



Ergonomic Analysis and Implementation of Solar-Powered LED Street Lighting in Rural Infrastructure Enhancement

M. Yusuf¹, I Wayan Marlon Managi²,
Made Ardikosa Satrya Wibawa³, I Wayan Suma Wibawa⁴,
and I Made Anom Adiaksa⁵

^{1,2,3,4,5} Mechanical Engineering Department, Politeknik Negeri Bali, Bali, Indonesia
yusuf@pnb.ac.id

Abstract. Limited access to reliable electricity in rural areas continues to pose safety, social, and ergonomic challenges for communities. This study presents a community-based intervention in Labak Suren Village, Bali, focusing on the implementation of solar-powered LED street lighting and its ergonomic impact on night-time mobility and safety. The objectives were to reduce psychological anxiety, improve pedestrian comfort, and enhance social and economic participation after dark. The project installed four solar-powered LED units in key village locations and employed both quantitative and qualitative methods, including pre- and post-intervention surveys, structured interviews, and ergonomic assessments. Key indicators such as perceived anxiety, traffic comfort, and lighting effectiveness were analyzed using descriptive statistics and paired t-tests. Results showed a 75% increase in illumination (lux levels), a 59% reduction in anxiety prevalence, and a 114% increase in reported comfort. Additionally, night-time event participation rose by 94%, and evening economic activity increased by 34%. The study demonstrates that integrating ergonomic analysis with renewable energy technology significantly improves rural quality of life, safety, and infrastructure usability. It offers a replicable model for sustainable development in underserved areas. These findings can inform policy-making and support broader strategies for equitable energy access and community resilience.

Keywords: Community-Based Development, Ergonomics, LED Lighting, Night-Time Safety, Rural Infrastructure, Solar Energy

1 Introduction

Public lighting is an essential component of infrastructure that supports safety, social, and economic activities in communities. In rural areas such as Labak Suren Village, West Selemadeg District, Bali, the lack of street lighting contributes to increased crime risk, reduced mobility, and diminished nighttime productivity. From an ergonomic perspective, this situation imposes psychological and physical burdens on residents who traverse uneven terrain in darkness, increasing the likelihood of falls, fatigue, and anxiety.

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The main problem addressed in this study is the absence of reliable and sustainable public lighting in remote rural areas, which affects community safety and daily functioning. While prior studies, such as Kumar (Kumar et al., 2024) and Gao (Sun et al., 2023), have examined the benefits of solar-powered lighting in enhancing energy access and promoting economic activities, these works often overlooked the psychosocial and ergonomic impacts, especially related to anxiety and comfort in nighttime traffic situations. The need for lighting for rural and remote community traffic has been widely researched; However, the installation of rural traffic lighting should also be followed up with further research on the social or other impacts (Fabiani et al., 2021; van der Waal, 2020).

This research fills the gap by incorporating both technological and ergonomic dimensions to assess the impact of solar-powered LED lighting on rural infrastructure. The novelty of this study lies in the integration of ergonomic indicators—such as perceived anxiety levels, psychological comfort, and subjective traffic safety perception—into the evaluation of solar street lighting systems. By doing so, the research presents a more holistic understanding of infrastructure's influence on human well-being.

Ergonomic analysis is critical in this context because it provides a framework for understanding how environmental conditions affect physical and psychological performance. Ergonomics aims to optimize human well-being and overall system performance by adapting the environment to suit user capabilities and limitations (Hansen et al., 2023; Meyer et al., 2017; Webster & Haut, 2024). In rural development, integrating ergonomic assessments allows for identifying stressors such as darkness, terrain instability, and mental strain, which are often underrepresented in infrastructure planning. Studies further emphasize the importance of human-centered design in achieving long-term functionality and user acceptance (Quandt et al., 2022; Younis & Chaudhary, 2020).

The study aims to: (1) reduce anxiety levels experienced by residents during nighttime travel; (2) improve traffic and pedestrian comfort through the deployment of solar-powered LED lighting systems; (3) evaluate the impact of lighting on social, economic, and psychological aspects of rural life; and (4) establish a replicable, community-based model for sustainable lighting infrastructure.

The implications of this research extend beyond rural electrification. It offers an interdisciplinary model that merges technical engineering solutions with human-centered ergonomic assessment. Findings can inform rural infrastructure policy, sustainable development strategies, and community-based energy programs. Furthermore, the approach encourages replication in other remote areas facing similar challenges, contributing to broader goals of energy equity, environmental resilience, and improved quality of life.

2 Methodology

2.1 Site and Population

The project was implemented in Labak Suren, a village with 108 households and predominantly agricultural livelihoods. The region is geographically hilly, with access paths often lacking illumination. The target population consisted of adult residents who regularly used the village's primary walking paths at night.

The sample size was determined using the Lemeshow formula for population proportions (Gupta et al., 2021; Pavlou et al., 2021).

$$n = \frac{(Z^2 \cdot p \cdot (1-p))}{d^2} \quad (1)$$

Where Z is the confidence level (1.96 for 95%), p is the expected proportion (0.5), and d is the margin of error (0.1). The initial calculation yielded a sample size of 96 respondents. Since the total population was finite ($N=108$), the adjusted sample size (n_{adj}) was calculated using the following formula:

$$n_{adj} = \frac{n}{1 + \frac{n-1}{N}} \quad (2)$$

This adjustment resulted in a final sample size of 50 respondents, who were then selected using simple random sampling.

2.2 Procedure

The project was carried out in four main phases. First, a site survey was conducted to identify strategic points for lighting based on resident movement patterns and terrain risks. Second, socialization and training sessions were held to educate villagers about solar technology and provide basic maintenance knowledge. Third, the installation phase involved deploying four solar-powered LED units in key locations. Finally, an evaluation was performed through ergonomic assessments before and after installation, using both observational analysis and structured interviews.

2.3 Variable Definitions and Instruments

The Perceived Anxiety Level is defined as the subjective psychological discomfort experienced while navigating poorly lit paths at night. It is measured using a 5-point Likert scale ranging from "Very Comfortable" (1) to "Very Anxious" (5). The Traffic Comfort variable refers to the perceived ease, stability, and safety while walking at night, measured through a structured questionnaire that assesses visibility, route familiarity, and emotional comfort. Meanwhile, Lighting Effectiveness is defined as the operational functionality and spatial coverage of the solar-powered LED systems, which is assessed through field observation and user-reported satisfaction.

2.4 Ergonomic Assessment

The ergonomic assessment was conducted through several key analyses. First, psychological stress during night mobility was examined, focusing on perceived anxiety when moving through dark areas. Second, the evaluation considered visual workload and physical posture, comparing walking conditions in unlit versus illuminated environments. Finally, subjective traffic comfort and emotional responses were measured both before and after the installation, using structured instruments and ergonomic observation protocols.

2.5 Data Collection and Analysis

Data collection was conducted through pre-test and post-test surveys, distributed to the 50 selected participants. The surveys captured quantitative data on perceived anxiety and traffic comfort, both before and after the lighting system was installed. In addition, qualitative feedback was gathered through structured interviews and focus group discussions.

Quantitative data were analyzed using descriptive statistics to summarize the average score of each variable, followed by paired t-tests to determine the significance of the changes. A reduction in the mean score of anxiety and an increase in the comfort score were expected post-intervention. Qualitative data were coded thematically to extract recurring issues, sentiments, and user experiences.

3 Result and Discussion

3.1 Result

Infrastructure Output. The installation of four LED units powered by photovoltaic panels significantly enhanced night-time visibility in high-traffic zones. Residents reported clear improvements in the brightness and coverage of lighting, particularly along agricultural paths and key access routes to community gathering points. Measured lux values in illuminated areas increased by 75% compared to baseline conditions, as shown in Table 1. This result supports the objective to improve environmental safety through lighting infrastructure.

Table 1. Road Visibility Analysis Results

Indicator	Pre-Intervention	Post-Intervention	% Change
Average Lux Level (lx)	8.4	14.7	+75%
Coverage of Main Pathways (%)	25	80	+220%

Ergonomic Outcomes. Post-intervention data indicated a significant reduction in perceived anxiety during night mobility. Before installation, 71% of respondents reported high anxiety levels; afterward, only 29% reported similar levels. In addition, 60% of respondents reported increased comfort and safety. These results can be seen

in Table 2 and aligned to reduce psychological discomfort and improve ergonomic conditions through environmental improvements (Pheasant & Haslegrave, 2016).

Table 2. Ergonomic Outcomes Analysis

Indicator	Pre-Intervention	Post-Intervention	% Change
High Anxiety Prevalence (%)	71	29	-59%
Reported Comfort/Safety (%)	28	60	+114%

Social and Economic Participation. The frequency of evening market activity and community events rose significantly post-intervention. These findings suggest that enhanced infrastructure can foster socio-economic activity. Reported attendance at night-time events increased by 94%, and frequency of night-time economic activity rose by 34%, as shown in Table 3.

Table 3. Increased Nighttime Activity

Indicator	Pre-Intervention	Post-Intervention	% Change
Night-time Event Participation Rate (%)	36	70	+94%
Evening Economic Activity Frequency (%)	40	54	+34%

3.2 Discussion

The results of this study confirm that the implementation of solar-powered LED street lighting in rural areas substantially enhances environmental safety, reduces ergonomic risk factors, and promotes social participation. The increase in lux levels and lighting coverage across critical access routes directly supports the research objective to improve infrastructure usability during nighttime. Enhanced illumination not only minimized visual workload but also facilitated more stable and confident pedestrian movement across uneven terrain.

From an ergonomic standpoint, the 59% reduction in perceived anxiety among residents, as shown in Table 2, aligns with Super and Taibi's (Super et al., 2025; Taibi et al., 2021) assertion that ergonomic interventions can mitigate psychological stress and improve human-system interaction. Increased perceived comfort (114%) post-intervention, as shown in Table 1, supports the hypothesis that improved visibility and spatial orientation can lessen cognitive load and emotional strain—key factors in rural mobility ergonomics. These findings are consistent with research that emphasizes the significance of environmental design in optimizing user performance and well-being (Barrios et al., 2023; Hasanain, 2024; Yusuf et al., 2024; Suarbawa et al., 2024; Yusuf et al., 2025a; Yusuf et al., 2025b).

Moreover, the increase in night-time participation in community events (+94%) and economic activities (+34%), as shown in Table 3, illustrates how infrastructural upgrades influence broader social behavior. As supported by Cañipa (Cañipa et al., 2019) and Azhari (Azhari et al., 2023), improved lighting fosters microenterprise opportunities and strengthens community bonds, particularly in areas where public infrastructure is traditionally underdeveloped.

Another critical aspect is the interdisciplinary approach adopted in this research. By integrating engineering design with human-centered ergonomic assessment, the study offers a holistic model for infrastructure development that goes beyond functional performance. This aligns with global efforts to implement inclusive and resilient infrastructure under the United Nations Sustainable Development Goals (SDG 7 and SDG 11).

The implications of this research extend into multiple domains. For policy-makers, the findings underscore the importance of incorporating ergonomic considerations into rural electrification programs—not only to improve safety but also to enhance quality of life. For community planners and NGOs, the study provides a replicable framework that integrates local participation, renewable energy technology, and ergonomic analysis to ensure long-term sustainability and acceptance.

In the academic domain, the study contributes to the growing body of literature on rural infrastructure ergonomics, highlighting the often-overlooked relationship between lighting conditions and human psychological response in non-industrial settings. It also sets the stage for future research involving smart lighting systems, adaptive brightness technologies, and IoT-based monitoring to further optimize energy use and user experience.

Lastly, this research supports the development of community-based sustainable lighting models that can be adapted to similar remote or underserved regions, contributing to energy equity, environmental awareness, and inclusive rural development strategies.

The rise in night-time event participation (94%) and economic activity (34%) also mirrors findings by Vernet (Vernet et al., 2019), who demonstrated that better rural lighting supports microenterprise development and social connectivity. Such enhancements not only meet practical energy needs but also contribute to broader socio-economic empowerment.

Overall, this study demonstrates that solar-powered LED lighting, when paired with community engagement and ergonomic assessment, represents an effective and sustainable solution for rural development. These results are relevant for policymakers and development agencies aiming to integrate human-centered design and renewable energy.

While this study provides valuable insights into the ergonomic and socio-economic benefits of solar-powered LED street lighting in rural settings, several limitations should be acknowledged. First, the intervention covered only a limited number of lighting units (four installations), which may not fully represent the broader infrastructural needs of the entire village. Second, the post-intervention evaluation was conducted over a relatively short time frame, limiting the ability to capture long-term behavioral and environmental impacts. Third, the study relied primarily on self-reported data for psychological and ergonomic indicators, which may be subject to bias or variations in individual perception. In addition, gender-specific experiences and the impact on vulnerable populations, such as the elderly or disabled, were not explored in detail. Lastly, environmental variables such as weather conditions, seasonal lighting demands, or equipment durability over time were beyond the scope of this initial assessment. Future research should consider longitudinal designs, expanded geographic coverage, and integration of smart monitoring systems to better understand the sustainability and scalability of similar interventions.

4 Conclusion

Integrating ergonomic assessment with solar-powered LED street lighting contributes significantly to enhancing rural infrastructure, particularly in areas with limited access to electricity. The implementation in Labak Suren Village resulted in measurable improvements in night-time visibility, a substantial reduction in perceived anxiety, and increased social and economic engagement.

The research findings revealed several significant impacts of the implemented program. Night-time travel anxiety was reduced by 59%, while traffic and pedestrian comfort showed a remarkable improvement of 114%. In addition, social and economic nighttime activities experienced an increase ranging from 34% to 94%. Beyond these measurable outcomes, the study also demonstrated the successful establishment of a sustainable, community-based lighting system that supports long-term benefits for the local population.

The ergonomic dimension—rarely explored in similar infrastructure studies—proved critical in capturing both physical and psychological user experiences. These results validate the importance of human-centered design in energy and infrastructure development.

Based on the outcomes of this research, several recommendations are proposed. First, the deployment of LED units should be scaled up to cover more village paths and high-traffic areas, thereby further reducing ergonomic risks and enhancing mobility. Second, the integration of IoT-based remote monitoring systems is recommended for future projects to improve maintenance efficiency and system reliability. Third, local governments and development agencies are encouraged to incorporate ergonomic analysis into rural electrification programs to ensure that interventions address both functional and human factors. Finally, the participatory, community-based model implemented in this study can be replicated in other off-grid rural regions as a blueprint for achieving sustainable and inclusive infrastructure development.

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