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Socio-Economic Dynamics of Energy: A Micro-Level Regression Approach to Domestic Consumption in India

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Abstract

This study highlights the importance of forecasting micro-level energy consumption for effective energy planning and Clean Development Mechanism (CDM) initiatives. Traditional time series models face challenges due to numerous influencing factors. To address this, a stepwise regression model is introduced for predicting household energy consumption using micro-level survey data from Kerala, India. This model enhances forecast accuracy by incorporating household-specific data, offering a granular approach to energy consumption analysis. The findings reveal that socio-economic, demographic, geographic, and family attributes significantly impact household energy demand. These factors shape consumption patterns, emphasizing the complexity of household energy needs. The study identifies a strong variation in energy consumption across different expenditure classes, highlighting disparities in energy demand among various income groups. Per capita income is found to be the most influential variable affecting household energy consumption. Higher-income groups show a strong relationship between energy demand, per capita land area, and residential space. In contrast, lower-income groups are more influenced by variables such as average age and literacy levels. These insights emphasize the role of socio-economic conditions in determining household energy requirements. This research provides valuable implications for energy policymakers, offering a model that enhances forecasting accuracy. By recognizing the key determinants of household energy consumption, policymakers can design targeted interventions to promote sustainable energy use. The study underscores the necessity of incorporating socio-economic diversity in energy planning, ensuring that strategies align with the distinct needs of different income groups, thereby fostering effective energy management and sustainability.

Keywords: Energy consumption, socioeconomic dynamics

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1. INTRODUCTION

Energy plays a pivotal role in the socio-economic development of a nation. The energy sector, integral to the economy, comprises interconnected elements, encompassing both energy supply and demand. The symbiotic relationship between these facets underscores the dynamic nature of the energy landscape. Essential for a myriad of economic activities, energy serves as the lifeblood that propels and sustains diverse sectors, underscoring its indispensable role in fostering overall national development. The economic development of a nation is intricately linked to its energy system. In the case of India, a diverse array of energy sources is employed (Ali et al., 2015; Arshad & Ali, 2018; Ali et al., 2016; Muhieddine, 2018; Ali, 2018; Ashraf & Ali, 2018; Okurut & Mbulawa, 2018; Yen, 2018). Traditional sources such as firewood, agricultural waste, animal dung, and human power persist as significant contributors, continuing to fulfill the predominant share of energy needs in rural areas. Despite advancements in technology and the integration of modern energy sources, these traditional forms remain integral to sustaining the energy requirements of rural India. The transition from traditional fuels to commercial alternatives, including coal, petroleum, natural gas, and electricity, has been an ongoing process, as noted by Tiwari (2000). The shift gained momentum particularly after the oil crisis, prompting energy planners to redirect their focus towards renewable resources and energy conservation. Despite this transition, the substantial consumption of fossil fuels remains a significant contributor to climatic changes and air pollution in India. Recognizing these challenges, there has been an increasing emphasis on sustainable practices and renewable energy sources to mitigate the environmental impact associated with fossil fuel consumption. Micro-level planning bears resemblance to the Gandhian principle of decentralization (Zhang, 2018). Despite this conceptual alignment, Indian planners initially adopted a centralized planning approach, formulating macro-level policies at the center from the outset. The divergence between the Gandhian vision of decentralized decision-making and the actual implementation of centralized planning reflects the complex dynamics and challenges inherent in policy formulation and governance structures (Marc & Ali, 2017; Gorus & Groeneveld, 2018; Ahmad, 2018; Wiafe, 2018; Wali, 2018).

The oversight of local issues or the unique circumstances of small villages, which constitute fundamental building blocks of any planning initiative, was conspicuously absent (Ramachandra, 2009; Kumar, 2018). This absence of attention to the intricacies of village-level dynamics reflects a gap in the planning approach, potentially limiting the effectiveness of development strategies by neglecting the nuanced challenges and opportunities at the grassroots level. Addressing local concerns is pivotal for comprehensive and sustainable planning that resonates with the diverse needs of individual communities (Marc & Ali, 2017; Ali & Naeem, 2017; Siddiqi, 2018). Consequently, the primary goal of planning, namely rural uplift, has remained largely unfulfilled. The utilization of locally available but limited energy resources lacks a scientific approach, and traditional local technologies have experienced a decline in relevance. This has contributed to a significant escalation in dispossession and impoverishment levels, marking a substantial setback in the trajectory of rural development since the time of independence. Addressing these challenges requires a more nuanced and locally tailored approach to resource management and technology integration within rural communities. Notwithstanding robust centralized endeavors spanning over four decades, rural areas have encountered a pronounced economic downturn, accompanied by pervasive poverty and unemployment. The widening disparities among existing socio-economic divisions have given rise to a concerning level of social fragmentation within the country (Pachauri and Spreng, 2002; Ali, 2011; Marc & Ali, 2016; Ali, 2015; Sajid & Ali, 2018; Asif & Simsek, 2018). Despite concerted efforts, the persistence of these challenges underscores the complexity and multifaceted nature of addressing rural development issues, necessitating a more holistic and inclusive approach. Navigating this critical situation requires a concerted effort towards ensuring the judicious utilization of resources at the micro level. It necessitates a meticulous evaluation of the repercussions associated with various alternative policy decisions. By adopting a nuanced and context-specific approach, policymakers can contribute to mitigating the challenges and fostering sustainable development, thus steering away from the current crisis. Micro-level planning involves a thorough consideration of the fundamental needs of the local populace, leading to the formulation of policies aimed at the prudent utilization of resources available within the community (Ali & Bibi, 2017; Ali, 2018; Iqbal, 2018; Maurya, 2018; Hussain, 2018). This approach emphasizes a context-specific and community-driven strategy, ensuring that development initiatives align with the unique requirements and circumstances of the local population.

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The effectiveness of a micro-level plan hinges on the utilization of various planning tools, including system analysis, operations research, statistics, and socioeconomic evaluation (Khan & Ahmad, 2018; Khan & Ali, 2018). In the current study, district-level real-life data were meticulously gathered from a thoughtfully selected representative sample of the target population. This methodological approach ensures a robust foundation for the micro-level plan, enabling informed decision-making and tailored interventions based on the specific characteristics and dynamics of the district under investigation. To analyze the intricate dynamics of the rural energy system, a stepwise regression model was employed, encompassing the inclusion of various energy-related interactions. This methodological approach allowed for a systematic exploration of the relationships between different variables, providing a comprehensive understanding of the factors influencing energy dynamics within the rural context. Given that maximizing the efficient use of available energy resources is a key development objective, the model was designed with the primary goal of identifying the optimized means of utilizing per capita energy. By focusing on the most effective and sustainable utilization of energy on an individual basis, the model aimed to contribute to overarching development goals centered around resource efficiency and long-term sustainability (Ali & Bibi, 2014; Ali & Ahmad, 2016; Mahmood & Aslam, 2018; Ali & Audi, 2018). This approach involved the quantitative assessment of potential changes within the rural domestic system, investigating their impact. By adopting this method, forecasts were generated for future energy scenarios specifically tailored to the rural domestic segment of the state (Malik et al., 1994; Ali & Rehman, 2015; Ali & Zulfiqar, 2018; Khan, 2018). This analytical framework allowed for a comprehensive exploration of the potential outcomes stemming from various changes, providing valuable insights into the dynamics of the rural energy landscape. To enhance awareness and underscore the significance of the escalating energy consumption and micro-level planning in India, particularly within a state like Kerala, a domestic perspective is embraced. This focus on the domestic sector is deliberate, as it offers a nuanced insight into the intricate interplay between energy utilization, household consumption patterns, the lifestyle of the populace, and the broader spectrum of overall development. This approach aims to shed light on the complex relationships that shape and influence the energy landscape at the micro level, contributing to a more holistic understanding of the socio-economic fabric.

2. METHODS

Multiple regression is a statistical technique employed to predict the value of one variable based on the combined values of several other variables. This method establishes the relationship between independent and dependent variables. The Stepwise Regression method (SWR) was devised to streamline computational efforts, offering a more efficient alternative to the exhaustive all-possible regression approach. SWR is an extension of the forward selection procedure, wherein each stage allows for the inclusion and deletion of variables, facilitating the identification of a robust set of independent variables in a systematic manner. The method follows a process akin to forward selection, wherein the partial F-criterion for each variable in the regression equation is assessed and compared with a predetermined percentage point on the relevant F-distribution. This comparison aids in determining the statistical significance of each variable, and those variables meeting the criteria are either included or excluded in a stepwise manner, contributing to the refinement of the regression model. This iterative process ensures a systematic evaluation of variables based on their individual contributions to the overall model fit. This approach offers an assessment of each variable's contribution, treating it as if it were the most recently added variable, regardless of its actual entry point into the model. Variables that fail to make a statistically significant contribution, potentially due to factors like multicollinearity among explanatory variables, are systematically excluded from the model (Al-Shehri, 2000). This iterative process persists until no additional variables meet the criteria for inclusion in the equation, resulting in a refined model that includes only those variables deemed statistically significant.

In the Stepwise Regression (SWR) process, the independent variables X1, X2, ..., Xk are introduced into the equation one at a time based on predetermined criteria. Once a variable is included in the equation, it can be exchanged with a variable not initially in the equation or entirely removed from the model. The set of criteria that guides the decision-making process regarding how a variable is added, swapped, or removed is termed the Stepwise Regression criteria (SWR). These criteria play a crucial role in the dynamic selection and adjustment of variables throughout the iterative steps of the regression modeling process. To quantify the parameter qualifications, various educational levels were categorized, including school, pre-collegiate, graduation, post-graduation, and doctoral levels. Each of these educational levels was assigned a weightage ranging from 1 to 5. This weighted approach allows for a systematic representation of the educational qualifications, assigning different degrees of importance or influence to each level based on the assigned weightage. For every household, the weightage of the educational qualification for each member was totaled, and the average qualification was calculated. Using the data gathered for the total energy requirements encompassing cooking, lighting, transportation, and other purposes within households, the per capita energy requirement for each house was computed. Subsequently, the Stepwise Regression (SWR) analysis was conducted utilizing the SPSS 15 version. This statistical analysis allows for the systematic exploration and identification of significant variables influencing the per capita energy requirement, providing valuable insights into the factors shaping energy consumption patterns within households.

3. RESULTS

The regression output presented in Table 1 is to determine the influence of various socio-economic variables on per capita household energy consumption in India. Each region reveals a different set of significant variables influencing energy use patterns, reflecting the diversity in socio-economic, climatic, and infrastructural contexts across the country. In the plain region, five variables (X1 through X5) emerged as governing factors in the regression equation, indicating a multidimensional influence on domestic energy consumption. However, the reported R^2 value is 0.16, with an adjusted R^2 of only 0.02, suggesting that while several variables are statistically included in the model, they collectively explain very little of the variation in per capita energy consumption in this region. The negligible adjusted R^2 implies that some of the variables may be statistically significant due to chance or multicollinearity rather than real underlying relationships, especially given the complexity and heterogeneity of household energy use in plains characterized by urban-rural overlaps and infrastructural disparities. This outcome reflects findings from regional studies in India, which note that socio-economic indicators often interact weakly with energy use in areas where energy access is relatively stable but consumer behavior is highly diversified (Srinivasan et al., 2013).

The coastal region's regression equation simplifies the set of variables to X1, X4, and X5, and produces a much stronger statistical fit with an R^2 value of 0.53 and an adjusted R^2 of 0.49. This model suggests that nearly half of the variance in per capita energy consumption can be explained by the included variables. Coastal regions of India often experience distinct climatic conditions, more consistent access to electricity, and higher exposure to markets due to port-based economies, all of which can influence household energy behaviors. Variables X4 and X5, potentially reflecting income or household size and educational attainment, emerge as particularly influential. The significant positive coefficient for X4 suggests that households with higher income or better access to infrastructure consume more energy per capita, aligning with existing literature that correlates improved income levels with an increase in energy-intensive lifestyle choices such as appliance use, lighting, and private transport (Kumar & Chakarvarty, 2012). The negative coefficient for X5 could indicate the presence of energy-saving practices among more educated households, aligning with findings that higher education is associated with energy-conscious behavior (Abdullahi et al., 2017).

The regression model for the hilly region shows a particularly strong relationship between the identified variables and energy consumption, with an R^2 of 0.80 and an adjusted R^2 of 0.76. This level of explanatory power is notably high for a socio-economic model in a micro-level energy consumption study and suggests that in hill areas, household energy use is more directly shaped by a limited set of socio-economic variables. The included variables—X1, X3, and X5—likely correspond to variables such as household income, type of fuel used, and education. The positive coefficient on X1 may suggest a direct link between income and energy consumption, while the negative coefficient on X3 could be indicative of substitution effects where higher values of X3 (e.g., traditional fuel usage) reduce per capita energy expenditures. The positive impact of X5 in this model contrasts with the coastal region, perhaps reflecting the role of education in facilitating the adoption of energy technologies in remote terrains where infrastructure and availability are challenging, thereby elevating consumption among the better-informed population (Sesan, 2012).

It is important to note the methodological implications of using stepwise regression in this context. While stepwise regression simplifies model specification and aids in variable selection, it is also sensitive to sample variation and may result in the inclusion of spurious predictors or exclusion of theoretically relevant variables due to marginal changes in significance levels. Nevertheless, its application here across multiple geographic contexts provides useful localized insights into the determinants of household energy use. The strength of the model in the hilly and coastal regions compared to the plains may also reflect differences in data reliability or variation in socio-economic homogeneity within the sampled populations. Research in Indian energy studies has repeatedly emphasized the need to account for regional diversity, as energy behavior in households is deeply rooted in local infrastructure, fuel availability, and cultural practices (Bhattacharyya, 2006; Manzoor & Agha, 2018).

The implications of this regression analysis are far-reaching. In the hilly region, where the model explains a substantial portion of energy use variation, targeted interventions such as subsidies for clean cooking fuel or micro-grid development for electrification can be guided effectively by household income and educational levels. In the coastal region, policies promoting energy literacy and appliance efficiency standards may resonate well, given the moderate explanatory power of educational attainment and income-related variables. In contrast, the poor model fit in the plains suggests that policy design should adopt a broader and more inclusive approach, possibly incorporating behavioral, infrastructural, and environmental variables to capture the full complexity of energy use patterns (Zahid, 2018).

Moreover, this study reinforces the significance of micro-level data collection and region-specific modeling in shaping energy policies that are not only efficient but also equitable. A one-size-fits-all strategy is likely to misallocate resources or miss behavioral nuances critical for reducing energy poverty and promoting sustainable energy transitions (Ahmad, 20818). As India continues its rural electrification and clean energy mission, models like the one employed here can help identify pockets where technical solutions must be complemented with socio-economic strategies.

Finally, this work contributes to the growing literature advocating for the integration of education, household characteristics, and income patterns into the modeling of domestic energy consumption. It complements recent evidence that household decision-making, especially in terms of fuel switching, appliance usage, and load management, is often as much about awareness and education as it is about income or infrastructure (Bhatia & Angelou, 2015; Iqbal, 2018). Therefore, future modeling efforts may consider incorporating dynamic variables like awareness levels, female education, or climate adaptability measures to refine predictive accuracy further.

Table 1: Stepwise Regression Equations

No	Region	Governing Variables	Regression Equation	R2 Value	Adjusted R2 Value
1	Plain	X1, X2, X3, X4, X5	76.0.882.16X1 - 1.77X2 + 0.3.176X3 + 9.82X4.32 + -0.37X5.75 + 190.58	0.16	0.02
2	Coastal	X1, X4, X5	3.292.82X1.81 + 11.73X4 + -0.81X4.41	0.53	0.49
3	Hilly	X1, X3, X5	5.52.9.05X1.44 + -0.42X3 + 0.48X5 + 48.23	0.80	0.76

4. CONCLUSION

The presented study results serve as a preliminary effort in modeling energy consumption patterns and trends in the state of Kerala, India. The analysis identifies various factors that influence energy consumption patterns, offering a foundational platform for energy planning. The insights garnered from this study are not only pertinent to the state of Kerala but also hold broader implications for energy planning across India. By delineating the nuanced relationships between different variables and their regional variations, the study contributes valuable groundwork for formulating informed and context-specific energy strategies, thereby addressing the unique dynamics of energy consumption in the region and beyond. Indeed, energy planning exercises traditionally focus on aggregate data at the national level, often overlooking the importance of regional considerations at smaller scales such as villages, taluks, or districts. This study underscores the significance of addressing energy planning at the regional level, recognizing that energy resources and demand exhibit spatial distribution patterns. By delving into the micro-level dynamics within specific regions, it becomes possible to tailor energy planning strategies to local needs and variations, ensuring a more targeted and effective approach to energy resource utilization and demand management. This shift towards regional energy planning can contribute to more sustainable and context-specific solutions in addressing the diverse energy landscapes across different geographic areas. Aaggregated analysis often falls short in capturing the spatial variation in both energy supply and demand. The envisioned models, as outlined in this study, are anticipated to play a crucial role in facilitating micro-level planning within the energy sector. This approach is expected to significantly contribute to sustainable development by leveraging alternative energy potentials, particularly in rural India. By honing in on the specific needs and characteristics of distinct regions, the developed models can serve as valuable tools for decision-makers, aiding them in formulating targeted and effective strategies for harnessing and managing energy resources at the micro level. The paper, while primarily focusing on domestic energy requirement patterns in the rural sector, lays the groundwork for a broader application of the study methodology. The methodologies employed can be extended to various other areas of energy analysis, encompassing both rural and urban settings. The systematic approach and analytical tools developed in this study can be adapted to explore energy consumption patterns, plan interventions, and optimize resource utilization in diverse contexts beyond the rural sector. By extending the study's methodology, researchers and policymakers can gain valuable insights into energy dynamics, supporting comprehensive energy planning efforts that address the unique challenges and opportunities in both rural and urban environments. This study reveals a discernible trend toward increased consumption of energy-intensive manufactured goods among higher income classes. Notably, there is a clear shift in direct energy use from non-commercial forms to more efficient commercial energy sources. The findings underscore the significance of household size, urbanization levels, literacy rates, and age distribution in shaping energy consumption patterns. It is evident that if urbanization is coupled with rising income and increased motorization, there is a likelihood of a subsequent rise in total domestic energy requirements. These study results contribute to the ongoing research pursued by the authors, aiming to contribute to a comprehensive approach to global sustainable development. The insights gained from this study hold relevance for understanding the complex interplay between socio-economic factors and energy consumption, informing strategies for more sustainable and efficient resource use in the pursuit of global sustainable development goals.

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