

Illuminating Inequality: Public Lighting Energy Consumption and Light Pollution in Urban and Rural Contexts

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This paper investigates the spatial and social dimensions of light pollution through the lens of electricity consumption and technical losses related to public lighting across Hungarian municipalities, focusing on the Western Transdanubia region. Unlike traditional approaches based on remote sensing, this paper employs local-level electricity use data as a proxy for assessing light pollution intensity. Notably, several sparsely populated rural settlements display disproportionately high per capita electricity use and losses, suggesting inefficiencies, potential over-lighting, and elevated exposure to light pollution. The inclusion of technical losses provides a more accurate picture of systemic inefficiency that may contribute to excessive artificial illumination without corresponding social benefit. These findings underscore the relevance of electricity data as an indirect but actionable source for evaluating light pollution and energy waste. The paper advocates for more data-driven, environmentally conscious, and socially equitable lighting policies that integrate energy efficiency and light pollution mitigation into local planning frameworks. Based on data from 657 municipalities, total public lighting consumption ranges from under 10 MWh in small villages to over 1,000 MWh in large cities, with a regional average of 51.3 MWh (SD: 338.3 MWh). Per capita consumption varies between 0.002 and 0.02 MWh/person, with technical losses up to 17.9 kWh/person in some rural areas. These results indicate that energy inefficiency and light pollution are often more pronounced in small settlements, highlighting the need for regionally tailored modernization strategies addressing both energy use and environmental impact.

1. Introduction

Public lighting constitutes a vital component of urban and rural infrastructure, contributing to safety, mobility, and the perceived quality of life (Castilla et al., 2024). However, it also represents a significant source of energy consumption and environmental disturbance, particularly through its contribution to light pollution (Ścieżor, 2021). In recent decades, the proliferation of artificial lighting has become a pressing ecological and social concern (Morgan-Taylor, 2023), with its impacts extending beyond energy inefficiency to include disruptions to circadian rhythms, biodiversity loss, and inequitable exposures among populations (Zielinska-Dabkowska et al., 2023). Despite growing awareness (Nadybal et al., 2020), the spatial and social disparities in public lighting practices remain underexplored, particularly in Central and Eastern European contexts, where infrastructural legacies and uneven development patterns continue to shape municipal energy use (Köteles and Torma, 2024). Light pollution remains a largely overlooked issue within the urban and community-related dimensions of the Sustainable Development Goals (SDGs), despite its growing relevance alongside other critical concerns related to environmental health, public safety, and quality of life (Macher et al., 2023b).

Studies have increasingly pointed to the uneven distribution of artificial lighting as a manifestation of broader spatial injustices (Zissis, 2020). Urban cores tend to concentrate technologically advanced lighting systems, often benefiting from smart infrastructure investments and policy attention, while peripheral and rural areas may rely on outdated or inefficient technologies (Wei et al., 2024). These disparities not only reflect economic and administrative capacity, but also raise normative concerns about environmental justice, as communities with limited resources may suffer both from under-illumination, affecting safety and accessibility, and from over-illumination, resulting in excessive energy use and light trespass (Tavares et al., 2021).

Light pollution is increasingly recognized as a systemic issue with far-reaching ecological consequences (Jägerbrand, 2020). Overexposure to artificial light at night disrupts nocturnal habitats, affects reproductive cycles of various species, and alters predator-prey dynamics (Russart and Nelson, 2018). In human contexts, the unequal spatial distribution of artificial light at night correlates with patterns of socioeconomic status, urban form, and infrastructure density, yet few studies have attempted to quantitatively link municipal-level electricity use with demographic or land-use indicators (Tong et al., 2021). Particularly in post-socialist countries such as Hungary, where historical infrastructure investments were shaped by central planning and later unevenly transformed through market liberalization, light pollution may take on unique forms that reflect both legacy systems and contemporary urban-rural divides (Kolláth et al., 2016).

Therefore, a closer examination of public lighting energy consumption through the lens of spatial equity and infrastructural geography is essential. Beyond environmental impacts, lighting infrastructure can be seen as a proxy for broader issues of territorial governance, administrative autonomy, and access to technological modernization (Nadybal et al., 2020). By disaggregating consumption patterns across different settlement types and relating them to socio-economic variables, this paper seeks to contribute to a more nuanced understanding of how light pollution is produced, distributed, and potentially mitigated within national and regional systems. This paper investigates the heterogeneity of public lighting energy consumption across Hungarian municipalities, with a specific emphasis on the urban-rural divide (Cox et al., 2022). While urban centers are often presumed to be the primary contributors to light pollution due to higher population densities and more intensive land use, emerging evidence suggests that rural areas may also display disproportionately high levels of artificial light, albeit for different infrastructural or administrative reasons (Cox et al., 2020). Addressing these patterns is critical for understanding the underlying drivers of light pollution and for designing equitable and efficient lighting policies.

The novelty of this research lies in its methodological approach. Rather than relying on remote sensing data, which, although widely used in light pollution studies, is often constrained by resolution and cloud cover limitations, this paper employs municipal-level electricity consumption data specific to public lighting. This dataset enables a more grounded and granular analysis of lighting-related energy use, situated within the socio-demographic and infrastructural characteristics of each locality.

By foregrounding public lighting as a nexus of energy justice, spatial planning, and environmental governance, this paper contributes to a growing interdisciplinary discourse on sustainable infrastructure. In doing so, the research seeks to inform policy interventions aimed at balancing visibility, safety, and environmental stewardship across diverse settlement types.

2. Methodology

This paper investigates the heterogeneity of public lighting energy consumption across Hungarian municipalities, with a specific emphasis on the urban-rural divide. The research employs municipal-level electricity consumption data specific to public lighting, enabling a more grounded and granular analysis of lighting-related energy use. This dataset is situated within the socio-demographic and infrastructural characteristics of each locality. The analysis aims to relate consumption patterns across different settlement types to socio-economic variables. The central hypothesis of this research is that municipality-level electricity consumption and technical losses from public lighting can serve as effective indirect indicators of light pollution and energy inefficiency. The study assumes that spatial and demographic characteristics, such as settlement size, population density, and infrastructure age, systematically influence both total and per capita electricity use. Conceptually, the paper integrates principles from energy justice, spatial inequality, and environmental governance, proposing that disparities in lighting efficiency reflect broader patterns of infrastructural inequity and environmental externalities.

2.1 Data Acquisition and Preparation

The empirical foundation of this paper is a municipality-level dataset that captures electricity consumption attributable to public lighting across Hungarian localities. Electricity usage data were obtained from the Hungarian Central Statistical Office, based on annual reports concerning electricity use for public service provision. The analysis is based on data from the year 2023, the most recent period for which complete records were available. The primary geographical focus of the research was the Western Transdanubian region of Hungary, encompassing the counties of Győr-Moson-Sopron, Vas, and Zala. This region serves as a representative context for examining spatial disparities in public lighting practices and energy usage, given its diverse settlement structures and uneven infrastructural development. The area is well-suited for exploring well-documented regional inequalities (Macher et al., 2023a), which have historically shaped differences in municipal service provision and energy infrastructure across Hungarian territories. All variables were harmonized at the municipality level to ensure consistency and comparability. Data preprocessing involved cleaning for missing or

erroneous entries and normalizing variables to facilitate meaningful comparisons across settlements of varying size.

2.2 Spatial Analysis Techniques

The basic spatial unit of analysis was the municipality, which in Hungary typically serves as the administrative entity responsible for managing public lighting infrastructure. To assess the degree of spatial clustering in public lighting electricity consumption, we applied spatial autocorrelation analysis. This helped evaluate whether high or low consumption values were randomly distributed or formed significant spatial clusters.

2.3 Analytical Framework

The choice of a data-driven, statistical approach over remote sensing was motivated by the availability of detailed, local-level electricity data and the need for quantitative comparability across municipalities. This approach enables the identification of hidden inefficiencies and supports the formulation of evidence-based lighting policies. A schematic overview of the research procedure is presented in Figure 1, illustrating the workflow from data acquisition to policy recommendations.

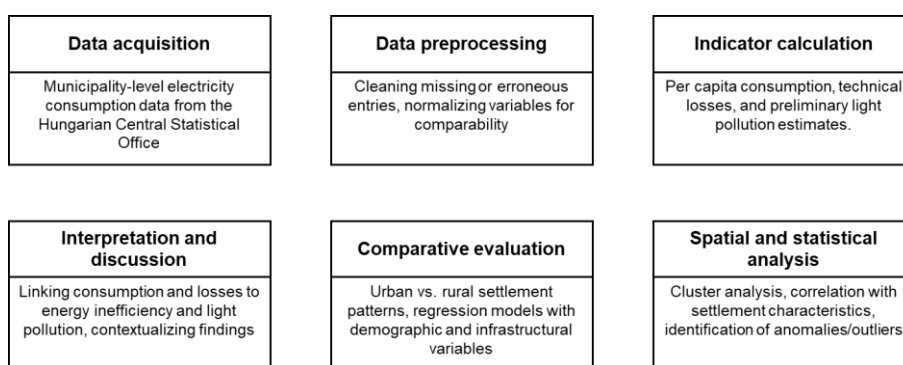


Figure 1: Detailed workflow of the research methodology, from data acquisition to policy recommendations

To operationalize the urban–rural divide, we followed the official Hungarian settlement classification. Municipalities were grouped into two broad categories: urban (including towns and cities with county rights) and rural (villages and large villages), enabling comparative analysis across differing settlement types. Comparative analysis relied on descriptive statistics to assess differences in mean consumption and distribution between urban and rural areas. Interaction terms were also introduced into the regression models to examine whether the effects of demographic and infrastructural variables varied by settlement type. This multidimensional framework, combining spatial statistical methods, regression modeling, and comparative analysis, provides a comprehensive basis for examining the energy geography of public lighting in Hungary. It also lays the groundwork for the development of a future quantitative light pollution indicator and for the formulation of more equitable and energy-conscious public lighting strategies. To support this aim, the paper applies a light pollution emission factor of 0.20 kWh/kWh, meaning that an estimated 20 % of public lighting electricity consumption is emitted as upward or misdirected light, directly contributing to light pollution (Marnane, 2022). This operational assumption enables the preliminary quantification of environmentally ineffective energy use and facilitates future light pollution footprint estimations at the municipal level.

3. Results

The analysis focuses on municipality-level data across the three counties of the Western Transdanubia region (Győr-Moson-Sopron, Vas, and Zala), examining public lighting electricity consumption, permanent population figures, and per capita electricity demand for public lighting. The dataset includes 657 settlements, and the analysis explores the annual public lighting electricity consumption (measured in 1 MWh), the number of permanent residents, and the derived indicator of per capita electricity use for public lighting (1 MWh/person), with emphasis on statistical and spatial patterns. The distribution of electricity consumption for public lighting across the municipalities of the region is strongly right-skewed, as evidenced by the high standard deviation (338.3 MWh) and an average value (51.3 MWh) that is significantly higher than the median (15.0 MWh). This skewness indicates that a few large cities with exceptionally high consumption substantially raise the average, while the majority of municipalities exhibit considerably lower consumption values. A similar distributional characteristic is observed in population figures, which underscores the urban-rural demographic divide. A large

proportion of the smaller settlements have populations in the range of 200-1,000 inhabitants, while a few major cities (such as Győr, Zalaegerszeg, and Szombathely) exhibit outstanding demographic weights, which are also reflected in their aggregated public lighting electricity demand (Figure 2a).

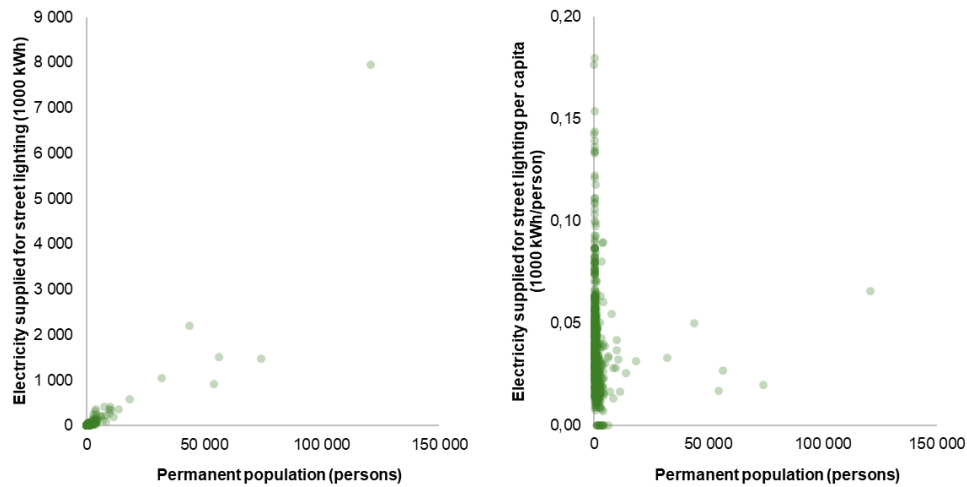


Figure 2: Comparison between the amount of electricity used for street lighting and the population of the municipalities (a: aggregate, b: per capita)

In contrast, the spatial and statistical patterns of per capita electricity consumption for public lighting differ significantly from those of the previous two indicators (Figure 2b). While aggregate consumption values are largely driven by the degree of urbanization, the per capita indicator does not show a linear correlation with either population size or settlement type. Descriptive statistics reveal a high degree of dispersion around the central value, with numerous outliers among smaller settlements reporting exceptionally high values. This suggests that in certain villages, public lighting energy consumption is disproportionately high relative to the population, potentially due to factors such as infrastructural characteristics, dispersed settlement structures, or deficiencies in energy efficiency. Such statistical anomalies, particularly extremely low or high per capita values, underscore the need for data-driven planning of electricity demand. Many of the highest values are observed in settlements with very low population numbers, where public lighting energy consumption represents a fixed cost that remains largely independent of demographic size. In contrast, larger cities tend to exhibit more stable and balanced per capita values, reflecting the economies of scale and the uniformity of service provision typical of urban infrastructure systems. Across the entire regional settlement structure, it can be concluded that public lighting electricity consumption is influenced not solely by demographic variables but also by factors such as infrastructure development, the proportion of public space, settlement morphology, and the technological characteristics of lighting systems. Therefore, the per capita consumption indicator, while informative, is not in itself sufficient for drawing conclusions about efficiency or sustainability. Rather, it serves an indicative function and should be interpreted in conjunction with qualitative and contextual analyses.

In addition to examining consumption levels and per capita indicators, the analysis also accounts for estimated electricity losses associated with public lighting systems. These losses, which arise from technical inefficiencies such as outdated infrastructure, suboptimal grid layouts, or transmission and distribution losses, can significantly distort the actual energy demand profile. By incorporating loss estimation into the spatial analysis, a more realistic assessment of electricity usage is achieved, particularly in cases where high per capita values may be partially attributed to inefficiencies rather than actual service needs. Figure 2 illustrates the calculated values of these losses across the municipalities, highlighting spatial disparities and drawing attention to areas where modernization efforts may yield substantial improvements in energy efficiency and cost-effectiveness.

Based on the settlement-level data regarding electricity losses related to public lighting, it can be concluded that there are significant disparities both in absolute values and in per capita losses. Larger cities - such as Győr, Mosonmagyaróvár, Szombathely, or Sárvár - naturally exhibit higher total losses, which can be attributed to factors such as population size, the scale of infrastructure, and the extent of the distribution network. However, the per capita values provide a more nuanced perspective on local efficiency. There are smaller settlements where, despite the low total losses, the per capita figures are relatively high (Csér, Bajánsenye, or Bük). In the latter case, one of the highest per capita losses (17.9 kWh/person) is observed alongside a low absolute loss,

a result of the small population inflating the per capita metric. In contrast, several medium-sized settlements display a more balanced profile, with both absolute and relative losses hovering around the average (Figure 3). It is also noteworthy that in the records for several municipalities, the value appears as zero, which may reflect either an actual absence of losses or indicate administrative shortcomings.

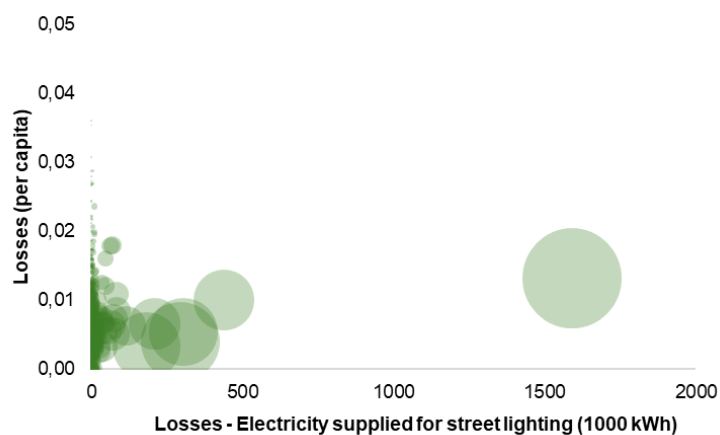


Figure 3: Comparison of the values of the loss factors and the population of the municipalities

Overall, the dataset shows substantial statistical variance, indicating that the energy efficiency of public lighting systems is highly heterogeneous across regions. The highest per capita losses exceed 0.02 MWh/person, while numerous settlements report values below 0.002 MWh/person, representing differences of up to an order of magnitude.

4. Discussion

The findings highlight that electricity consumption for public lighting and the associated energy losses are not solely technical or economic issues, but are also closely linked to the problem of light pollution. Several previous studies (Nadybal et al., 2020) emphasize that excessive, poorly directed, or outdated public lighting contributes not only to energy waste but also to significant environmental impacts, particularly in terms of nighttime ecosystem disruption, as well as human health and well-being.

The variation in per capita losses across the studied municipalities can, in part, be explained by the presence of oversized or inefficient lighting systems, which often lack modern control technologies such as timers, motion sensors, or light-sensitive switches. These systems not only waste energy but also generate unnecessary light pollution, especially in small, sparsely populated, or widely dispersed settlements (Agramelal et al., 2023). The link between light pollution and energy loss has been highlighted in previous research (e.g., Gallaway et al., 2010), which suggests that more efficient, properly directed lighting can simultaneously reduce energy use and mitigate artificial skyglow (Wang et al., 2025). The present paper supports this connection, particularly in municipalities where high per capita losses are observed despite low absolute energy use, indicating that infrastructure inefficiencies may lead to both energy and environmental costs (Pothukuchi, 2021). Modernizing public lighting systems can be justified not only on economic grounds, but also from an ecological perspective (Valiullin, 2020). The results suggest that improving energy efficiency and reducing light pollution are closely interrelated goals, and that spatial analysis of losses can effectively support targeted interventions in areas most in need of modernization.

5. Conclusions

This paper has revealed significant spatial and statistical disparities in public lighting electricity consumption and associated losses across municipalities in the Western Transdanubia region. While larger cities tend to show higher absolute values due to infrastructure scale, per capita indicators highlight efficiency issues in smaller settlements. The findings underscore that energy losses are not merely technical inefficiencies but are closely related to the problem of light pollution, especially in areas with outdated or oversized lighting systems. Enhancing energy efficiency through modern, targeted upgrades can simultaneously reduce public expenditures, environmental impacts, and unnecessary artificial illumination. The integration of loss-based indicators into municipal energy audits could improve decision-making transparency and guide prioritization of

modernization projects. These results support the need for integrated, data-driven approaches to public lighting modernization that consider both energy performance and ecological sustainability.

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