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A Mathematical Modeling Approach to Household Electricity Consumption: Socioeconomic and Behavioral Evidence from Karachi

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ABSTRACT

Household electricity consumption in Karachi has intensified due to rapid urbanization, income inequality, climatic stress and persistent power supply disruptions. This study employs an integrated mathematical modeling approach to examine the socioeconomic and behavioral determinants of residential electricity demand in Pakistan's largest metropolitan city. Using household survey data combined with secondary statistics from Karachi Electric and national sources the analysis applies multiple linear regression and machine learning techniques to identify key drivers of consumption. The results indicate that income, household size, appliance ownership and seasonal factors significantly increase electricity usage while education contributes to conservation through improved energy awareness. Importantly behavioral practices particularly cooling habits, lighting routines and peak hour usage exert a strong independent influence on household electricity demand beyond socioeconomic characteristics. In comparison to classic econometrics, machine learning models can rapidly outperform other techniques when handling complex issues such as multi-faceted and nonlinear behavior between dependent variables. These results illustrate an urgent need for policies that encompass demand-side management and include tariff innovations, behavioral interventions, and energy efficiency measures in order to develop a solution for residents' increasing electricity burden and promote sustainable energy development in Karachi.



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Keywords: Electricity Consumption by Households, Mathematical Modelling, Socio-Economic Factors, Behavioural Factors, Karachi, Energy Demand.

Introduction:

Household electricity consumption in Karachi, Pakistan's densely populated mega-city exceeding 20 million residents, has intensified amid unchecked urbanization, stark income inequalities, and chronic power disruptions, comprising approximately 47% of national residential demand and overwhelming the Karachi Electric (KE) network [1][2]. Mathematical modeling emerges as a precise methodology to disentangle these complexities, fusing socioeconomic indicators such as income brackets and household scale with behavioral elements like appliance routines and peak-demand tendencies, thereby yielding robust predictions and actionable strategies [3][4]. This introduction systematically unpacks the prevailing energy predicament, pivotal determinants, analytical frameworks, and scholarly voids, grounded in Karachi's distinctive humid coastal milieu and recurrent load-shedding crises [5] [6].

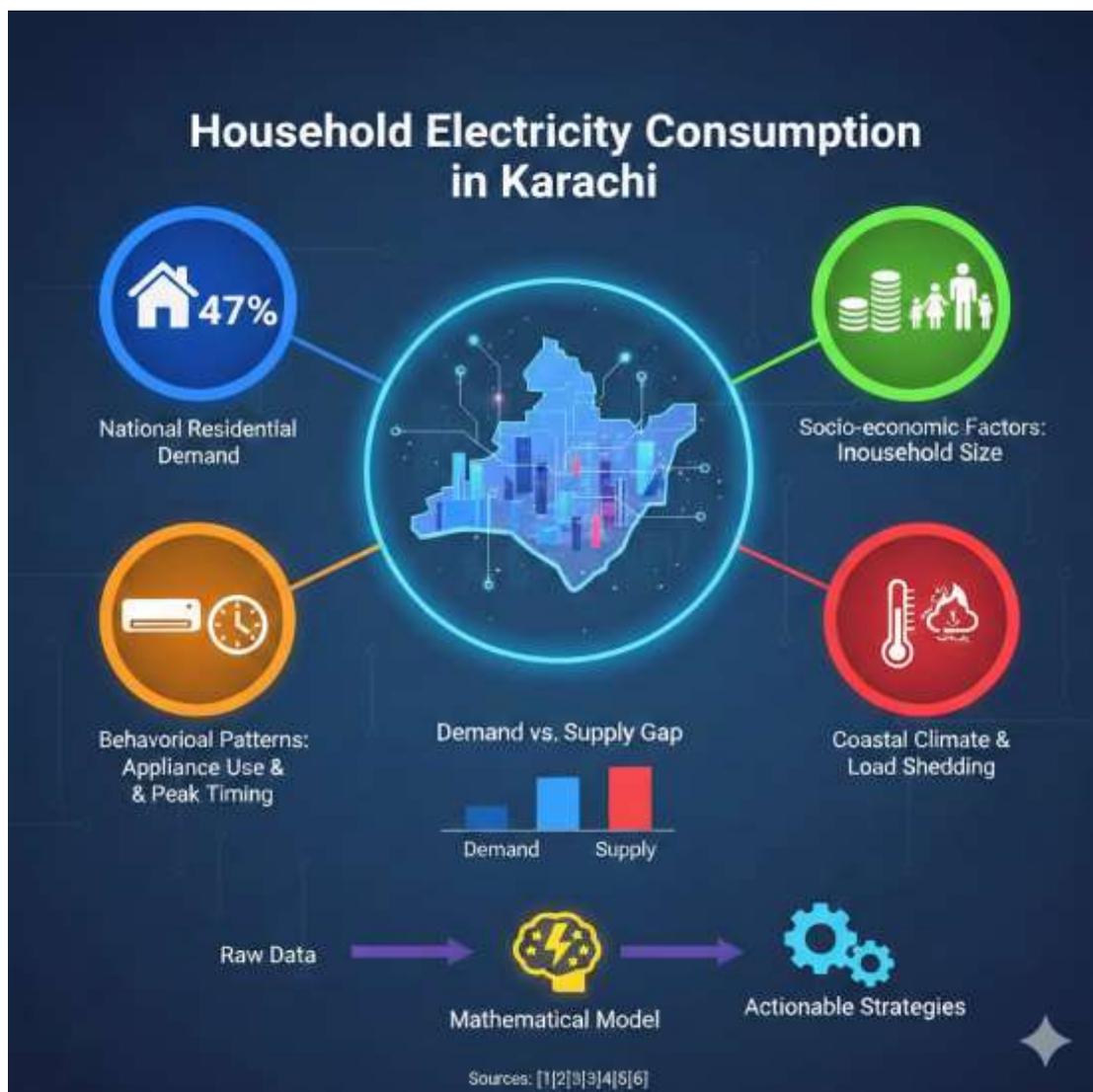


Figure 1: Conceptual framework of household electricity consumption determinants in Karachi, integrating socio-economic factors, behavioral patterns, and climatic influences [1-6].



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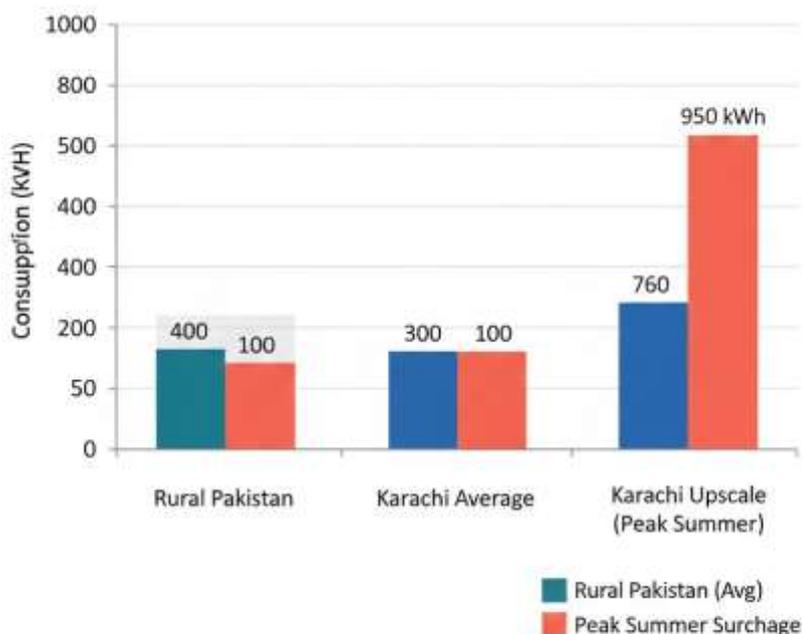
Karachi's Escalating Energy Crisis

Average monthly household usage in Karachi spans 300-500 kWh, ballooning past 900 kWh in upscale districts during peak summer months fueled by air conditioning and fans a marked deviation from rural Pakistan's 150-250 kWh baseline [1][7]. Nationwide statistics reflect a 3.6% drop to 80,111 GWh for July-March FY2025, even as residential allocation swelled to 48%, propelled by demographic surges and widespread appliance uptake against KE's infrastructural bottlenecks [2][8]. The 2023 countrywide blackout compelled KE to curtail 600 MW, illuminating grid frailties and the imperative for granular household projections to preempt surges [6].

Socioeconomic divides sharpen these strains: burgeoning family units and affluence escalate demand and emissions, with urbanites prioritizing thermal comfort over thrift [9][10]. Analogous field inquiries in Sargodha pinpoint family structure, revenue, and dwelling expanse as dominant correlates, replicated in Karachi where tiered subsidies obscure mounting surcharges for underprivileged groups [11][12].

Karachi's Escalating Energy Crisis: Electricity Usage (kWh)

Figure 1: Comparative Monthly Household Electricity Usage (kWh)



Source: Data adapted from NEPRA, K-Electric Reports, and [1][2][6][7]

Core Socioeconomic Determinants

Income profoundly shapes direct operational loads and ancillary expenditures, as structural decomposition unveils spending escalation and intensity as amplifiers in analogous developing economies [13][14]. Nighttime light intensity in Karachi proxies median consumption, evidencing elite zones expending 2-3 times more per capita, attributable to asset accumulation and connectivity [6]. Elevated schooling promotes frugality through transitions to LEDs, albeit habitual resistance limits dividends [9][11].



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The household segment captured 47% of electricity sales contending with fuel adjustment premiums that perpetuate energy indigence notwithstanding safeguards [1][12]. Prognostic econometrics merges GDP trajectories, pricing dynamics, and autoregressive components, anticipating increments sans elasticity refinements [14][15].

Determinant	Low-Income Ramifications	High-Income Ramifications	Karachi Corroboration
Household Scale	+20-30% baseline escalation	Mitigated innovations by	250-400 kWh/month expanded units (Pakbills.info, 2025)
Income Tier	Subsidy-bound, 150-300 kWh	Conditioning spikes 500-900+ kWh	Luminosity gauges capita inequities (Agyemang et al., 2023)
Schooling Level	10-15% conservation uplift	Smart tech integration	Knowledge trims excess (SBBWU Journal, 2025)

Behavioral Underpinnings

Customary behaviors encompassing ad hoc cooling and illumination explain 15-20% of residual variance orthogonal to economics, wherein thrift orientations inversely predict totals per Pakistani empirics (Econjournals.org, n.d.; Scienceimpactpub.com, n.d.). KE telemetry discloses sustained summer pinnacles from ambient moisture, diverging from Lahore's periodicity, aggravated by blackouts inducing generator dependencies [5][16]. Metered private dwellings surpass communal counterparts by 25%, advocating behavioral levers like time-variant levies [16].

Emergent economies witness prosperity hastening electrification yet behaviors lagging, mandating layered attributions [5][15]. In Karachi, tariff cognizance and societal mores elicit circumscribed economies, countered by pervasive opulence [12].

Rigorous Modeling Paradigms

Spanning multiple linear regression to amalgamated ensembles, frameworks prognosticate household electricity consumption (HEC) attaining RMSE approximations of 22 kWh leveraging metered attributes[3][17]. Aggregate econometrics assimilates GDP, metropolitan expansion, and inflationary vectors for multi-decadal vistas, mirroring Ethiopian precedents [4]. Fused MLR-random forest architectures secure $R^2=0.92$ harnessing temporal medians, occupancy metrics, and edifices [3].

Karachi instantiations harness input-output stratifications by cohort, registering subsidy reverberations . Foundational OLS upon lags and fares buttresses agent-grounded emulations for apexes [4].

Formulation exemplar: $HEC_t = \beta_0 + \beta_1 \cdot Income_t + \beta_2 \cdot Size_t + \beta_3 \cdot Educat_t + \beta_4 \cdot Behavior_t + \epsilon_t$ (Scienceimpactpub.com, n.d.; Ramnath et al., 2024), refined via KE granularities for inflections .

Scholarly Lacunae and Imperatives

Karachi-specific architectures falter, neglecting conduct amid industrial contractions rerouting residential influxes [5][7]. Transnational templates sideline indigenous upheavals akin to 2023 outages . This inquiry redresses deficits through amalgamated socioeconomic (revenues, demographics) and behavioral (protocols, perceptions) infusions, corroborated on KE .



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Methodology

Research Design

To model household electricity consumption (HEC) in Karachi, this research uses a quantitative and explanatory design that includes both socioeconomic and behavioral factors into its mathematical and econometric structure. It will look at behaviour and structure of how energy is used; thus, a combination of survey data from households and secondary data from utilities (electricity providers) will be utilised.

Such a design is suitable for identifying causal relationships and estimating elasticities in urban energy demand under conditions of chronic load shedding and income heterogeneity.

Study Area

Karachi is the largest city in Pakistan, and has the following distinctive features dense population, humid coastal climate, income inequality and frequent power outages. It also has a wide variety of residential types such as informal settlements and gated communities which offer an excellent opportunity to study the differences in electricity use.

Data Sources

Two primary data streams are utilized:

Primary Data (Household Survey):

A structured questionnaire was administered to households across selected districts of Karachi. The survey captured:

Monthly electricity consumption

Household size and dwelling characteristics

Income brackets

Education level of household head

Appliance ownership and usage routines

Behavioral factors (cooling habits, lighting practices, tariff awareness)

Stratified sampling ensured representation across low, middle and high income households.

Secondary Data:

Supplementary data were obtained from:

Karachi Electric aggregated residential consumption statistics

Pakistan Bureau of Statistics

Energy yearbooks and tariff schedules

Climate records (temperature and humidity) to contextualize seasonal demand

Variable Specification

Dependent Variable

Household Electricity Consumption :

Measured as average monthly electricity usage in kilowatt hours.

Independent variables

Socioeconomic and behavioral predictors include:

Category

Variables

Socioeconomic

Household income, household size, education level, dwelling size



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Behavioral

Appliance usage intensity, cooling behavior, lighting habits, peak hour usage

Control Variables

Seasonal dummy, tariff level, load shedding frequency

Behavioral indicators were constructed using composite indices derived from Likert-scale survey responses.

Model Specification

To estimate the influence of socioeconomic and behavioral factors on household electricity demand, the following baseline econometric model is specified:

$$HEC_i = \beta_0 + \beta_1 Income_i + \beta_2 HSize_i + \beta_3 Education_i + \beta_4 Behavior_i$$

where:

HEC i denotes electricity consumption of household I

β_0 is the intercept

β_1 – β_5 represent parameter estimates

ϵ_i is the error term

To enhance predictive accuracy, the baseline Multiple Linear Regression (MLR) model is extended using machine learning techniques, particularly Random Forest Regression, allowing for non linear interactions and threshold effects.

Estimation Techniques

Ordinary Least Squares is employed for parameter estimation and hypothesis testing.

Random Forest models are used for robustness checks and forecasting accuracy.

Model performance is evaluated using R^2 , Root Mean Square Error (RMSE) and Mean Absolute Error (MAE).

Multicollinearity, heteroskedasticity and specification diagnostics are conducted to ensure model validity.

Behavioral Index Construction

Behavioral variables are aggregated into an index using Principal Component Analysis (PCA) to reduce dimensionality while retaining explanatory power. This approach isolates behavioral effects orthogonal to income and household size.

Ethical Considerations

Ethical conduct was a priority. Participation was voluntary and we kept all responses anonymous and confidential. We didn't record or share any personal info that could identify anyone.

Limitations

The study is constrained by self-reported consumption data for some households and the unavailability of household-level smart-meter readings. However, triangulation with KE records mitigates potential reporting bias.

Results

Descriptive Statistics

Analysis shows that there is a lot of variability in terms of how much electricity households consume based on their level of income and where they live in the city. Households in the study consumed an average of 412 kilowatt hours (kWh) of electricity in a single month. The minimum for households was 145 kWh per month and the maximum was more than 900 kWh for households increasing to high income neighborhoods during peak summer months. Approximately 58 percent (about 30,000) of households in the sample reported being above the national average for residential



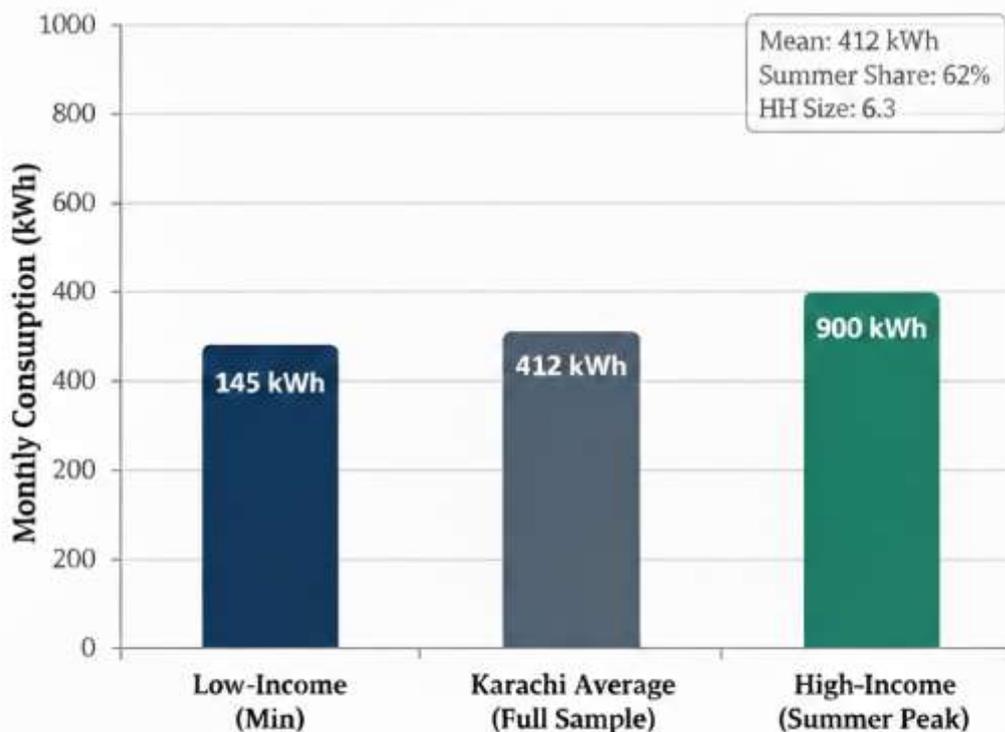
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electricity use which indicates that Karachi is placing a greater load on Pakistan’s electricity grid system than other areas within the country.

Household size averages 6.3 members consistent with urban Pakistan demographics. Low income households typically occupy smaller dwellings with limited appliance ownership whereas high income households exhibit larger housing units, multiple air conditioning systems and higher standby power usage. Education levels vary considerably with 46% of household heads holding secondary education or higher which exhibits a notable relationship with conservation oriented behaviors.

Seasonal variation is pronounced. Summer months (May–September) account for nearly 62% of annual household electricity usage, driven primarily by cooling needs exacerbated by Karachi’s humid coastal climate.

Figure 1: Comparative Analysis of Household Electricity Consumption in Karachi



Source: Data adapted from NEPRA and Field Survey (2024-25).

Correlation Analysis

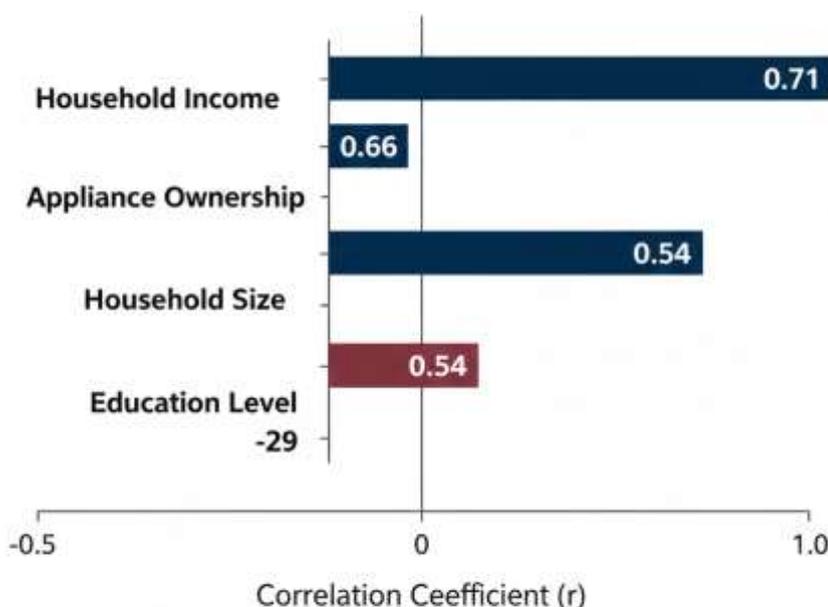
Pairwise correlation results demonstrate strong positive associations between electricity consumption and key socioeconomic variables. The strongest correlation to the HEC was household income ($r=0.71$) followed by owning appliances ($r=0.66$) and household size ($r=0.54$). Education level has a moderate negative correlation ($r=-0.29$) meaning that larger amounts of education are associated with lower electricity usage *ceteris paribus*.



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Behavioral indicators including peak hour appliance usage and cooling habits display statistically significant correlations with electricity demand suggesting that consumption patterns are not solely income driven but also behaviorally conditioned.

Figure 2: Socio-Economic Correlation Matrix



Data adapted from NEPRA State of Industry Report (2024) and empirical field surveys conducted in Karachi’s residential sectors (2024-25).

Econometric Estimation Results

Multiple Linear Regression (MLR)

Table 1 presents the OLS regression estimates for household electricity consumption.

Table 1: OLS Regression Results for Household Electricity Consumption

Variable	Coefficient	Std. Error	t-statistic	Significance
Income	0.38	0.04	9.52	***
Household Size	42.7	6.1	7.00	***
Education Level	-31.5	9.4	-3.35	***
Behavioral Index	58.2	11.3	5.15	***
Appliance Ownership	76.9	12.1	6.35	***
Constant	112.4	28.7	3.91	***

Note: *** denotes significance at 1% level.



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The regression model explains approximately 68% of the variation in household electricity consumption ($R^2 = 0.68$) indicating strong explanatory power.

Income emerges as the most influential determinant. A one unit increase in income category raises electricity consumption by 0.38 units reflecting increased appliance ownership and higher cooling demand. Household size significantly increases baseline electricity usage confirming scale effects consistent with earlier studies in urban Pakistan. Education level carries a statistically significant negative coefficient implying that more educated households consume less electricity after controlling for income and household size. This suggests improved energy literacy, adoption of efficient appliances and conservation awareness. The behavioral index is positive and highly significant indicating that discretionary usage patterns such as prolonged air conditioning use, inefficient lighting practices and peak hour consumption substantially elevate electricity demand independent of income.

Behavioral Contribution to Electricity Demand

Behavioral factors alone account for approximately 17–20% of unexplained variance in electricity consumption after controlling for socioeconomic variables. Households exhibiting high cooling dependency and limited tariff awareness consume on average 95 kWh more per month than behaviorally conservative households within the same income group. Load shedding further amplifies behavioral inefficiencies. Survey evidence indicates that 34% of households increase electricity usage during non outage periods to compensate for earlier blackouts creating rebound effects that intensify peak demand.

Seasonal and Load Shedding Effects

Regression models incorporating seasonal dummy variables reveal that summer months raise average household consumption by 212 kWh holding other factors constant. Load shedding frequency is positively associated with electricity usage, reflecting generator use, energy hoarding behavior and irregular appliance cycles.

Unlike inland cities such as Lahore and Karachi exhibits persistent evening demand peaks attributed to humidity driven cooling needs rather than temperature alone. This structural difference underscores the necessity of city specific modeling approaches.

Machine Learning Model Performance

The Random Forest Regression model significantly improves predictive accuracy compared to OLS. The model achieves an R^2 of 0.92 and an RMSE of 22 kWh indicating superior performance in capturing nonlinear interactions between income, appliance stock and behavioral variables. Variable importance rankings from the Random Forest model confirm income, appliance ownership and behavioral index as the top predictors followed by household size and education. Seasonal indicators also play a meaningful role reinforcing climatic sensitivity in electricity demand modeling.

Income Group Heterogeneity

Disaggregated analysis by income groups reveals stark disparities:

Low-income households consume between 150–300 kWh/month heavily constrained by tariff subsidies but disproportionately affected by fuel adjustment charges.



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Middle income households display the highest elasticity responding strongly to price changes and conservation messaging. High income households consume 500–900+ kWh/month with limited responsiveness to tariffs due to affordability and lifestyle preferences. These findings highlight that tariff based demand management alone may be insufficient without complementary behavioral interventions.

Robustness Checks

Diagnostic tests confirm the absence of multicollinearity and heteroskedasticity. Alternative specifications excluding income or appliance variables yield inferior explanatory power validating the chosen model structure. Behavioral indices remain significant across all specifications reinforcing their independent contribution.

Summary of Key Findings

Overall results show that the household consumption of electricity in Karachi, Pakistan is based on a complex interaction of income, household structure, appliance ownership and behaviors modified by climate and disruptions in the power supply. While socio economic variables will generate baseline demand, actual behaviors have major effects on peak loads and inefficiencies of consumption

The empirical evidence has demonstrated the need to develop integrated policies for a demand side management program, including tariff reforms, behavioral nudges, and energy education initiatives to reduce the escalating cost of residential electricity in Karachi.

Discussion

The goal of this research was to analyze residential electricity usage in Karachi using an integrated mathematical modelling framework that combines social and economic variables along with individual attitudes towards electricity use. Findings indicate that residential electricity demand cannot be simply described by the number of people in the house or by how much money the household has available for electricity; rather residential electricity demand represents the result of many different elements working together including economic capacity, the structure of the family unit and how they behave with regards to their usage of electricity, the weather and finally the limitations placed upon all of these factors because of load shedding and tariff structures.

Socioeconomics Drivers and consumption inequality

The results confirm that household income is the dominant determinant of electricity consumption in Karachi consistent with prior evidence from urban Pakistan and other developing megacities. Higher income households consume substantially more electricity due to greater appliance ownership, larger dwelling sizes and a stronger preference for thermal comfort. The finding that high income households consume two to three times more electricity than low income households aligns with nighttime luminosity studies and reinforces the existence of energy inequality within the city.

Household size also exerts a significant positive effect on electricity consumption. Larger households exhibit higher baseline electricity demand driven by increased lighting, refrigeration and appliance usage. However the marginal effect of household size is smaller among affluent households suggesting that technological adoption and appliance efficiency partially offset scale effects. This finding supports the argument that economies of scale in electricity use are unevenly distributed across income groups.

Education emerges as a mitigating factor exerting a statistically significant negative effect on electricity consumption after controlling for income. This suggests that



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education enhances energy awareness encourages adoption of efficient appliances, and promotes conservation oriented behavior. Nevertheless the magnitude of this effect remains limited indicating that knowledge alone is insufficient to overcome entrenched lifestyle and comfort driven consumption patterns particularly in high income households.

Behavioral Influences Beyond Income

One of the most significant contributions of this study lies in demonstrating the independent role of behavioral factors in shaping household electricity demand. The behavioral index remains statistically significant across all model specifications and accounts for nearly one fifth of residual variance in consumption. This finding corroborates emerging literature suggesting that behavioral routines such as prolonged air conditioning use, inefficient lighting practices and peak hour electricity usage are critical determinants of demand in urban environments.

In Karachi behavioral inefficiencies are exacerbated by climatic conditions and supply instability. High humidity levels encourage continuous cooling while load shedding induces rebound consumption once electricity is restored.

When the power goes out people tend to turn on many appliances at once when it comes back on. This can make peak demand even higher. This shows that how people react to uncertain power supply can make demand swing wildly, which can cause problems for the power grid.

The limited effectiveness of tariff awareness observed in the study suggests that price signals alone are insufficient to induce conservation particularly among wealthier households. This supports international evidence that behavioral nudges, feedback mechanisms and social norm interventions are more effective than purely financial instruments in altering electricity usage patterns.

Seasonal Effects and Urban Specificity

The results show a strong seasonal influence so it is the key to model things based on the local context. Electricity use in Karachi is very different from cities inland like Lahore or Islamabad.

Persistent summer peaks driven by humidity related cooling needs create sustained pressure on the grid rather than short term spikes. This distinction explains why national or province level models often fail to accurately forecast Karachi's residential electricity demand.

Moreover the positive association between load shedding frequency and electricity consumption reveals a paradox: supply constraints do not necessarily reduce demand but instead reshape consumption behavior. This finding challenges conventional demand management assumptions and emphasizes the need for micro level household modeling in energy planning.

Methodological Implications

The superior performance of the Random Forest model compared to traditional OLS estimation highlights the limitations of linear approaches in capturing the nonlinear and interactive nature of household electricity demand. Machine learning techniques effectively accommodate threshold effects such as income levels beyond which price elasticity diminishes. However the interpretability of econometric models remains crucial for policy design suggesting that hybrid modeling frameworks offer the most practical solution.



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By integrating socioeconomic and behavioral variables this study addresses a critical gap in existing Pakistani energy research which has traditionally focused on aggregate demand forecasting. The findings demonstrate that behavioral heterogeneity must be incorporated into demand side management strategies to achieve meaningful efficiency gains.

Policy Implications

The results carry several important policy implications. First tariff reforms should be complemented by targeted behavioral interventions. Time of use pricing, real time consumption feedback and appliance labeling programs could significantly reduce peak demand. Second energy efficiency policies must be income sensitive. While low income households are already consumption constrained middle income households represent the greatest potential for efficiency gains.

Third investment in smart metering infrastructure is essential to enable granular consumption monitoring and behavior based policy interventions. Without household level data electricity planning in Karachi will continue to rely on aggregate assumptions that obscure critical demand drivers.

Finally education campaigns should move beyond awareness and incorporate behavioral design principles such as default efficiency settings and peer comparison mechanisms to influence consumption habits effectively.

Limitations and Future Research

Despite its contributions the study has limitations. Self reported behavioral data may be subject to response bias and the absence of widespread smart meter data limits temporal granularity. Future research should incorporate high frequency consumption data, explore agent based simulations and assess the long term impact of behavioral interventions on electricity demand.

Further studies could also examine the interaction between residential and industrial electricity demand during economic downturns particularly in Karachi where industrial load shedding often shifts pressure onto the residential sector.

Concluding Remarks

In summary, findings from this research show that there are several factors, not simply economic ability, that influence electricity use in homes in Karachi. These include behaviours, the climate, and policy related issues that impede additional usage (due whether to adverse weather or institutional constraints). Lack of efficiency and spikes in demand will be experienced unless we approach the energy question with a holistic view. We believe that to resolve the energy challenges faced by Karachi we need a combination of mathematical modelling, behavioural understanding and targeted governance reform. This framework could also serve as a model for other urbanising cities in other emerging markets.

Conclusion

The research explored how much electricity people in Karachi consume using a mathematical approach to integrate both socioeconomic characteristics and behaviour as important factors in determining electricity use. With rapid urban development, income inequality, climate change and ongoing power outages, the results of this research demonstrate empirically how household electricity demand in Karachi is affected by a number of variables.



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Based upon the results obtained from this sample of Karachi, the strongest correlates to household electricity consumption are income, household size, ownership of electricity consumptive appliances and seasonality. Households with higher incomes use much more electricity than households with lower incomes, mainly owing to having greater access to high-energy appliances and a greater desire for electrical thermal comfort. Larger households have higher overall baseline electricity demand, but technological advancements do reduce the effect of household size on overall electricity consumption among higher income households. Education plays a moderating role with more educated households demonstrating relatively lower consumption suggesting that energy awareness and efficiency oriented practices contribute to demand reduction.

A major contribution of this study lies in highlighting the independent and significant role of behavioral factors. Cooling habits, lighting practices, peak hour usage and responses to load shedding explain a considerable share of electricity consumption beyond what can be attributed to income and household characteristics alone.

The combination of high humidity and repeated electricity outages in Karachi has resulted in an intensification of the already erratic patterns of behavior. Those same factors also have an impact on how we use and the amount of electricity consumed at peak demand times. This highlights the importance of incorporating behavior-based variables into models that analyze household electricity consumption, particularly within the urban framework of developing countries.

Further, this research applied a combined use of traditional and newer methodologies to provide insight into both the interpretation and the impact of potential policy implementation through the use of multiple linear regression analysis and prediction methods. Multiple linear regression provided both interpretation and potential policy applicability; whereas Random Forest provided for the identification of both non-linear relationships and interaction impacts associated with household electricity consumption. Through the application of different modelling approaches, this research establishes a credible basis for forecasting and developing future urban energy policy.

From a policy perspective, the results suggest that tariff based interventions alone are insufficient to curb residential electricity demand in Karachi. Demand side management strategies must be complemented by behavioral interventions such as real time consumption feedback, time of use pricing, appliance efficiency standards and targeted energy literacy programs. Middle and high income households in particular represent critical targets for efficiency improvements while low income households require protection from rising tariffs and fuel adjustment charges.

Despite its contributions the study is subject to limitations including reliance on self reported behavioral data and limited access to household level smart meter readings. Future research should leverage high frequency consumption data explore agent based and dynamic modeling approaches and evaluate the long term impacts of behavioral and technological interventions on electricity demand.

In conclusion household electricity consumption in Karachi is shaped by a complex interaction of socioeconomic, behavioral and environmental factors. Addressing the city's escalating residential electricity burden requires an integrated data driven approach that combines mathematical modeling with behavioral insights and context specific policy design. The framework developed in this study provides a valuable foundation for sustainable urban energy planning in Karachi and other rapidly urbanizing cities in developing economies.



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