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Mitigating Electricity Consumption Challenges through Data Analysis: A case of an Asian Megalopolis

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Abstract

This report presents the important role of data analysis in understanding and reducing demand for electricity consumption in Karachi, Pakistan. This comprehensive study conducted an in-depth analysis of Karachi's electricity consumption and aimed to develop a suitable model for forecasting the country's future electricity consumption (ECC). The study relied on extensive data from 2010 to 2020, including electricity consumption (E.C.), number of consumers (NOC), population (P), humidity (H), and temperature (T) of various sectors Data are included as parameters. Notably, the study revealed a strong correlation between E.C. in various sectors (household, commercial, industrial, agricultural, streetlight, other) with parameters. Due to the strong positive correlation between E.C. with different parameters, multiple linear regressions were applied for the analysis of electricity consumption in Karachi Pakistan. To predict Population, Humidity, Temperature and Number of Consumers different mathematical model such as linear, Exponential, Polynomial and logarithmic models were applied on data. In order to get the best fitted model a number of goodness-of-fit tests Coefficient of Determination (Adj-R2), Mean Absolute Percentage Error (MAPE), Mean absolute deviation (MAD), Mean Signed Difference (MSD) applied and got the polynomial model to be the most effective one for the above-mentioned parameters. According to the model's projections, the expected electricity consumption for the Industrial, agricultural, domestic, and commercial sectors will be as follows.

In 2024: Industrial - 4935.235 KWh, Agriculture - 163.6702 KWh, Domestic - 10048.48 KWh, Commercial - 2409.322 KWh.

In 2030: Industrial - 6152.609 KWh, Agriculture - 163.581 KWh, Domestic - 14306 KWh, Commercial - 3238.007 KWh.

In 2040: Industrial - 7072.418 KWh, Agriculture - 120.0209 KWh, Domestic - 18010.15 KWh, Commercial - 4101.986 KWh

This study provides valuable insights into the impact of various factors on Karachi's electricity demand. This study makes a significant contribution to energy management by providing precise predictions of electricity consumption patterns across a variety of sectors in 2024. Policymakers, urban planners, and energy managers can benefit from the findings. Using this guidance, Karachi can make well-informed decisions regarding electricity crises and sustainable energy practices.

Keywords: Energy in Karachi, Data Analysis, Power Crises, Statistical Analysis, Data-driven Insights , Demand Forecasting

BACKGROUND

The use of electricity has become a necessity, similar to the use of oxygen, water, and food. Its uses include heating, lighting, refrigeration, and operating diverse electronic devices, such as computers. Additionally, the significant role played by electricity in a nation's economic development further underscores its significance in modern society. In modern industries like mining, manufacturing, communication, and transportation, electricity plays a crucial role as a catalyst for economic development. The production and consumption of electricity greatly influence the provision of goods and services. Its role in socioeconomic development is well-established (Cuarteros 2021). Existing literature indicates that a number of factors contribute directly to increased electricity consumption, including population growth, urbanization, industrial expansion, and a rise in appliance usage.

While electricity has existed for thousands of years, it is still a vital part of contemporary life because of its multifaceted contributions across multiple domains. We rely heavily on electricity for many of our daily technologies. According to Ali et al. (2013) and Yasmeen et al. (2014), the amount of electricity required depends on factors including temperature, wind velocity, precipitation, and daily routines. According to Etkin et al. (1999), heightened temperatures increase electricity consumption, particularly through air conditioning and other appliances. In 2008, Pakistan's electricity generation reached approximately 11,500 MW per day, a jump to around 20,000 MW in 2010, a testament to its growing significance in the economy (Yasmeen et al., 2013). According to Khan et al. (2008), electricity consumption and supply have increased by nearly 40 times in the last three decades. Pakistan's economic progress is heavily influenced by the availability of electricity. At present, it suffers from a significant electricity deficit (Luo et al., 2020). Although the population has grown by 5.81%, it falls short of the 6.6% needed to address unemployment and poverty, which are compounded by the ongoing electricity crisis. Pakistan's predicament has substantial repercussions across all economic sectors (IEEFA, 2018; Deb et al., 2017). A growing population, estimated at about 3 percent annually, is driving the surge in electricity demand. It is becoming increasingly necessary to use resources such as natural gas, lubricants, and liquefied petroleum gas to meet this demand. Pakistan Economic Survey (GOP Y, 2018) indicates that the electricity sector consumes 38.8 Million Tons of Oil Equivalent (MTOE) every year. According to a World Bank study by Rufael (2006), enhancing a nation's financial system through cutting-edge technology is imperative for effective electricity provision.

In Pakistan, electricity is generated from hydropower, oil, natural gas, nuclear power, and other sources. Energy mix, economic factors, and demand-supply dynamics contribute to a shortfall in electricity output. Due to their limited power generation potential and environmental concerns (Ali et al., 2012), hydropower and coal resources contribute to energy shortages despite their cost-effectiveness (Ali et al., 2012). It is a developing agricultural nation in the South Asian region that holds a crucial position. As of 1980, the installed capacity had increased to 10.16 million kW despite the generation capacity of 3.76 million kW (Shakeel et al., 2015). With a population of 197 million in 2018, electricity consumption had increased to 98,500 GWh, while installed generation capacity had decreased to 29,953 MWh, resulting in a significant gap between consumption and capacity. Power outages lasted as long as 12 hours during the summer in both urban and rural areas in 2015 when the electricity consumption deficit reached 7000 MW (Zhang, T. 2018). Due to this dire situation, many businesses have curtailed or ceased operations (Lin et al., 2019; Kessides, 2013). Pakistan's power crisis is influenced by a number of significant factors, including population growth, weak governance, and suboptimal power plants (Shakeel and Farhan, 2015). Various mathematical models have been studied to mitigate these challenges in the existing literature. For Pakistan's electricity consumption forecasts (Fazal et al., 2018; Hussain et al., 2016), Holt-Winters and ARIMA models have been employed. China's total energy output and consumption were estimated by Xie et al. (2015) utilizing the Optimized Single Variable Discrete Grey Forecasting Model (ODGM) and QP-Markov technique. To predict Turkish electricity consumption, Coskun (2014) used an Optimized Grey Model (OGM) (1,1).

DATA DESCRIPTION AND METHODOLOGY

Economic status, temperature, population size, number of consumers, and humidity levels all play a role in determining electricity consumption. A statistical analysis of Karachi's temperature (T), population (P), humidity (H), number of consumers (NoC), and electricity consumption for the period 2010 to 2020 has been conducted in this study. Data was taken from the handbook of the Sindh Planning & Development Board.

Over time, all parameters of electricity consumption have exhibited a strong positive trend, as shown in figure [1]. As a result of the COVID-19 pandemic, which affected a number of sectors of the economy, agriculture consumption is likely to decline in 2019 and 2020. However, the rapid increase in domestic EC during the lockdown is likely the result of the increased use of electricity for household activities.

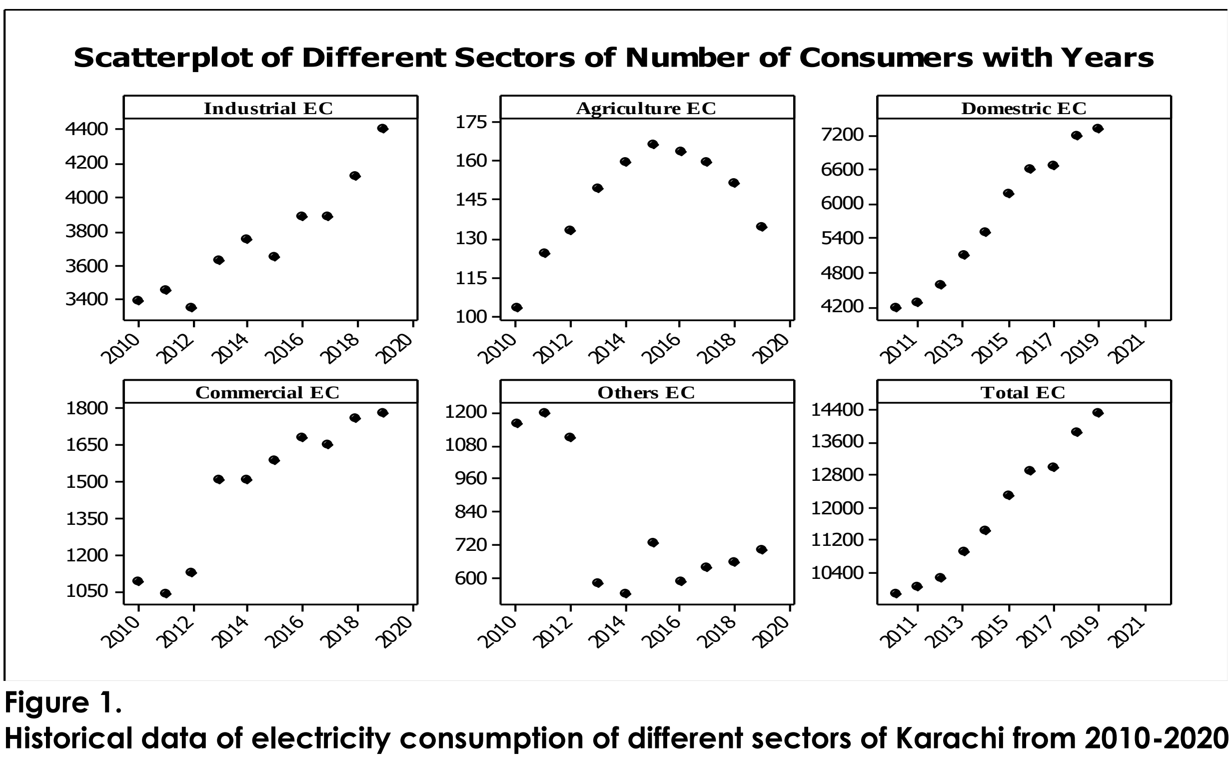

Figure 1.
Historical data of electricity consumption of different sectors of Karachi from 2010-2020

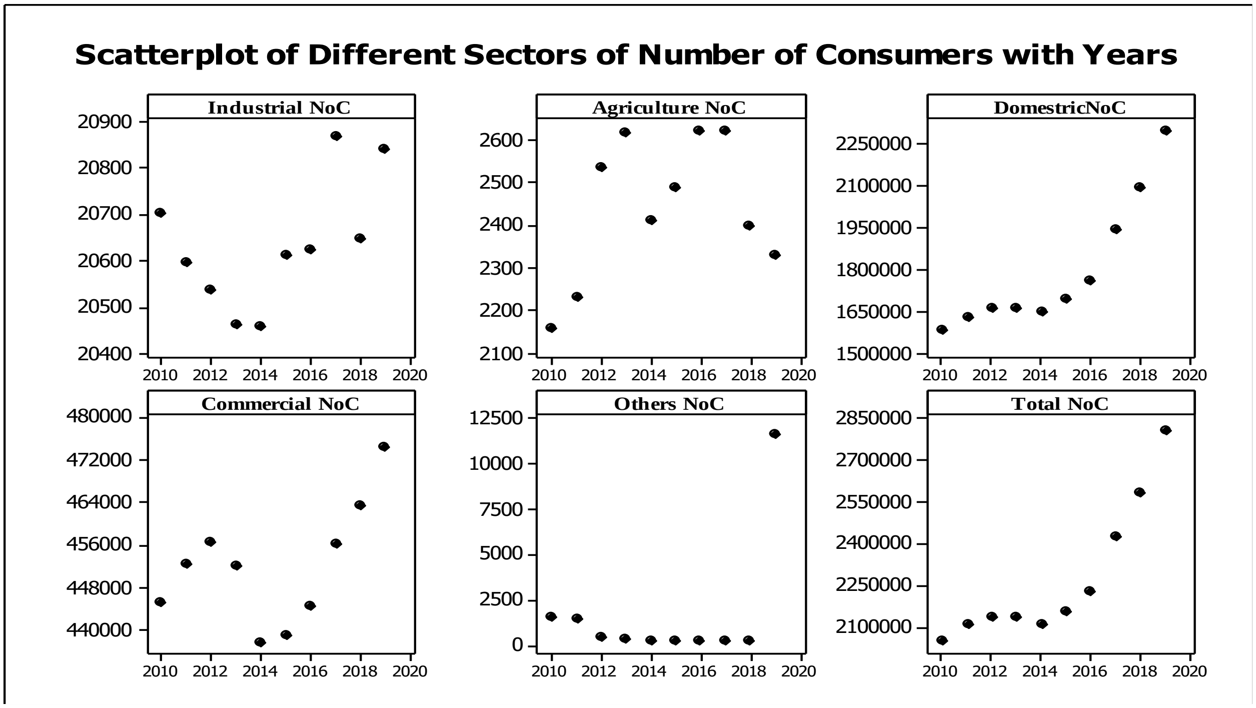

Figure.2.
Historical data of Numbers of consumers from 2010-2020.

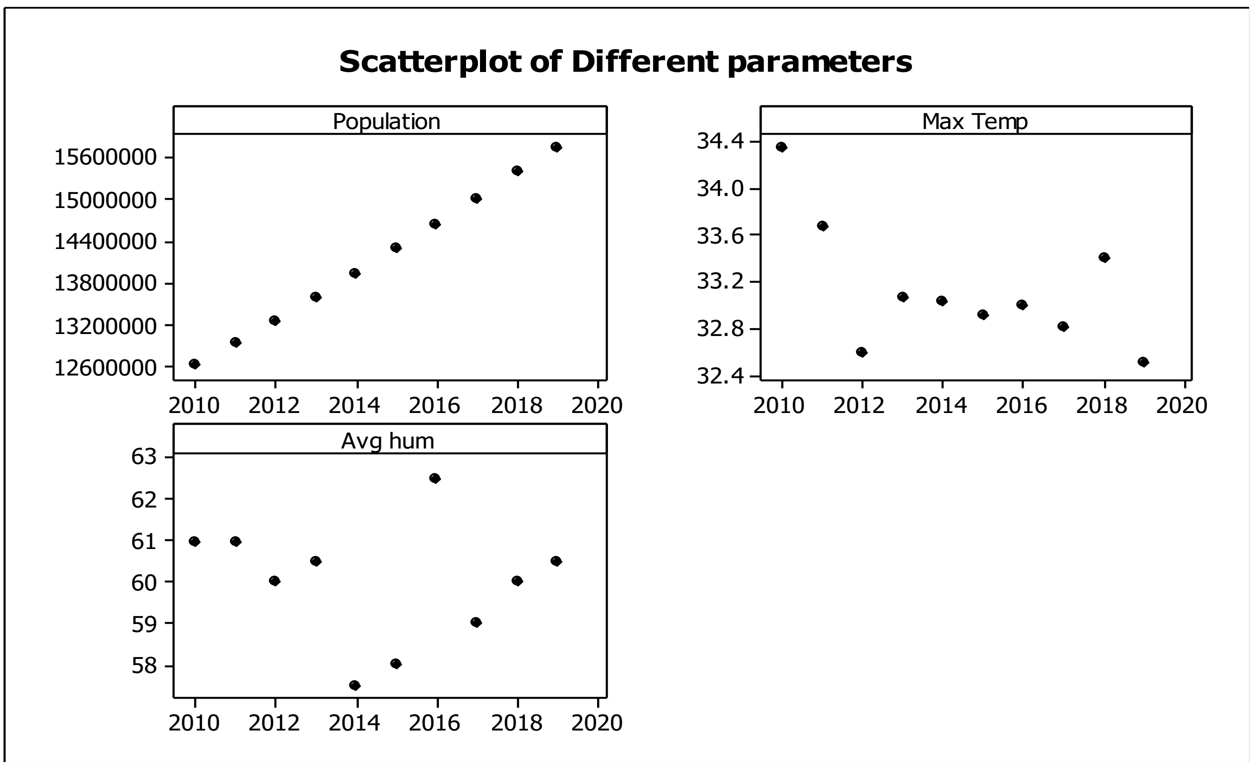

Figure 3.
Historical data for population, average temperature and humidity in Karachi from 2010-2020.

The data of the number of consumers of different sectors of electricity consumption for the same period is reported in Fig. 2, agriculture and industrial sectors have constant consumers while others different sectors have an increasing trend throughout the considered period.

The data of the population for the same period is reported in Fig. 3, and it has an increasing trend throughout the considered period. While mean maximum temperature and humidity is also reported in Fig. 3

Prediction Methods

The proposed models are designed to help us understand how different factors, such as population, temperature, and humidity, affect electricity consumption in various sectors. We can gain a better understanding of electricity consumption by analyzing these relationships. Different models were used to forecast population, population number, humidity, and temperature (Kerry, 2017 Oscar Mario, 2018), including linear, exponential, quadratic, and logarithmic models. Jeffrey K.2003, Naizhuo Zhao 2017) and selected the model that provided the best fit to the data, which improved the accuracy of predictions.

Multiple Linear Regressions

Multiple linear regressions are a statistical method used to model the relationship between a dependent variable and multiple independent variables. In this method, a multiple linear equation is used to predict the value of the dependent variable based on the values of the independent variables. Generally, the longer the data set, the more accurate the final result (Mati et al., 2009).

The multiple linear regression trend models are generally expressed as follows:

$$y=a+b_1 x_1+b_2 x_2+b_3 x_3+b_4 x_4$$

Where;

y: Dependent variable

a: Constant parameter of model

b_1,b_2,b_3,b_4: Coefficient of independent variables

x_1,x_2,x_3,x_4: Independent variables

Correlation Between Different Sectors of Electricity Consumption with Population and GDP

The correlation between electricity consumption in different sectors (domestic, commercial, industrial, Agriculture) with population, number of consumers, mean maximum temperature and average humidity are given below in table 1.

Model of Different Parameters

The models of electricity consumption in different sectors (Domestic, commercial, industrial, Agriculture and total are given below in table 2.

Error Analysis

Models of different sectors check by using of different goodness of test such as Adj R2, SSR, SSE, MSE, and F-Value (see table 3).

Table 1.

Correlation b/w electricity consumption with different parameters

MODEL	No Of Consumer	Population	Max-Temp	Avg Hum
Domestic	0.84	0.988931	0.52567	-0.09825
Commercial	0.28.	0.933017	0.53269	-0.16395
Industrial	0.527	0.946346483	0.432	-0.00321
Agriculture	0.7704	0.569319	0.60747	-0.41519
Total	0.8716	0.991893	0.50191	-0.06072

Table 2.

Mathematical Model of Different Sectors of Electricity Consumption in Karachi

Model	Equation	Parameters
Domestic	$EC = -20534 - 0.00144NOC + 0.00146P + 198T + 27.0H$	$\beta_0 = -20534, \beta_1 = -0.00144, \beta_2 = 0.00146, \beta_3 = 198, \beta_4 = 27$
Commercial	$EC = 516 - 0.00797NOC + 0.000293P - 6.6T + 10.5H$	$\beta_0 = 516, \beta_1 = -0.00797, \beta_2 = 0.000293, \beta_3 = -6.6, \beta_4 = 10.5$
Industrial	$EC = -3376 - 0.090NoC + 0.000338P + 95T + 17.4H$	$\beta_0 = -3376, \beta_1 = -0.090, \beta_2 = 0.000338, \beta_3 = 95, \beta_4 = 17.4$
Agriculture	EC =- 211+0.0944NOC+0.000008P+9.6T-5.07H	$\beta_0 = -211, \beta_1 = 0.0944, \beta_2 = 0.000008, \beta_3 = 9.6, \beta_4 = -5.07$

Table 3.

Error analysis for different sectors of electricity consumption in Karachi

Model	Adj-R^2	SSR	SSE	MSE	F values
Domestic	99.1%	12691661	60518	12104	262.15
Commercial	88.1%	672079	47587	9517	17.65
Industrial	85.7%	936948	81002	16200	14.46
Agriculture	69.1%	3040.4	630.5	126.1	6.03

Analysis For Number of Consumers Noc

According to the analysis conducted on the consumer data, various mathematical models including linear, exponential, polynomial, and logarithmic models were applied on data for forecasting. The model of different sectors of number of consumers is given below in table 4.

Table 4.
Mathematical model of number of consumers for different sectors of electricity

Model	Polynomial	Exponential	Linear	Logarithmic
Domestic	$y = 13253x^2 - 5E+07x + 5E+10$	$y = 8E\text{-}27e^{0.037x}$	$y = 69463x - 1E+08$	$y = 1E+08\ln(x) - 1E+09$
Commercial	$y = 911.79x^2 - 4E+06x + 4E+09$	$y = 98.347e^{0.0042x}$	$y = 1926.6x - 3E+06$	$y = 4E+06\ln(x) - 3E+07$
Industrial	$y = 10.598x^2 - 42678x + 4E+07$	$y = 2043e^{0.0011x}$	$y = 23.752x – 27212$	$y = 47813\ln(x) - 343135$
Agriculture	$y = -16.235x^2 + 65430x - 7E+07$	$y = 0.0001e^{0.0084x}$	$y = 19.497x – 36836$	$y = 39329\ln(x) - 296776$
TOTAL	$y = 14461x^2 - 6E+07x + 6E+10$	$y = 6E\text{-}21e^{0.0304x}$	$y = 71955x - 1E+08$	$y = 1E+08\ln(x) - 1E+09$

Models of different sectors check by using goodness of fit test such as coefficient of determination (Adj. R2). Based on coefficient of determination test, it has been determined that the polynomial model provides the best fit to the data. This conclusion is supported by the results presented in Table 5.

Table 5.
Goodness of Fit test for different sectors of number of consumers in Karachi

Model	Polynomial	Exponential	Linear	Logarithmic
Domestic	$R^2 = 0.9676$	$R^2 = 0.8108$	$R^2 = 0.7848$	$R^2 = 0.7843$
Commercial	$R^2 = 0.6489$	$R^2 = 0.2606$	$R^2 = 0.2667$	$R^2 = 0.2663$
Industrial	$R^2 = 0.6074$	$R^2 = 0.2664$	$R^2 = 0.2671$	$R^2 = 0.2667$
Agriculture	$R^2 = 0.6934$	$R^2 = 0.1375$	$R^2 = 0.1275$	$R^2 = 0.1279$
TOTAL	$R^2 = 0.9602$	$R^2 = 0.7836$	$R^2 = 0.763$	$R^2 = 0.7625$

Analysis For Population

To forecast population different mathematical model have been applied to data (linear, exponential, polynomial and logarithmic model) (Kerry, 2017, Oscar Mario, 2018. Jeffrey K.2003, Naizhuo Zhao 2017). Based on goodness of fit test polynomial is the best fitted model as shown in table 6.

Table 6.
Model and Goodness of Fit test for population in Karachi

	Polynomial	Exponential	Linear	Logarithmic
Model	$y = 3276.5x^2 - 1E+07x + 1E+10$	$y = 3E\text{-}15e^{0.0248x}$	$y = 350212x - 7E+08$	$y = 7E+08\ln(x) - 5E+09$
Adj-R²	$R^2 = 0.9999$	$R^2 = 0.9999$	$R^2 = 0.9994$	$R^2 = 0.9993$
MSE	5.19	6.54	7.4	9.29
F values	208.308	29.4	26.55	47.01

Analysis For Temperature

To forecast temperature different mathematical model have been applied to data (linear, exponential and polynomial model. Based on goodness of fit test polynomial is the best fitted model as shown in table 7.

Table 7.
Model and Goodness of Fit test for mean maximum temperature in Karachi

	POLYNOMIAL	EXPONENTIAL	LINEAR
MODEL	$y = 34.389 - 0.4405x + 0.0302273x2$	$y = 33.7190 * (0.996778^x)$	$Y = 33.724 - 0.108x$
MAPE	0.796819	0.951852	0.953044
MAD	0.263382	0.316839	0.317200
MSD	0.131209	0.178919	0.179452

Analysis For Humidity

Different mathematical model has been applied to data (linear, exponential and polynomial model). Based on goodness of fit test polynomial is the best fitted model as shown in table 8.

Table 8.
Goodness of Fit test for different sectors of electricity consumption

	POLYNOMIAL	EXPONENTIAL	LINEAR
MODEL	$Y = 62.0833 - 0.935606x + 0.0795455x2$	Y = 60.3193 * (0.998985^x)	$Y = 60.3333 - 0.0606061x$
MAPE	1.47678	1.84712	1.84235
MAD	0.88636	1.10317	1.10000
MSD	1.63561	1.96971	1.96970

Forecasted Result

The projected outcomes are presented in table 9 for the time period between 2024 and 2035 (see table 9).

Table 9.
Forecasted result of number of consumers of different sectors in Karachi Pakistan

Years	Industrial NOC	Agriculture NOC	Domestic NOC	Commercial NOC	TOTAL NOC
2024	21730	2638.77	2457937	470659	3021774
2025	21965.7	2661.1	2527400	472585	3115044
2026	22222.7	2683.62	2596863	474512	3211193
2027	22500.8	2706.33	2666326	476438	3310310
2028	22800.1	2729.23	2735789	478365	3412486
2029	23120.6	2752.32	2805252	480292	3517816
2030	23462.3	2775.62	2874715	482218	3626397
2031	23825.2	2799.1	2944177	484145	3738329
2032	24209.3	2822.79	3013640	486072	3853716
2033	24614.6	2846.68	3083103	487998	3972665
2034	25041.1	2870.77	3152566	489925	4095285

2035	25488.8	2895.06	3222029	491852	4221690

Table 10.
Forecasted result of different parameters of electricity consumptions in Karachi Pakistan

Years	Population	TEMPERATURE	Humanity
2024	17649000	33.201	65.947
2025	18077000	33.4557	67.477
2026	18520000	33.7709	69.167
2027	18978000	34.1465	71.015
2028	19449000	34.5826	73.023
2029	19934000	35.0792	75.189
2030	20432000	35.6362	77.515
2031	20944000	36.2536	80
2032	21469000	36.9315	82.644
2033	22007000	37.6699	85.447
2034	22560000	34.5826	88.409
2035	23128000	35.0792	91.53

Forecasted Result by Model

The projected outcomes are presented in table 11 for the time period between 2024 and 2035 (see table 11).

Table 11.
Forecasted result of different sectors of electricity consumption in Karachi Pakistan

Years	Industrial model	Agriculture model	Domestic NOC	Commercial NOC	TOTAL NOC
2024	4935.235	163.6702	10048.48	2409.322	17556.7
2025	5109.504	163.8902	10665.07	2533.759	18472.23
2026	5295.458	164.0177	11319.86	2663.865	19443.21
2027	5493.071	164.0619	12012.78	2799.634	20469.55
2028	5701.7	163.9977	12740.98	2940.484	21547.16
2029	5921.651	163.8431	13505.86	3086.697	22678.05
2030	6152.609	163.581	14306	3238.007	23860.2
2031	6394.896	163.2216	15142.84	3394.683	25095.64
2032	6648.183	162.7607	16014.92	3556.437	26382.3
2033	6912.47	162.1973	16922.26	3723.279	27720.21
2034	6819.245	124.24	17098.3	3921.427	27963.21
2035	7072.418	120.0209	18010.15	4101.986	29304.57

RESULTS AND DISCUSSION

Based on various parameters, such as number of consumers (NOC), temperature (T), population (P), and humidity (H), the equations provide predictions for electricity consumption (EC) in different sectors. The equations in Table 2 help us understand how different factors affect electricity consumption. For instance, in domestic sectors, when the city's population increases or the temperature goes up, people tend to use more electricity, and the number of consumers also matters. In commercial sectors, the number of consumers and the city's population impact electricity usage, and temperature and humidity also have an effect on electricity consumptions. Industrial sectors are affected by these above-mentioned parameters, and agriculture sectors benefits from more consumers and higher temperatures. The Electricity consumption of Karachi city patterns across different sectors are influenced by an involved interplay of environmental and the demographic variables.

CONCLUSION

In conclusion, the presented mathematical models in table 2 provide important and valuable insights into the complex relationship between electricity consumption and a range of different parameters in different sectors. Using these mathematical models, electricity consumption of city patterns can be easily understood and predicted value systematically by examining parameters such as number of consumers, population, temperature, and humidity. These mathematical models demonstrate the importance of taking into account multiple variables when evaluating electricity consumption trends. According to our findings, the number of consumers and demographics play an important role in shaping electricity consumption behavior in different sectors. In addition, mathematical models explain the different determinants of temperature and humidity on electricity consumption in the city, highlighting the need for critical strategies to manage electricity demand in diverse environments.

These mathematical model frameworks not only modify the correct understanding of dynamic power consumption but also offer practical applications. Policy makers, urban planners, and power sector managers can use these models to improve city and sustainability electricity efficiency. A strategy can be customized based on the coefficients derived from these equations to optimize energy distribution, predict future consumption patterns and mitigate the challenges of power crisis. This study demonstrates the potential of data analysis and mathematics in solving critical power problems and offers a path towards a more stable and resilient power system. Providing a systematic approach to mitigating the power crisis and ensuring reliable power supply and demand for various sectors is critical as societies strive for sustainable power solutions.

This study provides valuable insights into the impact of various factors on Karachi's electricity demand. This study makes a significant contribution to energy management by providing precise predictions of electricity consumption patterns across a variety of sectors in 2024-2035. Policymakers, urban planners, and energy managers can benefit from the findings. Using this guidance, Karachi can make well-informed decisions regarding electricity crises and sustainable energy practices.

IMPLICATIONS LIMITATIONS OF THE STUDY

Comprehensive research on mathematical modeling and data analysis provides important new perspectives on Karachi's energy consumption trends. The results are very helpful and can be used by urban planners and policymakers to formulate better power policies and reduce inefficient allocation of power resources. Predictions can be helpful for urban planners to optimize infrastructure development and power sector managers to optimize electricity consumption. This leads to load shedding and power outages. Despite its contributions to research, it has limitations to consider. It is based on historical data up to 2020, which may miss new trends or unexpected disruptions. It is possible that historical patterns do not always repeat themselves. Through the use of linear regression models, the complexity of power consumption, which is influenced by many variables, is illustrated. External factors such as fluctuations in global energy markets and political stability are not taken into account. Finally, since the results are specific to Karachi, their immediateness.

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Consent to Participate: Not Applicable
Consent for publication and Ethical approval: Because this study does not include human or animal data, ethical approval is not required for publication. All authors have given their consent.

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