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Measurement of the Impact of Meteorological and Macroeconomic Factors on Electricity Demand: An Empirical Analysis Based on Multiple Linear Regression

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Abstract. This study aims to analyze the combined effects of meteorological and macroeconomic factors on electricity demand in Zhejiang Province, China, using 2024 panel data, capturing China's unique post-pandemic economic recovery and energy transition context. By employing a multiple linear regression framework augmented with non-linear term analysis, results reveal a pronounced U-shaped relationship between temperature and consumption, driving dual-peak demand patterns in summer and winter, yet also identify a core tension between these efficiency gains from industrial upgrading and surging demand fueled by electrification and extreme weather. The study further diagnoses five systemic challenges, including extreme weather vulnerability, storage deficits, and a growing decoupling between electricity demand and GDP trends. To address these challenges, a policy suite is proposed, comprising dynamic pricing, industrial energy retrofits, and hybrid storage solutions. Collectively, these recommendations provide a strategic framework to bolster grid resilience and offer a transferable model for high-growth economies navigating similar energy transitions.

Keywords: Electricity Demand Forecasting, Multiple Linear Regression, Industrial Energy Efficiency, Energy Transition, Zhejiang Province

1. Introduction

1.1. Research background

The global transition to decarbonization and the increasing frequency of extreme weather events have heightened the importance of accurate electricity demand forecasting. In China, as the world's largest electricity consumer, understanding the drivers of electricity demand is critical for grid stability, energy policy formulation, and sustainable development. According to the National Energy Administration, China's total electricity consumption reached 9852.1 billion kWh in 2024, a year-on-year increase of 6.8%.

Meteorological factors (temperature, precipitation) and macroeconomic indicators (GDP, industrial output) are two key determinants of electricity demand. For instance, in 2024, due to the heat wave, the highest summer electricity load of the Shanghai power grid reached 40.3 million

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kilowatts, breaking through the 40 million kilowatt mark for the first time and increasing by 9.7% year-on-year. Meanwhile, the recovery of manufacturing (industrial added value up 5.8% in 2024) and the expansion of the service sector (retail sales growth 5.5%) further strained power grids during peak hours. Notwithstanding these empirical observations, existing studies often focus on either meteorological or macroeconomic factors in isolation or rely on outdated data (pre-2020). There is an urgent need to integrate both dimensions using recent, high-resolution data to inform adaptive strategies for the evolving energy landscape. To address this need, it is essential to first examine the existing body of literature on the key drivers of electricity demand.

1.2. Literature review

First, regarding meteorological factors, Zhang et al. estimate the causal effect of extreme temperatures on household electricity consumption using the China Residential Energy Consumption Survey. They found that one extra day with a mean temperature exceeding 32°C, relative to a day in the 10°C–16°C range, leads to an 8.9% increase in annual electricity consumption. This underscores the critical influence of temperature on consumption, yet its focus is on households rather than the total provincial-level demand that is central to grid planning [1].

Second, macroeconomic factors have also been well-documented. Lin et al. propose that GDP remains the leading factor driving electricity demand [2]. This establishes GDP as a foundational driver, but it may not fully capture the nuanced structural changes in a modern economy, such as the rapid growth of the digital and service sectors.

Third, Staffell et al. combine an analysis of the three key parts of the future power system affected by weather – wind generation, PV generation, and demand – to develop a framework for modelling the impacts of weather on electricity supply and demand [3].

Most existing studies focus on either meteorological or macroeconomic factors individually, or integrate them using outdated data. For example, Zhang et al. analyzed meteorological impacts but did not simultaneously control for macroeconomic variables like industrial structure changes [1]. Conversely, Zhou et al. examined macroeconomic drivers but overlooked recent meteorological extremes and their interaction with economic activities [4].

Moreover, few studies use 2024 data to capture China's unique post-pandemic recovery context, where service sector growth and green energy transitions have further complicated electricity demand patterns. Consequently, a significant gap exists in understanding the synergistic effects of contemporaneous meteorological and macroeconomic factors on electricity demand within China's current economic and climatic context. By contrast, this study fills these gaps by integrating both meteorological and macroeconomic factors and using 2024 panel data.

1.3. Research framework

First, integrate provincial-scale electricity consumption, meteorological observations, and macroeconomic data in 2024, eliminate dimensional differences through Z-score standardization, and construct a panel dataset consisting of four independent variables (temperature, humidity, industrial output, and consumption expenditure) and one dependent variable (electricity consumption).

Second, based on the theory of multiple linear regression, a benchmark model is set, where Y is the monthly electricity consumption (in billion kWh), X corresponds to temperature (°C), humidity (%), industrial output value (in billions of yuan), and consumer expenditure (in yuan), and ε is the random error term.

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$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \varepsilon \quad (1)$$

Finally, using OLS to estimate parameters, diagnosing heteroscedasticity through White Test, verifying sequence correlation through the Durbin Watson Test, and finally comparing the predictive performance of traditional ARIMA models through MSE (mean square error) and MAPE (mean absolute percentage error) indicators. Should heteroscedasticity or autocorrelation be detected, robust standard errors or alternative estimation techniques (e.g., Feasible Generalized Least Squares) will be employed to ensure the efficiency and reliability of the coefficient estimates.

2. Case description

To empirically investigate the drivers of electricity demand, this study conducts a focused case analysis on Zhejiang Province for the year 2024. Zhejiang was selected as a representative case study based on three criteria: (1) developed economy and significant energy consumption, ranking among China's top provinces in GDP; (2) high susceptibility to extreme weather events, particularly summer heatwaves and humid winters; and (3) diverse economic structure, featuring a robust mix of manufacturing and service industries, making it a microcosm of the national energy challenge and integrating meteorological observations and macroeconomic indicators to explore the dynamic impacts of climate factors and economic activities on electricity demand. This diverse economic profile, combined with its climatic vulnerability, makes Zhejiang an ideal microcosm for analyzing China's national energy challenges. This study leverages this context by integrating meteorological and macroeconomic indicators to explore the dynamic impacts of climate and economic activity on electricity demand. The primary objective is to develop a scientific electricity consumption prediction model, supporting energy planning and policy-making, with a particular focus on electricity demand changes under extreme weather and economic fluctuations. This study is the first to integrate multi-dimensional provincial data, revealing non-linear relationships between climate, economic factors, and electricity consumption. It provides quantitative evidence to address summer peak loads and winter heating demand.

3. Driving factors and structural shifts in electricity demand

3.1. Non-linear relationships of meteorological factors

Meteorological factors show complex, non-linear associations with electricity demand. The non-linear prototype of meteorological variables and electricity consumption: Temperature (X1) and electricity consumption (Y) exhibit a pronounced U-shaped relationship (both high temperatures in summer and low temperatures in winter affect the peak value of applied electricity), rather than a strict linear correlation; The negative correlation between humidity (X2) and electricity consumption is only significant in the high humidity range (>80%), reflecting the impact of humid environments on the efficiency of household appliance use.

Macroeconomic indicators, by contrast, demonstrate strong and direct driving forces. The dominant driving force of economic variables: The Pearson correlation coefficient between industrial output value (X3) and electricity consumption is high, indicating that the secondary industry is still the core pillar of electricity demand in Zhejiang; The correlation between consumer expenditure (X4) and electricity consumption is decent, but the lagged correlation coefficient is higher by one period, indicating a one month transmission delay in the driving force of household consumption on electricity demand.

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3.2. Macroeconomic drivers and industrial upgrading

Growth of High-Tech industries driving efficient electricity utilization: In 2024, the “three new” economic added value, characterized by new industries, new formats, and new models in Zhejiang Province, is expected to account for 28.5% of the province’s gross domestic product. The added value of core industries in the digital economy was 1.106 trillion yuan, an increase of 8.1% over the previous year. The added value of manufacturing, the core industry of the digital economy, above a certain scale, increased by 7.6%. In industries above designated size, the added value of equipment manufacturing, high-tech industries, and high-tech manufacturing increased by 10.0%, 8.3%, and 8.1% respectively, all of which were higher than the average level of industries above designated size [5]. These sectors are characterized by high added value and energy-efficient production processes, leading to a more rational allocation of electricity resources. This industrial upgrading not only boosted economic growth but also optimized electricity demand patterns, thereby reducing overall energy intensity and mitigating inefficiencies.

Policy-driven electrification accelerates demand: The province’s “dual carbon” targets have stimulated investment in electric vehicle charging infrastructure and smart grids. In 2024, the sales of electric vehicles increased by 35.8% year-on-year, and the installation of solar panels also increased, amplifying electricity demand for charging and grid balancing. Despite these positive structural shifts, Zhejiang’s power system faces significant challenges that threaten its stability and sustainability.

3.3. Emerging challenges and systemic risks

Zhejiang’s power system is confronted with five interconnected systemic risks that compound each other, threatening grid reliability, equity, and decarbonization goals.

3.3.1. Heatwave-induced grid overload: surging peak demand from concurrent cooling needs

Increasingly frequent and intense heatwaves are pushing the provincial grid to its operational limits. Extreme heat waves exacerbate power grid stress and drive peak electricity demand: In 2024, Zhejiang Province experienced 50 days of high temperature warnings (≥35°C), causing tension in the distribution networks of cities such as Hangzhou [6]. The simultaneous operation of air conditioning, industrial cooling systems, and commercial refrigeration units leads to local overload, resulting in frequent temporary power outages in the suburbs. In addition, high humidity increases the energy loss of transmission lines, further reducing the efficiency of the power grid.

3.3.2. Structural inertia: misalignment between traditional industrial base load and clean energy supply

The persistence of energy-intensive traditional industries creates a high base load that is misaligned with clean energy generation profiles. The industrial transformation of high-energy-consuming industries lags behind: Despite the overall industrial upgrading, the cumulative industrial electricity consumption in Zhejiang Province for the year was 443.54 billion kilowatt hours, a year-on-year increase of 8.2%. Traditional industries still rely on thermal power and outdated machinery, resulting in low electricity utilization rates. During the winter heating season, when the temperature drops below 0°C, the demand for industrial steam surges, forcing coal-fired power plants to increase production. This not only increases carbon emissions but also creates a mismatch between clean energy supply and the inflexible basic load demand of traditional industries. This creates a structural

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lock-in effect, perpetuating reliance on fossil fuels and delaying the integration of cleaner energy sources.

3.3.3. Residential load polarization: widening daily peak-valley gaps from divergent consumption patterns

Socioeconomic polarization in residential electricity use is widening the daily load gap, as inefficient consumption in low-income households coincides with high-wattage, extended-use patterns in affluent homes, thereby destabilizing grid balance. The polarization of residential electricity load deteriorates the stability of the power grid: In 2024, the electricity consumption of urban and rural residents reached 102.64 billion kilowatt hours, a year-on-year increase of 14.2%, and there was a clear polarization between low-income and high-income households. Low-income households in rural areas often rely on old and inefficient appliances, which increases energy waste. At the same time, high-income households in major cities such as Hangzhou have adopted high-power household appliances and extended the use of air conditioning, resulting in a significant increase in nighttime peak load. This polarization widens the daily load gap, making it more difficult for the power grid to balance supply and demand without expensive peak shaving units.

3.3.4. Renewable curtailment crisis: grid-scale storage deficit undermining decarbonization

A severe shortage of grid-scale energy storage capacity leads to significant curtailment of renewable generation, forcing continued dependence on fossil-fuel peaking plants and hindering decarbonization progress. Insufficient energy storage infrastructure for intermittent renewable energy sources: Despite a substantial and growing share of renewable generation in the energy mix (solar and wind combined generated 31.742 billion kWh), a severe shortage of grid-scale energy storage capacity leads to significant curtailment. In 2024, the power generation of thermal, hydro, nuclear, wind, and solar power in Zhejiang Province will be 339.68 billion kilowatt hours, 17.61 billion kilowatt hours, 75.54 billion kilowatt hours, 15.71 billion kilowatt hours, and 16.032 billion kilowatt hours, respectively. Due to the mismatch between peak renewable energy generation and demand cycles, the rapid expansion of solar and offshore wind power in Zhejiang has posed challenges to grid integration. Solar energy output reaches its peak at noon, while residential and commercial loads surge in the morning and evening, resulting in excess electricity not being used. By 2024, only a small portion of renewable energy will be stored in batteries, while the rest will either be reduced or exported to neighboring provinces. This inefficiency not only wastes clean energy but also increases reliance on fossil fuel peaking power plants during periods of low renewable energy, undermining the province's decarbonization goals. This curtailment-representation gap represents a critical bottleneck for achieving high renewable penetration.

3.3.5. Forecasting model breakdown: decoupling of electricity demand from GDP trends

The fundamental decoupling of electricity demand growth from GDP trends, driven by rising electrification, invalidates traditional forecasting models that rely on historical elasticity coefficients, introducing systematic downward bias into demand projections into predictions. Meteorological-GDP coupling introduces model bias: In recent years, the growth rate of electricity consumption in China has consistently exceeded that of GDP. When analyzing the relationship between the growth rate of electricity consumption and economic development, the elasticity coefficient of electricity consumption (electricity consumption growth rate/GDP growth rate) is usually used as a research

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indicator. However, there is a significant structural difference between China's electricity consumption and GDP, resulting in a deviation between the growth rate of electricity consumption and GDP. In recent years, the increase in electricity consumption per unit of GDP has led to a higher growth rate of electricity consumption than GDP in most years, and the improvement of the electrification level is the main reason for the increase in electricity consumption per unit of GDP. Due to efficiency gains and rising electrification, traditional elasticity-based forecasting models are becoming systematically biased and require fundamental recalibration [7].

4. Policy recommendations and mitigation strategies

Despite the positive structural shifts and efficiency gains outlined in Section 3, Zhejiang's power system faces five persistent and interconnected challenges that threaten its stability, equity, and progress in decarbonization. These recommendations are prioritized to address immediate grid reliability concerns while laying the groundwork for long-term structural reform.

4.1. Dynamic pricing mechanisms for extreme weather mitigation

To address the peak grid stress from extreme heatwaves (Challenge 1), this study proposes implementing real-time electricity pricing models to incentivize off-peak consumption during heatwaves. A study by Chin et al. demonstrated that dynamic tariffs reduce peak demand by 15–20% through price elasticity [8]. Zhejiang could adopt tiered pricing structures with AI-driven demand response systems to balance grid stress during extreme temperatures, targeting a peak demand reduction of 15-20% during heatwave alerts.

4.2. Industrial energy efficiency retrofits

To mitigate the high base load and inefficiency of traditional industries (Challenge 2), this study recommends a program to target high-energy-consuming sectors with subsidies for advanced technologies like variable-frequency drives and heat recovery systems. Wang et al. showed that retrofitting industrial boilers can lower electricity intensity [9]. Pilot programs in Zhejiang's industrial zones could serve as scalable models. Specific actions include establishing an energy efficiency retrofit fund and creating a 'white list' of subsidized technologies, with a goal to reduce sectoral electricity intensity by 10% within five years.

4.3. Smart grid-enabled residential load management

To bridge the residential consumption polarization and stabilize the grid (Challenge 3), this study proposes deploying IoT-enabled smart meters and community-level energy management platforms to optimize residential consumption patterns. Moniruzzaman et al. highlighted that peer-to-peer energy trading in smart grids reduced peak-to-average load ratios in pilot projects [10]. The provincial government should initiate a subsidy program for low-income households to upgrade to energy-efficient appliances, which could also mitigate polarization.

4.4. Hybrid energy storage solutions

To resolve the renewable energy curtailment and storage shortage (Challenge 4), a hybrid solution is essential: Integrate battery storage with pumped hydro storage to absorb surplus renewable energy. The International Energy Agency reported that hybrid systems can significantly increase renewable

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utilization rates [11]. Zhejiang should prioritize coastal regions for pumped hydro projects due to leveraging its coastal mountainous terrain for pumped hydro storage. Immediate steps should involve conducting feasibility studies for coastal pumped hydro sites and launching tenders for large-scale battery storage projects.

4.5. Elasticity model refinement

To overcome the bias in traditional forecasting models (Challenge 5), this study advocates for the development of a hybrid forecasting model incorporating weather normalization and structural breaks to decouple GDP-electricity correlations. Wang et al. validated that such models reduce forecasting errors in transitioning economies [12]. This study urges the provincial energy bureau to establish a joint working group comprising grid operators (State Grid Zhejiang) and academic institutions (e.g., Zhejiang University) to refine parameter specifications.

5. Conclusion

This study advances understanding of electricity demand drivers in China's post-pandemic era by integrating meteorological and macroeconomic factors through a timely and granular 2024 provincial panel dataset. This paper's analysis reveals that Zhejiang's electricity system is caught in a critical transition, where climate vulnerabilities and institutional inertia concurrently strain the benefits of industrial upgrading and electrification. Key findings reveal non-linear temperature effects, industrial modernization's mixed impacts, and systemic risks from storage gaps. A central tension identified is the coexistence of progressive demand-side modernization alongside persistent, system-level fragilities. Strategic recommendations—dynamic pricing, industrial retrofits, smart grids, hybrid storage, and model refinement—provide a strategic framework to bolster grid resilience.

Research Significance: The findings bridge theoretical frameworks and practical applications, providing policymakers with validated tools to navigate climate-energy-economic tradeoffs. From an industrial perspective, the emphasis on efficiency retrofits and storage integration aligns with global decarbonization trends, positioning Zhejiang as a replicable model for emerging markets.

Limitations: Secondary data constraints limited the granularity in behavioral analysis. Future research should prioritize primary data collection, including household surveys, to empirically quantify income-driven consumption polarization. Furthermore, longitudinal case studies tracking the performance of large-scale storage deployments are essential for validating and refining the proposed policy recommendations. Notwithstanding these limitations, this study provides a comprehensive diagnostic framework and an actionable policy toolkit for navigating the complex energy transition facing Zhejiang and other similarly positioned high-growth economies.

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