among the counties. Such an analysis gives more insights into the spatial variations on the consumption of various energy sources, which is critical in the formulation of energy policies that seek to reduce regional disparities in the consumption of clean energy sources at the household level.

As presented in Figures 8–13, LISA analysis identifies counties of High-High clustering (red), which signifies Counties with spatial clustering of high consumption (hot spots) and Low-Low clustering (Blue) means counties with spatial clustering of low consumption (cold spots). The

Table 1. Global Moran (1) Index and significance test for mean energy consumption for various sources.

Energy source	Global Moran's I index	p-valor/value
Electricity	0.05	0.05*
LPG	0.50	0.05*
Kerosene	0.21	0.05*
Charcoal	0.01	0.05*
Firewood (collected)	0.07	0.05*
Firewood (purchased)	0.60	0.05*

*statistically significant at the 5% (p ≤ 0.05) probability level.

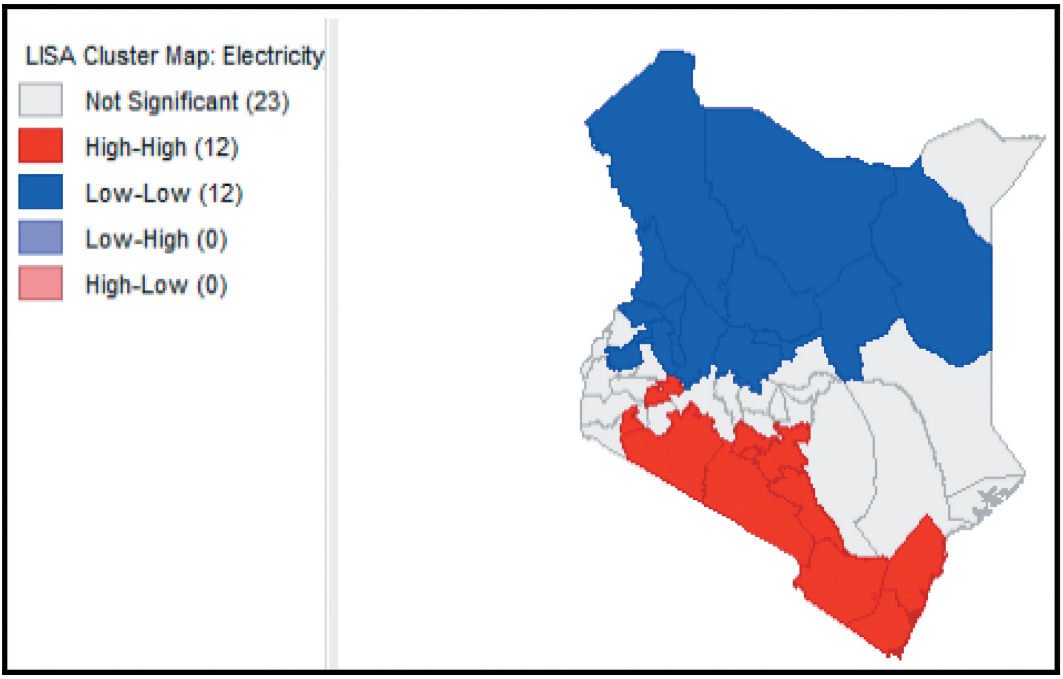

Figure 8. LISA cluster map on the consumption of electricity among Counties.

above mentioning clustering show statistically significant positive spatial autocorrelation, that is, regions surrounded by counties with similar values. High-Low (pink) and Low-High (pale blue) signify counties that are spatial outliers. These areas show statistically significant negative spatial autocorrelation, that is, Counties surrounded by Counties with different Consumption levels for an energy source. Lastly, Counties with gray clusters indicate no significant autocorrelation.

Regarding electricity LISA maps (Figure 8), 24 Counties contributed significantly to electricity consumption while 23 Counties had a non-significant association with electricity consumption. Specifically, counties in the south, south-western, and central regions were hot spots with high-high clustering. The hot spot counties in electricity consumption include Nairobi, Kajiado, Murang' a, Kiambu, Nakuru, Machakos, and Makueni. The high consumption of electricity in these Counties is linked to urbanization, which is associated with improved access and intensified electricity consumption (Mbaka et al., 2019). Counties in the south (coastal), including Mombasa, Kilifi, Kwale, and Taita-Taveta, which host popular tourist destinations sites, revealed high-high clustering. Besides the higher urban population, it is attributable to intensive electricity use in these Counties as they host holiday homes (Marunda et al., 2013). Contrastingly, counties in the north-eastern and north-western regions, which are mainly off-grid, exhibit low-low clustering due to the low penetration of grid-connected electricity.

LPG consumption exhibits high-high, low-low, and high-low clustering (Figure 9). The hotspot Counties include; Kitui, Makueni, Kajiado, Machakos, Kiambu, Nakuru, Kericho, Kwale, Mombasa, Kilifi, and Tana-River. This implies that the Counties, as mentioned above, are surrounded by Counties with high consumption of LPG. More so, most of these Counties comprise a significant proportion of the urban population who use LPG as a primary source for cooking purposes (KIHBS, 2016/17). On the other hand, low-low clustering is concentrated in the northern and western Counties, including; Bungoma, Trans-Nzoia, West-Pokot, Turkana, Marsabit, Wajir, Isiolo, Samburu, and Baringo. Kisumu is the only high-low cluster, which indicates the high consumption of LPG in the County and low consumption in the neighboring Counties.

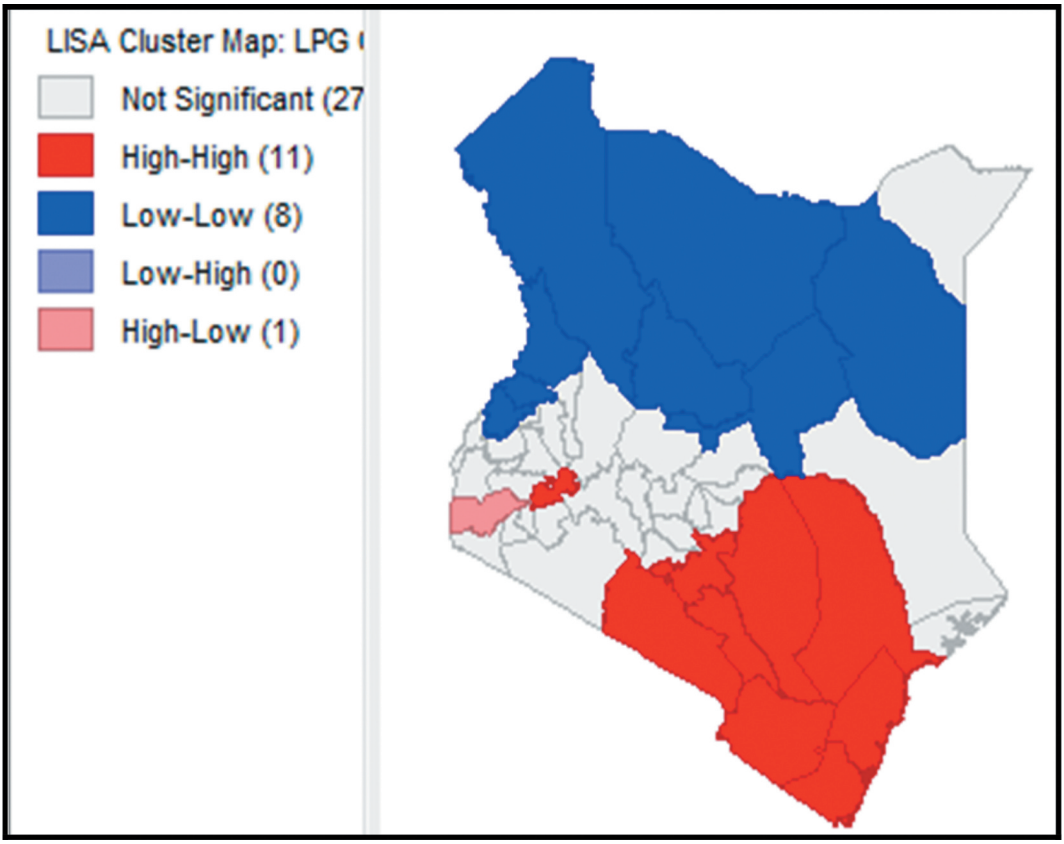

Figure 9. LISA cluster map on the consumption of LPG among Counties.

The consumption of kerosene reveals low-low, high-high, and low-high clustering patterns (Figure 10). Among other energy sources, kerosene has the highest number of low-high clustering, as evident in nine Counties. The low-high clustering was apparent in Makueni, Laikipia, Baringo, Nyeri, Narok, Bomet, Nyamira, Kericho, Kakamega. Counties, which is indicative of Counties with low consumption in neighborhood of high consumption Counties. The low-low clustering is prevalent in counties in the northern, eastern region, including Marsabit, Wajir, Mandera, Garissa, and Isiolo. On the other hand, kerosene's high-high clustering is evident in Kisumu, Kisii, Nakuru, and Uasin Gishu Counties. This indicates that these Counties high consumption and in the neighborhood of low Counties with low consumption.

For charcoal, high-high and low-low clustering was exhibited (Figure 11). The low-low clustering was concentrated in 12 Counties situated in northern and western regions. This was indicative of cold spots Counties for charcoal consumption. High-high clustering was also observed in 12 other Counties located in Nairobi and Metropolitan Counties and the coastal region indicative of hot spots of charcoal consumption.

The LISA analysis shows two low-low clustering of purchased firewood in northern and western Counties, including Wajir, Isiolo, Baringo, West-Pokot, Kwale, and Bungoma (Figure 12). High-high clustering was prevalent in 16 Counties, which are mainly situated in the western and southern regions. For the collected firewood collected, Turkana and Isiolo Counties showed high-high clustering (Figure 13). Notably, a high number of Counties; 41 out of 47 Counties had insignificant spatial clustering and were mainly located in the western region.

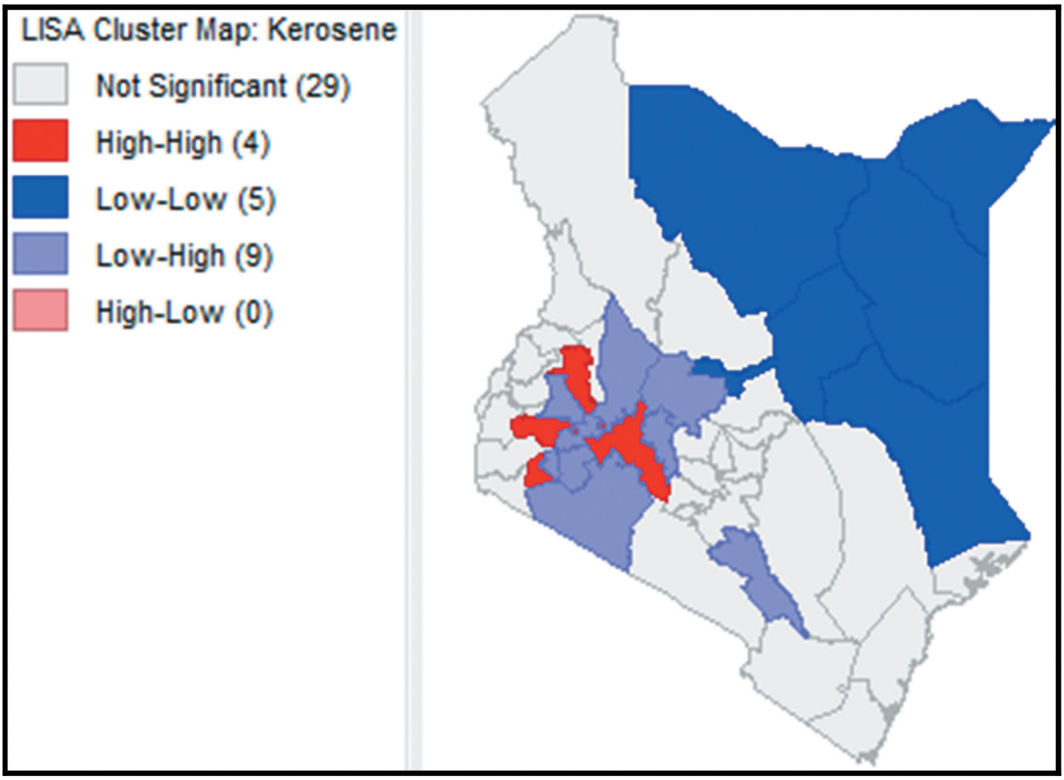

Figure 10. LISA cluster map on the consumption of kerosene among Counties.

Conclusively, LISA cluster maps reveal that various energy sources have diverse spatial clustering patterns, including the hot spots, cold spots, and outliers for the consumption of clean and non-clean energy sources among the 47 Counties. Generally, clean energy consumption tends to be much more tightly clustered around counties with higher urban populations. In contrast, non-cleaner sources' consumption is more pervasive in Counties with ease of access and availability of the energy resources, dispersed population, and poverty levels. Notably, few spatial outlier clusters were observed for various energy sources.

Further analysis established the locations with significant local Moran statistics (Figures 14–19). Discretized LISA cluster maps have different green (the corresponding p values; in the legend) and colorless for counties with insignificant LISA. Counties that observed clustering in electricity consumption had p-values of 0.1 and 1% (Figure 14). For instance, counties in the far north and southern parts recorded a significantly high level of clustering. This trend was also observed among the clustered counties in relation to LPG consumption (Figure 15). For kerosene consumption, more than half of clustered Counties recorded were significant at 5%, one County at 0.1%, and five counties at 0.1% (Figure 16). For the counties that exhibited clustering in charcoal consumption majority that was significant at 0.1 and 1% were mainly in the north-eastern and southern regions, respectively (Figure 17). Firewood purchased clustered Counties reported as a significant level of 1 and 5% (Figure 18). In comparison, firewood collected only showed significance at 1% in only one County while the majority significant at 5%, with most the Counties appearing in the northern region (Figure 19).

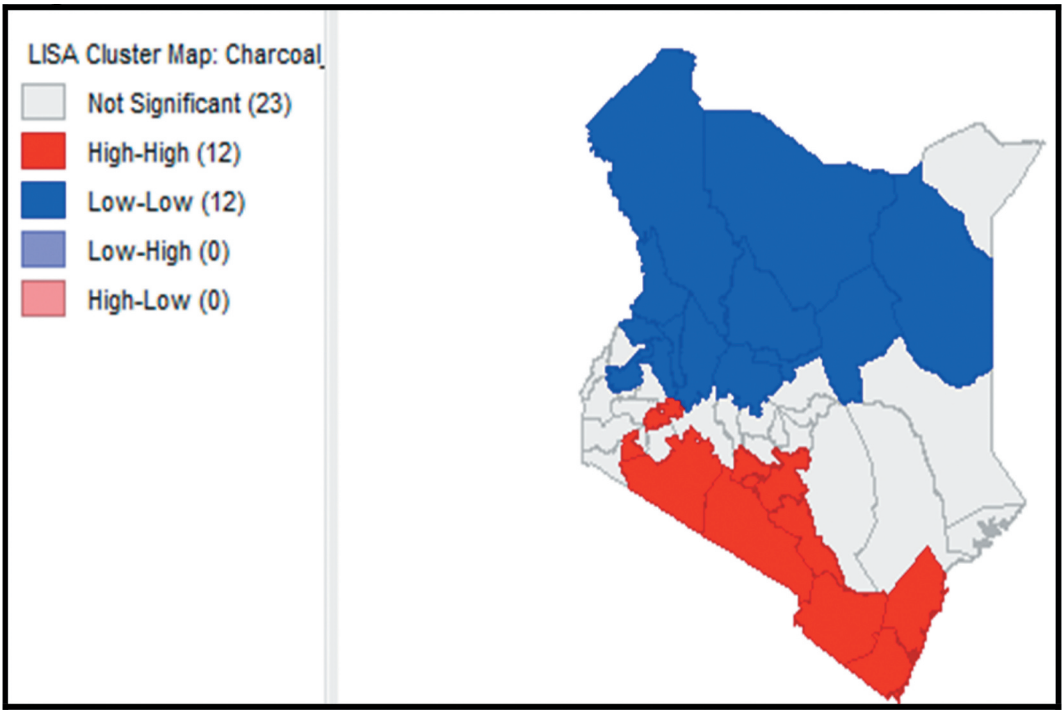

Figure 11. LISA cluster map on the consumption of charcoal among Counties.

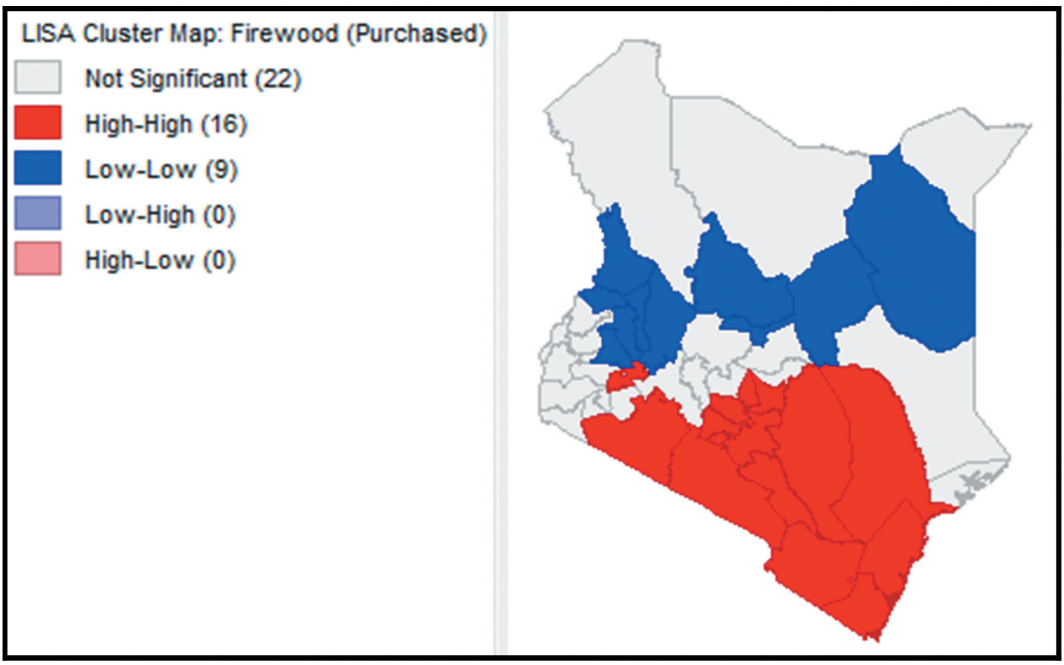

Figure 12. LISA cluster map on the consumption of firewood (purchased) among Counties.

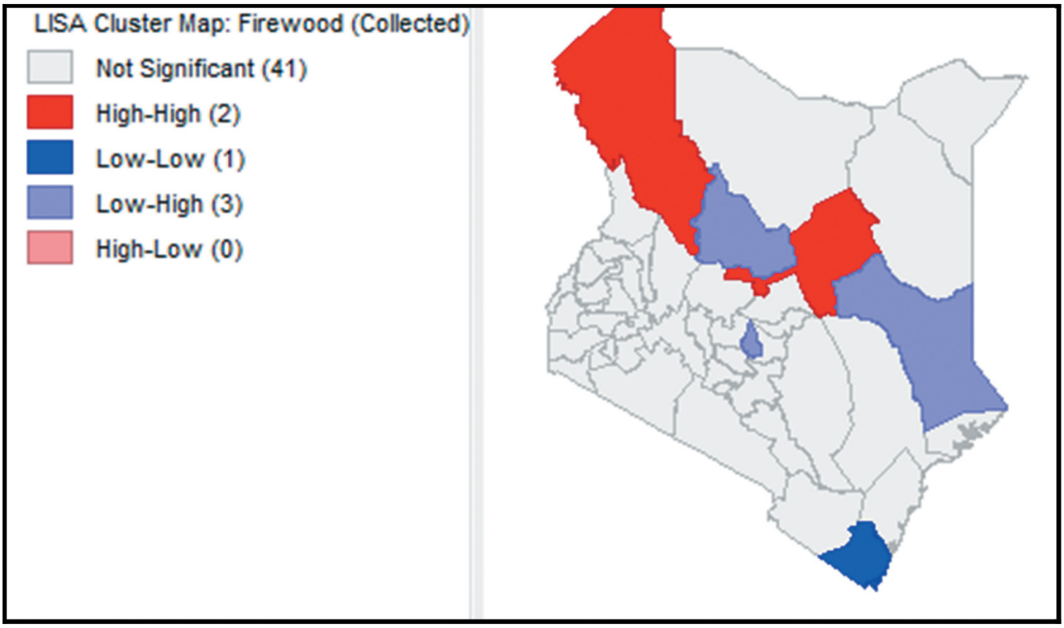

Figure 13. LISA cluster map on the consumption of firewood (collected) among Counties.

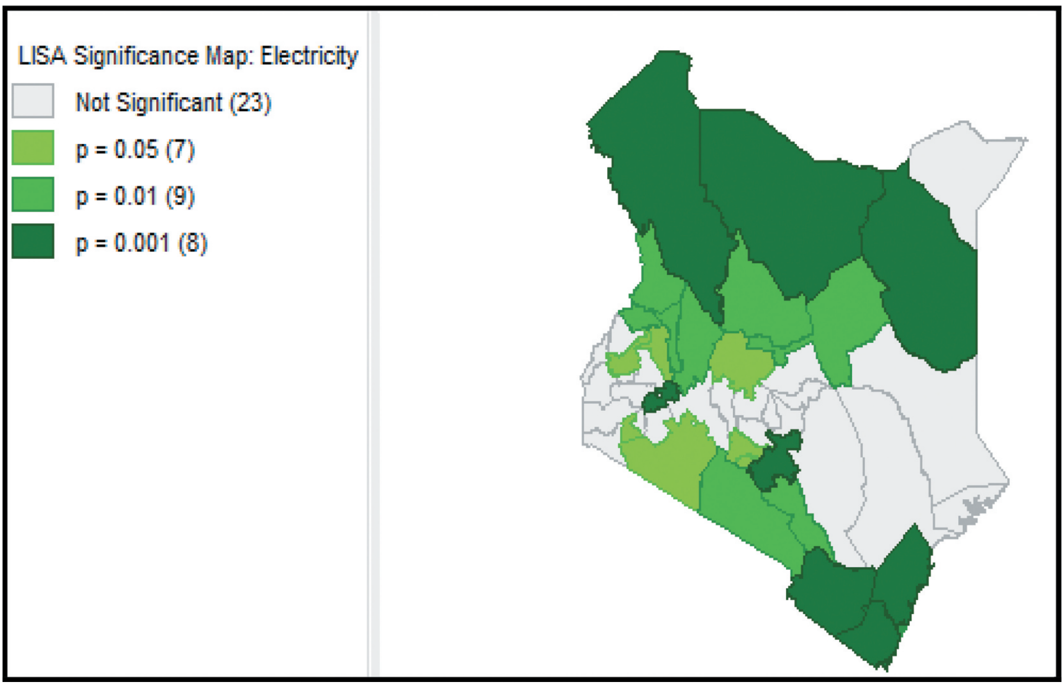

Figure 14. LISA cluster significant map on the consumption of electricity across counties in Kenya.

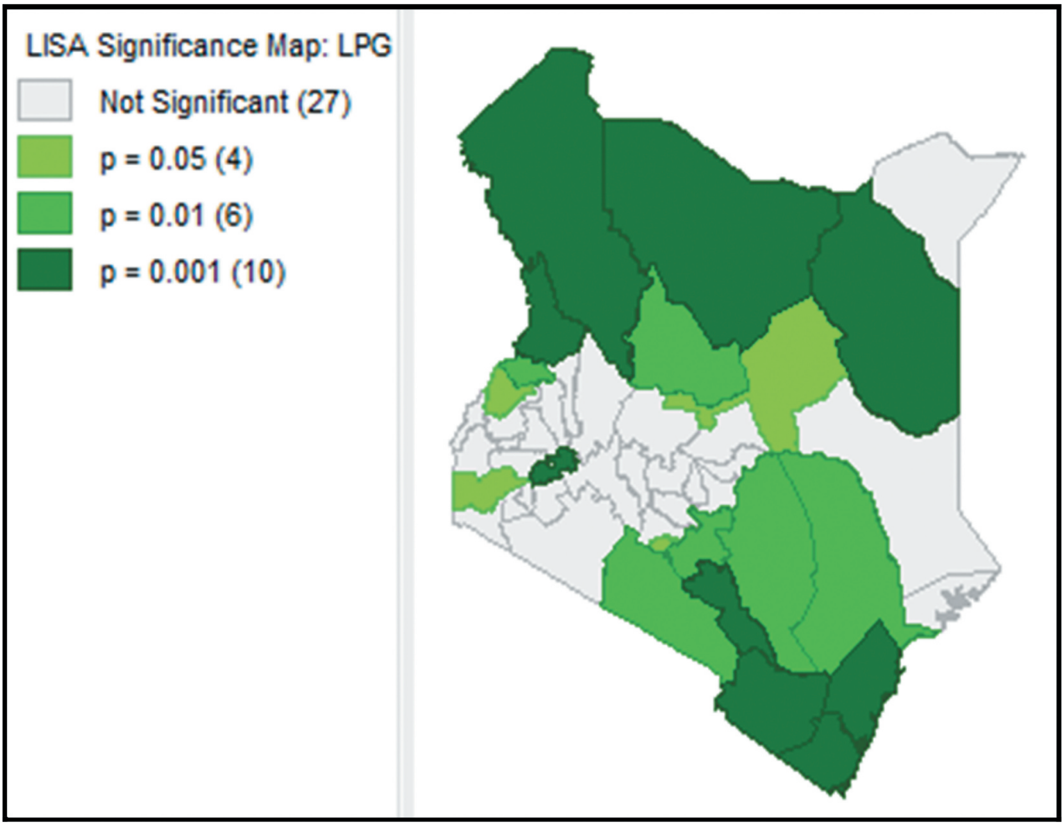

Figure 15. LISA cluster significant map on the consumption of LPG across counties in Kenya.

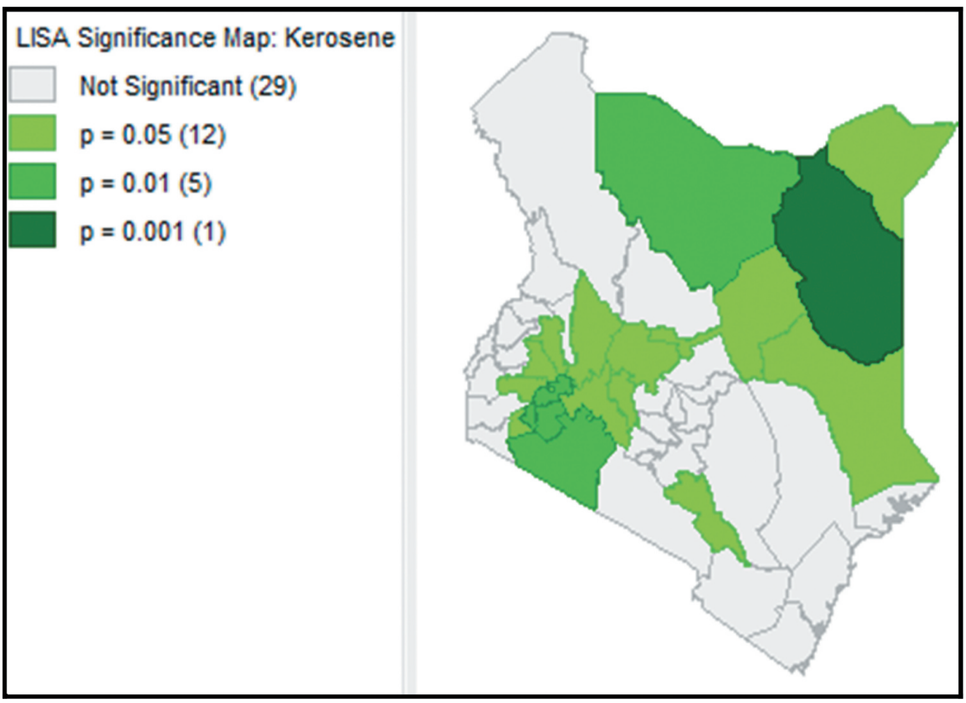

Figure 16. LISA cluster significant map on the consumption of kerosene across counties in Kenya.

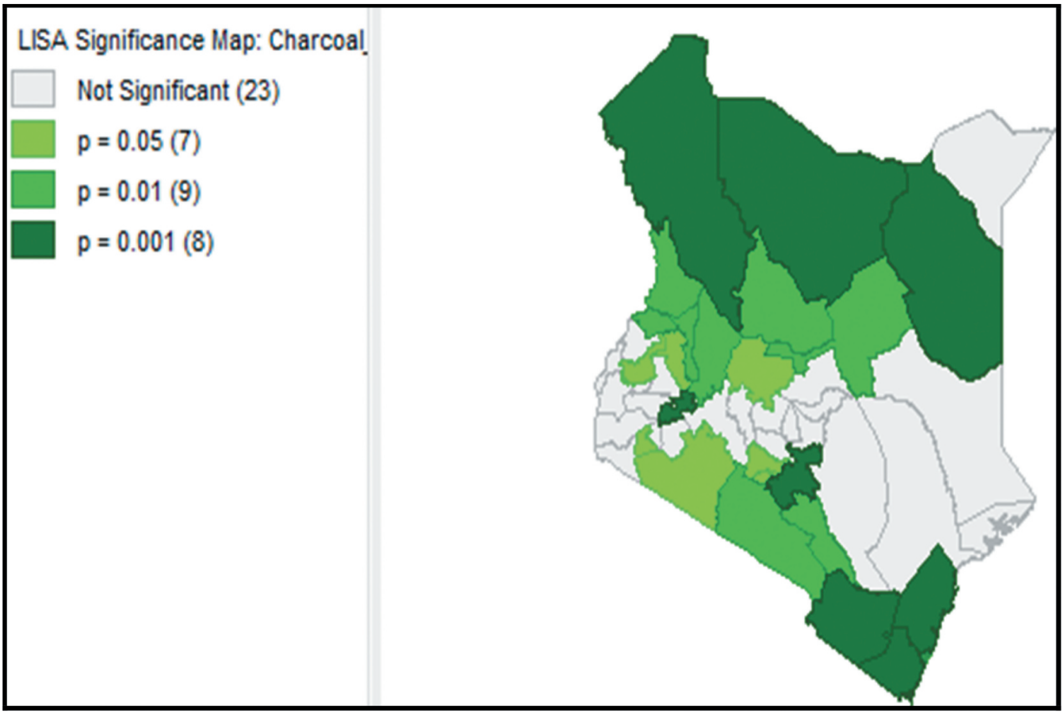

Figure 17. LISA cluster significant map on the consumption of charcoal across counties in Kenya.

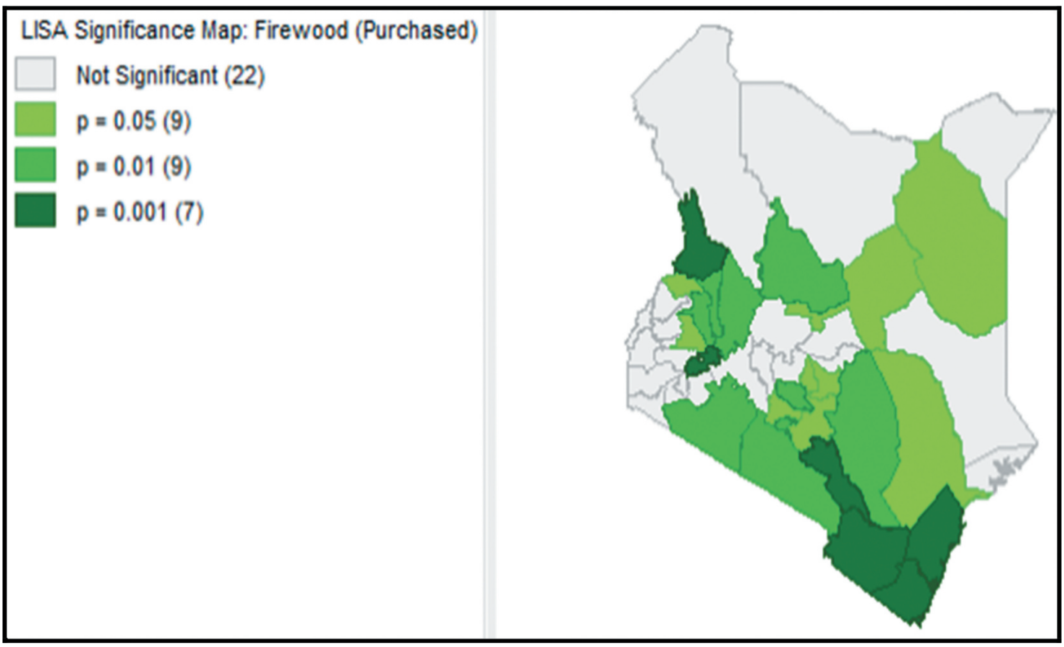

Figure 18. LISA cluster significant map on the consumption of firewood (purchased) across counties in Kenya.

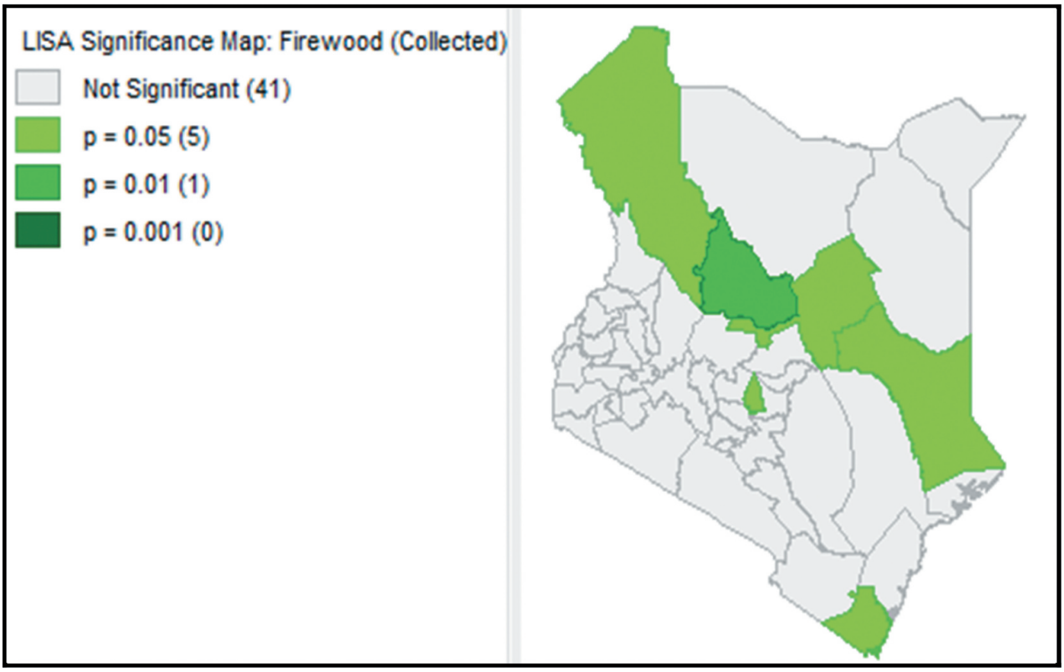

Figure 19. LISA cluster significant maps for consumption of firewood (collected) across counties in Kenya.

5. Conclusion and Policy Implications

5.1. Conclusion

The study explored the spatial disparities in the consumption of clean and non-clean energy sources at the household level across counties in Kenya that support the following conclusions. Substantial spatial variations are evident in electricity consumption, LPG, kerosene, charcoal, and firewood (purchased and collected). Overall, non-clean energy sources registered a higher mean monthly energy consumption levels compared to the non-clean sources.

Counties with high levels of electricity consumption are closely linked to higher penetration of grid electricity, a significant proportion of the urban population, higher population density, and high-income groups. The study also revealed that several counties with high penetration of grid electricity recorded relatively low consumption. This illustrates that households limit electricity use to basic services such as lighting, even with access to power. Therefore, despite the remarkable progress at the national level, many segments of the country's population still lack electricity because they live in historically underserved areas, geographically isolated, and economically marginal. The consumption of LPG was also a spatially variant. Counties that register high consumption of LPG had a high proportion of urban and peri-urban households characterized by higher household income and proximity to the denser LPG retail networks as a result of high population density. On the same note, low consumption was dominant in counties with a higher proportion of the rural population with limited access to LPG distribution, high poverty levels, and wood fuel resource availability. High consumption of kerosene was spread out in counties with a high proportion of the urban population, as is the leading source of energy among the urban poor. Increased charcoal consumption was dominant in rural Counties that are keen on the production of charcoal and urban-dominated Counties, which are the main markets for charcoal. Consumption of collected and purchased firewood recorded the highest mean monthly consumption and more pronounced in counties that had abundant wood fuel resources and a high proportion of the rural population. On the other hand, the global Moran I test indicated that consumption of various energy sources is spatially clustered. On the other hand, LISA test detected hot spots, cold spots, and outliers in the consumption of different energy sources across Counties. LISA analysis forms a critical basis in the formulation of local energy policies that seek to reduce regional disparities in the consumption of clean energy sources at the household level. Therefore, a clear understanding that the consumption of clean energy sources is unlikely to be spatially uniform and the conditions that may constrain or promote uptake across different counties can be useful in policymaking.

5.2. Policy Implications

The insights presented in this paper may be of interest to policymakers in designing and implementing decentralized energy transition plans. From the preceding, the one-size-fits-all type set of energy policy guidelines are inadequate in addressing constraints in the transition to clean energy sources energy among counties. First, the sector needs to ensure equitable electricity access by fast-tracking existing policy plans and strategies geared toward universal access through the grid and off-grid solutions across counties. For instance, Counties' energy plans and policies should leverage plans to the Least Cost Geospatial Electrification Plan for the grid, off-grid and cooking solutions.

Counties need to leverage on the energy potential and opportunities among the regional level economic blocks as they provide economies of scale for energy development. For instance, counties can utilize the wheeling system as stipulated in the Energy Act, 2019 to improve electricity access from renewable energy sources.

In order to increase electricity consumption for basic services and productive activities, energy access programs should be implemented simultaneously with campaigns that create awareness and provide incentives for electrical equipment to spur productive electricity benefits that are unique to each county.

To increase electricity consumption, the energy sector should coordinate with other sectors to take advantage of complementarities and provide appropriate inputs to productive economic activities. For instance, coordinating development initiatives in agriculture, industrialization, micro-access to finance, and labor to prioritize and amplify income generation as a shared responsibility of all decision-makers at the national, regional, and local level.

To increase the uptake of LPG, policy interventions must seek to provide targeted subsidy and pay-as-you-go options. Besides, the sector should promote sensitization forums on safety, health/environmental impacts, marketing, and illegal and unsafe refilling of the cylinders. Penetration of LPG can also be enhanced through strengthening distribution and retail networks by increasing LPG filling facilities, distribution, and retail sales points across Counties. The penetration of LPG needs to focus on affordability. There is a need to consider a targeted subsidy program, payment in installment for the cylinders' upfront cost, and pay-as-you-go options.

Since energy transition is a gradual process, one of the short-term measures would be to continue promoting advanced biomass cookstoves that may serve as a transitional alternative to the most modern cooking solutions. This will also require technical standards and a certification system whereby cookstoves carry a stamp that indicates their performance level in terms of efficiency, pollution, and safety.

The use of charcoal will remain an essential fuel for cooking purposes in the transition process. Therefore, to plot a successful energy transition, the sector will need to deploy more efficient biomass-stoves, especially among households that experience extreme poverty in various ways as they reduce charcoal consumption. Also, there is a need to create awareness of alternative sources, such as briquettes, which are less harmful and efficient than charcoal.

The sector needs to promote biogas as a substitute for firewood through household-scale biodigesters by providing incentives to local manufacturers of biogas plants and equipment and offering subsidies to households for the upfront cost of installing a biodigester. Biogas is ideal for counties with communities practicing crop farming and livestock because of the availability of agricultural residues and animal manure, respectively, as a raw material for biogas production.

Lack of awareness of the negative impacts associated with smoke from solid fuels limits the adoption of cleaner sources for cooking. There is a need to develop and implement public awareness programs on the benefits and potential clean energy sources such as LPG, biogas, and electricity through technology focusing on Counties with high potential and receptive to clean energy sources. This could have further benefits through spatial contagion and spill over. Early users of clean energy sources at the households communicate their experiences through local networks and stimulate new activity in neighboring areas.

Notes

1. The high values are not necessarily ‘high’ in absolute value, but they are the high values from the dataset.
2. The low values are not necessarily ‘low’ in absolute value, but they are the low values from the dataset.

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