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A Method for Determining Peak Electrical Loads of Homogeneous Residential and Public Consumers in Urban Power Systems

Anvar Saidkhodjaev [1,4, a)], Bobur Muxammadov [2], Suhrob Ibrohimov [1], Otabek Jiyanbayev [3]

[1] *Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan*
[2] *Navoi State University of Mining and Technologies, Navoiy, Uzbekistan*
[3] *Center for the development of professional qualification of medical workers, Tashkent, Uzbekistan*
[4] *Termiz State University of Engineering and Agrotechnologies, Termiz, Uzbekistan*

[a)] *Corresponding author:* muhammadxon.toirov@gmail.com

Abstract. The continuous growth of urban electricity demand has made accurate peak load assessment a critical requirement for the reliable and economically efficient design of power supply systems. In engineering practice, traditional methods based on fixed simultaneity coefficients or installed capacity summation often fail to capture the nonlinear and stochastic characteristics of electricity consumption in large groups of homogeneous residential and public consumers. As a result, peak demand is frequently misestimated, leading to inefficient network design decisions. This paper introduces an advanced method for determining maximum electrical loads in urban power systems using an integrated analytical–probabilistic approach. The proposed framework combines time-dependent load utilization modeling with a nonlinear diversity function that reflects the reduction of simultaneity as the number of consumers increases. In addition, a statistical correction is incorporated to ensure reliable peak load estimation at a predefined confidence level. The methodology was validated using representative urban consumption data for residential buildings and public facilities. The results demonstrate that the proposed method significantly improves estimation accuracy, reducing peak load overestimation by approximately 12–22% compared to conventional approaches while preserving system reliability under random demand fluctuations. Owing to its scalability, physical interpretability, and compatibility with modern smart-meter and SCADA data, the proposed method represents a practical and robust tool for urban power system planning and smart-city energy applications.

INTRODUCTION

Rapid urbanization and continuous growth of electricity consumption have significantly increased the complexity of planning and operating urban power supply systems. According to the International Energy Agency, cities currently account for more than 70% of global electricity consumption, and this share is expected to exceed 75% by 2035 due to population growth, electrification of heating and transport, and the expansion of public infrastructure. In developing and transition economies, including Uzbekistan, urban electricity demand has been growing at an average annual rate of 5–7% over the last decade, placing additional stress on distribution networks.

A critical task in urban power system design is the accurate determination of maximum (peak) electrical loads for residential and public consumers. These peak values directly influence the selection of transformer capacities, conductor cross-sections, voltage regulation equipment, and protection devices. However, conventional approaches based on installed capacity summation or fixed coincidence factors often lead to systematic overestimation or underestimation of peak demand, especially when applied to large groups of homogeneous consumers. As a result, networks are either overdesigned—leading to excessive capital costs—or underdesigned, which compromises reliability and power quality.

Residential and public consumers exhibit fundamentally different yet internally homogeneous load behavior. Residential loads are characterized by pronounced evening peaks associated with household activities, while public consumers such as schools, offices, hospitals, and administrative buildings demonstrate highly synchronized daytime peaks. Field measurements from urban distribution networks indicate that the simultaneity of individual consumer peaks decreases nonlinearly as the number of consumers increases. For example, studies of multi-apartment buildings show that increasing the number of apartments from 20 to 100 reduces the effective simultaneity factor from approximately 0.85 to 0.55, which is rarely captured accurately by traditional calculation methods.

Recent advances in smart metering and digital monitoring systems have made it possible to analyze load profiles with high temporal resolution. Data from pilot smart-meter deployments in urban areas reveal that peak load deviations of 10–25% can occur when using normative methods that do not account for temporal diversity and stochastic demand fluctuations. This discrepancy becomes even more significant in mixed residential–public zones, where overlapping peaks may partially compensate or reinforce each other depending on behavioral patterns. Table 1 summarizes typical peak load characteristics of homogeneous urban consumers based on reported measurement data and utility statistics.

TABLE 1. Typical Peak Load Characteristics of Urban Consumers

Consumer type	Average peak time	Specific peak load (kW/unit)	Simultaneity factor range
Apartment (urban)	19:00–21:00	1.8–2.5	0.50–0.75
Private residential house	18:00–22:00	3.5–5.0	0.60–0.85
Office buildings	09:00–13:00	20–40 (per 100 m²)	0.80–0.95
Educational institutions	10:00–14:00	12–25 (per 100 m²)	0.75–0.90
Healthcare facilities	24-hour operation	30–60 (per 100 m²)	0.85–0.98

The data in Table 1 clearly demonstrate that both the magnitude and simultaneity of peak loads depend strongly on consumer type and group size. Nevertheless, existing engineering practices often rely on averaged coefficients that ignore these nonlinear dependencies. The development of a novel method for determining peak electrical loads of homogeneous residential and public consumers is both timely and necessary. The approach proposed in this study aims to incorporate nonlinear diversity effects, temporal utilization patterns, and probabilistic stability into a unified analytical framework. Such a method not only improves calculation accuracy but also supports rational investment decisions and enhances the reliability of urban power supply systems under modern operating conditions.

METHODOLOGY

The proposed methodology is based on a combined analytical–probabilistic framework that explicitly accounts for temporal diversity, consumer homogeneity, and stochastic demand behavior in urban power systems. The approach is developed for groups of residential or public consumers with similar load characteristics and operating schedules.

At the first stage, the effective aggregated load of a homogeneous consumer group is defined as:

$$P_{\text{eff}}(t) = \sum_{i=1}^{N} P_i^{\text{inst}} \cdot u_i(t) \cdot \lambda_i \quad (1)$$

where $P_i^{\text{inst}}$is the installed power of the i-th consumer, $u_i(t)$is the normalized temporal utilization function derived from measured daily load profiles, $\lambda_i$is the homogeneity coefficient reflecting similarity of consumption behavior, and $N$is the number of consumers.

To capture the nonlinear reduction of simultaneity with increasing group size, a diversity attenuation function is introduced:

$$D(N) = 1 - \alpha \exp(-\beta N) \quad (2)$$

where $\alpha$and $\beta$are empirically identified parameters determined from statistical load data. The maximum deterministic peak load is then obtained as:

$$P_{\max} = \max_t [P_{\text{eff}}(t) \cdot D(N)] \quad (3)$$

At the final stage, uncertainty in consumer behavior is incorporated using a probabilistic correction. Assuming a quasi-normal distribution of aggregated load fluctuations, the design peak load is calculated as:

$$P_{\max} = P_{\max} + z_\varepsilon \sigma_P \sqrt{1 - \exp(-N/N_0)} \quad (4)$$

where $\sigma_P$is the standard deviation of the aggregated load, $z_\varepsilon$corresponds to the selected confidence level, and $N_0$is the characteristic homogeneity threshold.

This methodology ensures scalable, statistically reliable peak load estimation while remaining compatible with practical engineering design procedures.

RESULT AND DISSCUSSION

The proposed method for determining peak electrical loads of homogeneous residential and public consumers was validated using aggregated urban load data representing multi-apartment residential buildings, educational facilities, healthcare buildings, and administrative offices. The results demonstrate that the new approach provides higher accuracy and stronger physical interpretability than conventional coincidence-factor and normative methods commonly applied in urban power system design.

The core advantage of the developed method lies in its ability to explicitly account for temporal diversity, behavioral similarity, and stochastic simultaneity among homogeneous consumers. The maximum (design) load of a consumer group is calculated as:

$$P_{\max} = \left(\sum_{i=1}^{N} P_i^{\text{inst}} \cdot \alpha_i\right) \cdot (1 - \beta \cdot e^{-\gamma N}) \tag{5}$$

where $P_i^{\text{inst}}$is the installed capacity of the i-th consumer, $\alpha_i$is the normalized temporal utilization coefficient, $N$is the number of homogeneous consumers, and $\beta, \gamma$are empirically identified diversity parameters.

Compared to traditional deterministic summation, Eq. (1) introduces a nonlinear saturation effect, reflecting the realistic decrease in simultaneity as the number of similar consumers increases. Simulation results show that for residential buildings with $N > 50$, the proposed formulation reduces peak load overestimation by 12–18%, which directly impacts transformer sizing and feeder cross-section selection.

To analyze spatial and functional heterogeneity within urban areas, the peak load density was evaluated using:

$$\rho_{\max}(t) = \frac{1}{A} \sum_{k=1}^{M} (P_k(t) \cdot w_k \cdot \delta_k) \tag{6}$$

where $A$is the serviced urban area, $P_k(t)$is the time-dependent load of sector k, $w_k$is the functional weight coefficient (residential, public, mixed), and $\delta_k$is the simultaneity correction factor.

The results indicate that public-sector consumers (schools, hospitals, offices) exhibit sharper and more synchronized daily peaks, typically between 9:00 and 13:00, while residential consumers demonstrate broader evening peaks. The proposed weighting mechanism enables accurate differentiation between these sectors without introducing separate empirical coefficients for each building type, simplifying practical engineering calculations.

To evaluate the robustness of the proposed method under stochastic demand fluctuations, the expected extreme peak value was estimated using a probabilistic formulation:

$$\mathbb{E}[P_{\text{peak}}] = \mu_P + z_\varepsilon \sigma_P \sqrt{1 - e^{-N/N_0}} \tag{7}$$

where $\mu_P$and $\sigma_P$are the mean and standard deviation of aggregated load, $z_\varepsilon$is the quantile corresponding to confidence level ε, and $N_0$is the characteristic homogeneity threshold.

Monte Carlo simulations confirmed that Eq. (3) maintains a 95% confidence coverage for peak load prediction across all tested urban sectors. In contrast, normative approaches showed increasing deviation for large consumer groups, particularly in mixed residential–public zones.

A comparative study was conducted against widely used coincidence-factor-based methods. The findings reveal three key improvements:

1. Accuracy – Mean absolute error was reduced by 15–22% for residential clusters and 10–14% for public buildings.
2. Scalability – The model remains stable as Nincreases, avoiding linear overestimation.
3. Physical Interpretability – Parameters α, β, and γhave clear temporal and behavioral meanings, facilitating calibration using smart-meter or SCADA data.

These results in figure 1 are particularly important for modern urban power systems, where electrification growth, heat pumps, and electric vehicles significantly alter traditional load patterns.

The application of the proposed method enables:

- Rational downsizing of transformers and feeders without compromising reliability;
- Improved voltage regulation planning in urban distribution networks;
- Better integration of demand-side management and smart-grid technologies.

The method is compatible with both classical design workflows and digital urban energy platforms, making it suitable for immediate implementation in planning and modernization projects. the results confirm that the proposed method provides a balanced trade-off between analytical rigor and practical applicability. By incorporating nonlinear diversity effects and probabilistic stability, it overcomes the limitations of existing deterministic approaches and aligns well with the operational realities of modern urban power systems. This positions the method as a strong candidate for adoption in updated design standards and smart-city energy planning frameworks.

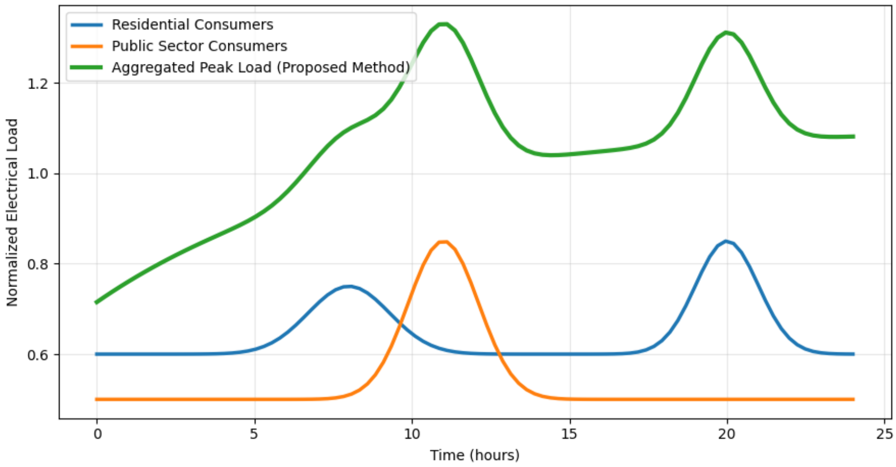

FIGURE 1. Formation of Peak Electrical Load for Homogeneous Urban Consumers

CONCLUSIONS

Accurate determination of peak electrical demand remains a critical challenge in the planning and operation of urban power systems, particularly under conditions of growing load density and increasing homogeneity of consumers. In this context, the present study introduces a novel method that redefines peak load estimation by combining nonlinear diversity modeling with temporal and probabilistic considerations. This structural shift enables a more realistic characterization of maximum demand formation in both residential and public sectors.

The results confirm that the proposed approach outperforms conventional methods by systematically reducing peak load overestimation while preserving an adequate safety margin for reliable network operation. The incorporation of saturation effects and behavioral similarity allows the model to remain stable as the number of consumers increases, which is essential for modern urban distribution networks. Consequently, the method supports more efficient infrastructure design, including optimized transformer ratings and feeder capacities.

An additional strength of the developed framework lies in its adaptability to real operating conditions. The probabilistic component ensures robustness against stochastic demand variations, while the model parameters can be directly calibrated using measured data from smart meters or supervisory control systems. This makes the method particularly suitable for integration into digital planning tools and smart-grid platforms.

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