Assessment of annual aggregate commercial energy loss due to day-on road lights: a field research study

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ABSTRACT

The electrical vitality utilization is at a quick rate as compared to its era driving towards the need for vitality reserve. Every nation is concerned about addressing the energy security issue and most of their attention during the past few years has been focused on the very essence of energy conservation opportunities. It is the responsibility of all the electricity consumers to ensure that no portion of electrical vitality gets wasted either hastily or intentionally. Unfortunately, as a result of day-on-road lights (DORL), electricity is being wasted in several villages and towns. This claim is validated through the performed field research (FR) presented in this manuscript. From the FR, it is inferred that approximately 13.2% of the total road lights were found turned-on during the day hours, resulting in an annual vitality loss of approximately 55.75 MWh. It is being wasted because of the mismanagement of switches and manmade errors; because of this, it forms a part of the overall commercial loss of 4.8 tonnes of oil equivalent (toe) and accounts for the release of about 47.4 tonnes of CO_2 (tCO_2) emissions per annum. This paper presents on broad investigation on the FR performed to recognize a yearly total commercial misfortune of vitality with techno-commercial analysis.

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1. INTRODUCTION

To exemplify, the vitality is the capacity to perform the work. Without vitality, it is inconceivable to imagine the presence of anything. One of the specific secondary sources of vitality is electricity. Different sources of producing electricity include solar, wind, geothermal, hydel, and fossil fuel-based power generating systems. India is one of the most densely populated and economically expanding countries in the world. It covers the demand for increasing and growing vitality to support its fiscal resilience and growing population. As a result of its multi-ecosystem and population growth, the use of vitality is expanding rapidly. In addition, the country's energy control involves the centralized and decentralized system, making it a little complicated.

By November 2024, the installed power generation capacity in the country is about 456,757 MW. The significant contribution of about 53.2% is exclusively by energy plants, depending on the fossil fuels and 46.4% are through coal-based energy plants. To be more precise, residential segment, commercial segment, industrial segment, transport segment, and the agricultural segments are different segments of vitality in India.

In accordance to the Energy Insights India 2023 report, the annual compound escalation rate (ACER) of power utilization for the period of 2012-13 and 2021-22 is around 5.7%. The Industrial segment accounted for the biggest share (41.16%) followed by the residential (25.77%), agricultural (17.67%), and commercial segments (8.29%) out of the entire power utilization during 2021-22. During the aforesaid tenure, among assorted segments, the residential segment has the most noteworthy ACER about 6.8.

Public road lighting is a major contributor to municipal energy consumption worldwide (Stellios *et al.* [1] and Alvarez *et al.* [2]). In India, the rapid expansion of public road lighting—especially in rural and semi-urban areas—has significantly increased energy usage. A persistent and often overlooked issue is the waste of electrical energy due to road lights remaining switched on during daylight hours, a phenomenon known as day-on road lights (DORL). This inefficiency leads to substantial energy loss, increased operational costs, and unnecessary carbon emissions, undermining national energy conservation goals (Energy Insights India, 2023).

The lighting, in particular road lighting, is plausibly the foremost critical system that consumes electrical vitality within the commercial segment. Road lighting system forms an important electrical power infrastructure for the rural and urban development across the world. In general, they are installed on supporting poles, or on posts or other supporting structures along the roads, side walking areas and or any other open zones. The major reason for prioritizing the road lighting is to provide adequate lighting on the roadways, subways and any public open spaces amid night hours [3], [4]. They play a vital role in ensuring safety and security to the passers and avoid noticeable criminal action. However, they are being misused in several places, because of which the electrical vitality used for powering road lights is getting squandered. The content presented in this manuscript elevates and addresses the aforesaid issue by performing thorough investigation on the DORLs.

This research aims to systematically quantify the annual aggregate commercial energy loss due to DORL in a representative mandal of Tirupati District, Andhra Pradesh. It not only estimates the local impact but also extrapolates the findings to provide a state-wide perspective. Furthermore, the study proposes practical scalable solutions, namely, the integration of astronomical clock switches (ACS) and village-wise master controllers (VMC) to mitigate these losses. By addressing this gap, our study seeks to inform policy and operational improvements for public lighting infrastructure in similar contexts.

The rest of this article is organized as follows: section 2 reviews the literature and highlights the limitations of existing approaches. Section 3 describes the field research (FR) method, how the data was collected and data analysis and shares the findings and explains how energy is being lost due to poor DORL. Section 4 discusses the main causes and proposes corrective strategies. Section 5 discusses the critical discussion of the results, their implications and future directions and finally, section 6 concludes the study and describes the policy and practice recommendations.

2. LITERATURE REVIEW

A bolt-IoT platform-based LED road lamp control system with the ability to detect vehicle movement and density was proposed by Sorif *et al.* [5]. Balsky and Terrich [6] talked about how optimizing the distribution of luminaries' luminous flux could improve road lighting efficiency and reduce light trespassing. Strielkowski *et al.* [7] examined the economic efficiency influencing factors, and evaluated the necessities intended for vitality security in smart cities, LED road lighting can drastically lower the energy consumption of any contemporary metropolis.

In an IoT-based case study on an energy-efficient smart road lighting system in Nagpur, Prasad *et al.* [8] predicted the effective results of swapping out outdated road lights for LED lights with motion sensors. LDR sensors were utilized by Jebaseeli *et al.* [9] to save energy in the road lighting system. Pachamanov and Kassev [10] investigated the potential for public lighting rehabilitation in the Republic of Bulgarian municipalities, including road lighting monitoring and management through local and cloud-based apps as well as public land mobile networks, including IoT.

Mohanty *et al.* [11] proposed an intelligent street light management system for smart cities, enabling efficient monitoring and control of road lighting to reduce unnecessary energy consumption. Anthopoulou and Doulos [12] demonstrated the energy savings achieved by replacing high pressure sodium lamps with LED instead of traditional lamps. Qaisar *et al.* [13] proposed a solar-powered road lighting system and a sensor assembly with a front-end controller to detect the vehicle movement and adjust the road lights appropriately. Al-Smadi *et al.* [14] proposed an intelligent system capable of detecting and appropriately control the road lighting when a car is moving on the road. An IoT-based smart lighting system that effectively controls road lights by employing sensors to dim and brighten them as needed was presented by Suseendran *et al.* [15].

Yashaswini *et al.* [16] shown how automatic LED-based road light control may save energy by recognising vehicle movement detected by infrared sensors and photo diodes. To save energy, Abdullah *et al.* [17] suggested a motion-detection-based road light controller system. An autonomous solar-powered road lighting system with wireless monitoring via router duty mode was introduced by Saymbetov *et al.* [18]. For precisely managing road lighting, Kadirova and Kajtsanov [19] demonstrated a real-time control system for road lighting using GPS to retrieve pertinent data about local dawn and sunset. Singh and Sisodia [20] introduced an adaptive road lighting system based on movement detection technology (MDT) and a light-dependent resistor (LDR). An intelligent lighting solution, that uses LED lights, Zig Bee wireless network and the Zig Bee cluster library messaging protocol was suggested and developed by Samy and Adly [21].

In order to avoid vitality wastage and ensure safety Abinaya *et al.* [22] suggested a smart embedded system with a monitoring camera integrated to control the road lights based on sunshine detection. By examining life cycle cost and energy efficiency, Kim and Hwang [23] evaluated the feasibility of LED-based road lighting. Automated solar photovoltaic systems (SPVS), that may boost efficiency through LED lighting while simultaneously conserving energy, were suggested by Jha and Biswal [24]. In order to make road lights self-powered, Dey *et al.* [25] concentrated on auto lighting jerking pressure that is wasted when cars cross speed bumps on the highways.

From the aforesaid literature appraisal, it is clear that, majority of the researchers are focusing on automated and diverse control of road lighting. Their approach differs elementally by means of utilizing the driven lighting system control, viz. LDR based sensors, intervention of automation through different advances viz. GSM/GPRS, ID3 calculations, IoT, and also integration of renewable systems. However, it is clear that electrical vitality loss due to DORL, a real-world existing problem is not being taken care of. The research presented in this manuscript addresses the concern knowledge gap by investigating the root-cause and effects of DORL and proposing the remedial measures to mitigate the effects.

3. FIELD RESEARCH: INVESTIGATION FOR ESTABLISHING DORL

The method adopted in this study was designed to systematically quantify the annual aggregate commercial energy loss due to DORL in a representative mandal of Tirupati District, Andhra Pradesh. The approach combined standard field survey techniques with novel, context-specific data analysis to ensure both accuracy and replicability.

3.1. Study area and zoning

The method considered in carrying out the FR and acquainting the wastage of electrical vitality due to DORL is illustrated in Figure 1. As a token of concern, one of the mandals of Tirupati District of Andhra Pradesh State is taken into consideration and commenced the investigation. The mandal concerned (CM) consists of 18 village councils (VC) also referred to as gram-panchayats and about 80 sub-villages (SV). As per the existing roadway interconnectivity, these SVs are estranged into four diversified zones for performing the FR.

Rural mandals in Andhra Pradesh generally follow similar technical norms for road-lighting, as prescribed in the Panchayat Raj and Rural Development guidelines. Most of them use comparable pole spacing, lamp ratings, and switching practices, and many still depend on manual operation. Because of this, the DORL problem tends to appear under similar conditions across different mandals. Conducting detailed field inspections in all mandals is not feasible, so one mandal was selected as a representative unit for in-depth study. The findings from this location are used to provide a reasonable indication of the broader situation in the state, while acknowledging that the extrapolation offers an estimate rather than a precise statewide value.

3.2. Data collection

As per the method furnished in Figure 1, FR was performed by physically visiting all the four zones of SVs corresponding to VCs and investigating on the existing DORLs. During this course of action, the following primary data is collected. VC (gram panchayat) wise villages of CM, village wise number of roads and road lights, street wise number of roads lights and village wise power consumption details of road lights. Through FR, the total numbers of RLs which were dynamic amid daytime were identified. The major sightings of the FR are portrayed in Figures 2 to 4.

3.3. Justification of method

A field-based approach was chosen to capture real-world operational practices and human factors contributing to DORL, which are often missed in remote or automated assessments. This direct observation method ensures the reliability of the data and allows for accurate quantification of energy loss. The methodology is described in sufficient detail to enable replication by other researchers or practitioners. The field survey was conducted by three independent teams, each consisting of two trained members. Surveys were carried out over six months, with observations made at three different times of day (morning, midday, and afternoon) to ensure consistency and account for temporal variability. Each location was visited on two separate days to validate the findings and minimize observational bias.

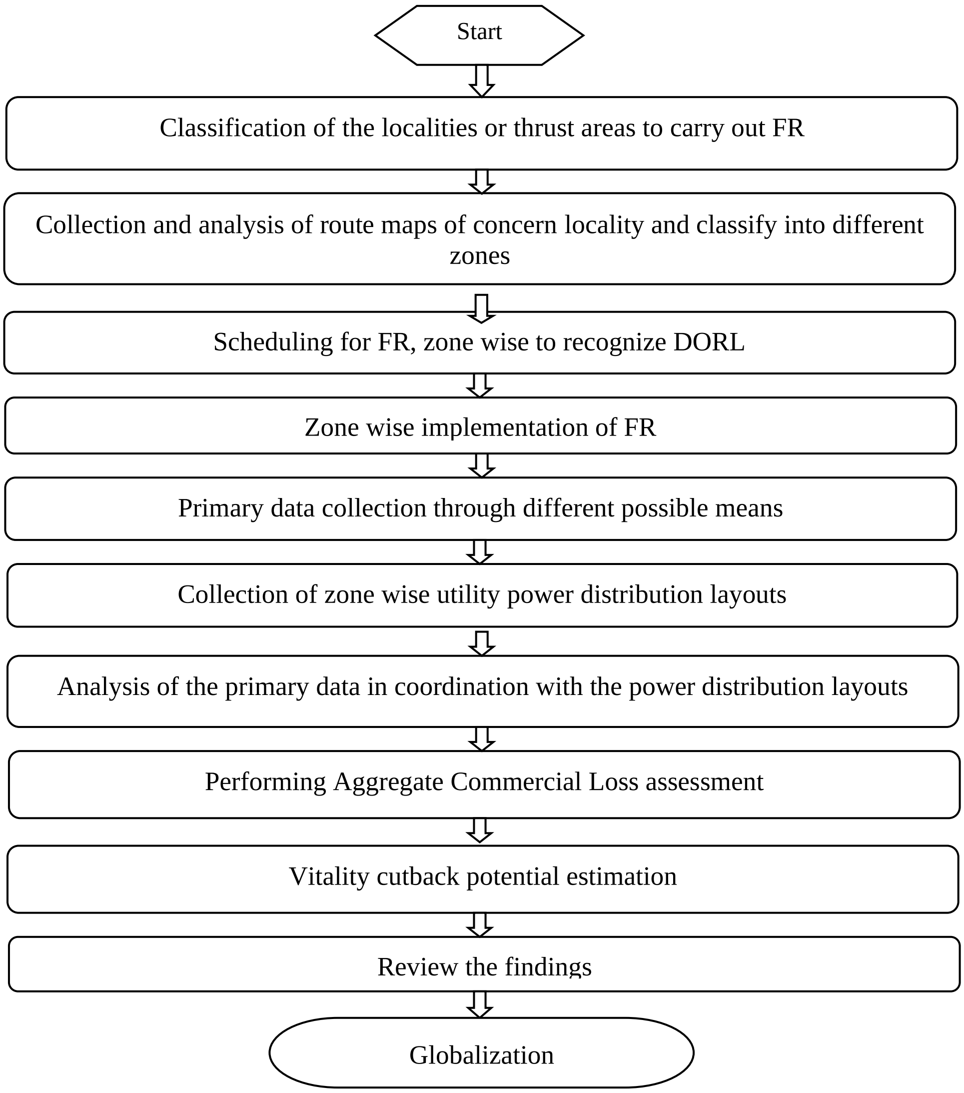

Figure 1. Technique to perform FR

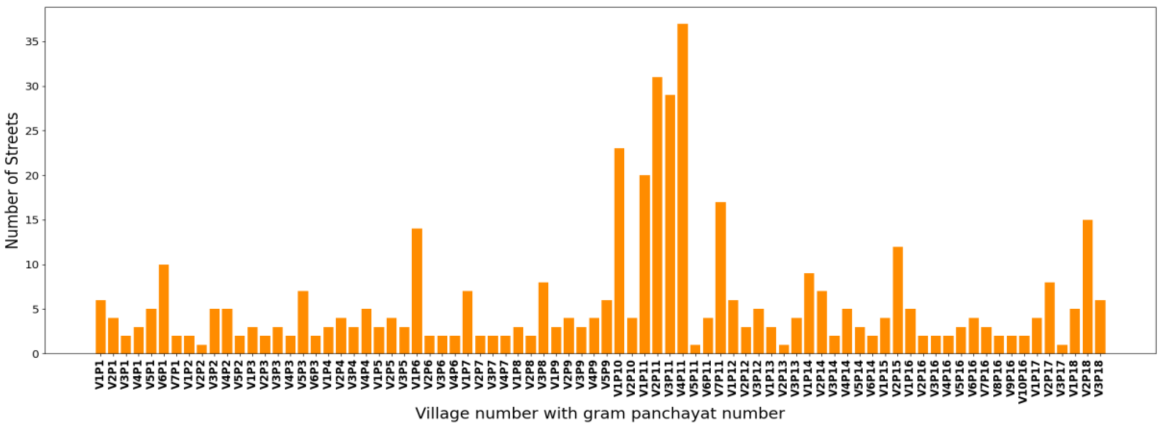

Figure 2. Number of roads or streets per village-VC

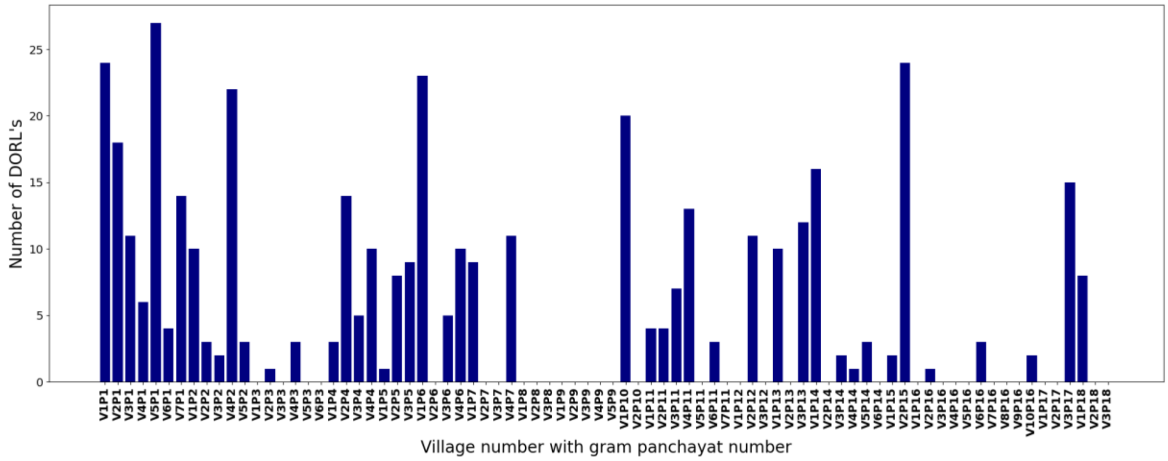

Figure 3. Number of DORL’s per village-VC

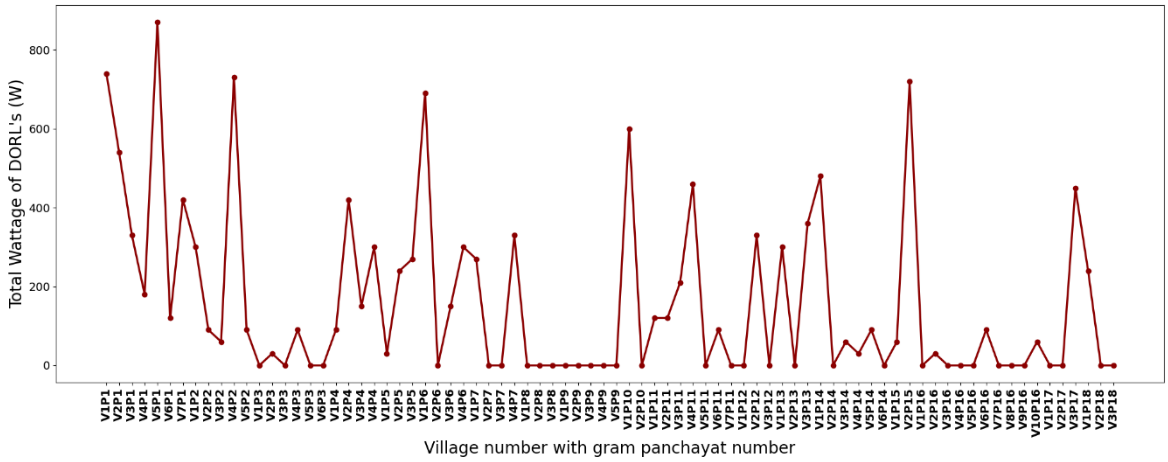

Figure 4. DORLs power consumption

3.4. Data analysis

The quantity of RLs in a village, the overall numbers of RLs in a mandal, the numbers of DORLs in a town and the overall numbers of DORLs in a mandal is assessed by utilizing (1) to (4). The village wise power consumption details of DORLs and the total power consumption details of CM is evaluated by using (5) and (6).

$$N_{RL} = \sum_{i=1}^{n}\left(L_{oi} + L_{fi}\right) \quad (1)$$

$$N_{TRL} = \sum_{j=1}^{m} N_{RL\,j} \quad (2)$$

$$N_{ORL} = \sum_{i=1}^{n} L_{oi} \quad (3)$$

$$N_{TORL} = \sum_{j=1}^{m} N_{ORL\,j} \quad (4)$$

$$P_{ORL} = \sum_{i=1}^{n}(L_{30i} + L_{40i} + L_{50i} + L_{100i}) \quad (5)$$

$$P_{TORL} = \sum_{j=1}^{m} P_{ORL\,j} \quad (6)$$

In (1) to (6),
n is the total numbers of roads in a village;
m is the total numbers of villages in a mandal;
L_{oi} is the numbers of day-on road lights in ith road;
L_{fi} is the numbers of day-off road lights in ith road;
L_{30i}, L_{40i}, L_{50i}, and L_{100i} is the quantity of 30 W, 40 W, 50 W, and 100 W day-on road lights in ith road;
N_{RL} is the numbers of road lights in a village;
N_{TRL} is the total numbers of road lights in CM;
N_{ORL} represents the total numbers of DORLs in a village;
N_{TORL} represents the total numbers of DORLs in CM;
P_{ORL} represents the total wattage of DORLs in a village;
P_{TORL} represents the total wattage of DORLs in CM.

The primary data explores that, within the SV of CM, the total number of roads and the total quantity of road lights are 455 and 3,170 respectively. It is also found that 417 road lights out of the total 3,170 lights i.e., 13.15% of total road lights were found turned-on during day hours. Besides, the road lights must illuminate the roads during night times and must remain inactive during daytime, making to consider the aforesaid case very seriously.

For the concerned CM, the quantity of roads, village wise is illustrated in Figure 2. Within the CM, village 4 in Panchayat 11, V4P11 (37) shares maximum quantity of roads while village 2 in Panchayat 11, V2P11 (31) and village 3 in Panchayat 11, V3P11 (29) projects second and third positions respectively.

For the concerned CM, the quantity of DORLs, village wise is illustrated in Figure 3. Within the CM, the village V5P1 (27) contributes maximum quantity of DORLs while V1P1 (24) and V2P15 (24) shares next positions. In line to them the villages V1P6 (23), V4P2 (22), and V1P10 (20) occupies consecutive positions.

For the concerned CM, village wise power consumption by the DORLs is illustrated in Figure 4. In view of the lamp capacity, the wattage of existing RLs within the CM are found 100 W, 50 W, 40 W, and 30 W. The total number of 100 W RLs used are 2, 50 W RLs used are 3, 40 W RLs used are 2 and 30 W RLs used are 410. Regarding power consumption by lamps, the maximum contribution is by the RLs in the village V5P1. Villages V1P1, V4P2, V2P15, V1P6, and V1P10 occupy the consecutive positions. RLs in V5P1 consumes 870 W, V1P1 consumes 740 W, V4P2 consumes 730 W, V2 P15 consumes 720 W, V1P6 consumes 690 W, and V1P10 consumes 600 W.

The power consumption by DORLs in V4P2 is found more than V2P15, although the quantity of RLs is only 22 in disparity with 24. It is only because of the existence of 100 W light within the former village. As a result of FR and analyzing the data collected, it is clear that the total capacity of RLs found turned-on during daytime is 12.73 kW. To be specific, the admissible dynamic duration (ADD) of RLs is only from 6 PM to 6 AM while the non-admissible dynamic duration (NADD) of RLs is from 6 AM to 6 PM. However, it is found that total 417 RLs were found active during NADD hours leading to the daily electricity consumption of 153 kWh and annual electricity consumption of 55.757 MWh. The latter can be accounted as annual aggregate commercial loss (AACL) due to DORL.

3.5. Root cause and effect exploration

To explore the root cause behind the DORLs, second round of investigation was carried out by physically inspecting all the villages within the CM. Furthermore, accessible representatives of the villages were interviewed to establish the reason behind the DORLs and the following major motives behind those were noted:

a. Powering of RLs directly from the distributor lines.
b. Absence of switch gear.
c. Damage or no-operation of existing switchgear.
d. Non assignment of road light operator jobs.
e. Unawareness about the need for maintain the RLs.

4. STRATEGIES FOR CURTAILING AAC LOSS DUE TO DORL

To minimize the identified AAC loss due to DORL, the following two strategies were proposed.

4.1. Integration of astronomical clock switches

Installation of “ACS” to control the RLs is proposed for each road, or for cluster of roads or centralized based on the possibility. ACS is basically an intelligent clock integrated with a time switch based light controller. It is a microcontroller technology-based device with integral battery backup for about 1,000 hours. Its direct load interfacing capacity is about 3 kW. For controlling the RLs within the villages of CM the maximum quantity of ACS required are 455. As the vendor price of GLES make ACS is about Rs. 2124/-, the estimated total investment for establishing 455 numbers of ACS is about Rs. 10.12 Lakhs which includes supply cost of Rs. 9. 66 Lakhs and installation cost of Rs. 0.46 Lakhs. By establishing the aforementioned ACSs, an amount of Rs. 2.99 Lakhs /- per annum can be saved directly. Besides it is estimated to get returned within 3.4 years. During the field survey, instances of road lights operating during daytime were observed in different rural locations. Figure 5 presents field photographs captured at Kuchi Vari Palli (VIP2) and Vykuntapuram (V4P2) villages, clearly illustrating daytime-on road lighting (DORL) conditions observed during the study, showing road lights operating during daytime.

Figure 5. Field photographs captured in Kuchi Vari Palli (V1P2) and Vykuntapuram (V4P2) villages

4.2. Integration of village-wise master controller

It is proposed to restructure the existing supply system for RLs and erect a separate power distribution (SPD) network for RLs from the distribution transformer existing in every village. The source side of the SPD is to be provided with a current measured based road light counter (RLC) and master controller. A village VMC is a single switch and multi-lamp controller integrated with a data acquisition and a transceiver system intended to communicate the data to the control center located at the concerned utility substation. The RL activation and de-activation commands to all the VMCs existing in the purview of the substation will be sent daily on 6:00 AM and 6:00 PM respectively. This timely operation of the VMCs ensures that no RLs are active during day-hours, thereby minimizing AACL due to DORL. However, to identify the failed RLs, the SLC counts the number of turned-on RLs based on their rated current drawn and shares the information to the control center [8]. The control center processing system analyzes the data received and estimates the quantity of DORLs and also the one that are malfunctioning and takes necessary corrective actions.

5. RESULTS AND DISCUSSION

The field survey revealed that 13.2% of road lights in the studied mandal were operational during daylight hours, resulting in an annual energy loss of 55.75 MWh. When extrapolated to the entire state of Andhra Pradesh, the potential annual loss exceeds 39,000 MWh. These findings are consistent with previous reports of inefficiencies in public lighting, such as those by Stellios *et al.* [1], Prasad *et al.* [8], and Jebaseeli *et al.* [9], but our study uniquely quantifies the impact of DORL in a rural context. The results highlight the need for targeted interventions, such as the integration of ACS and VMC, which could significantly reduce energy wastage. The results have been compared with official reports and benchmark data from government sources (e.g., Energy Insights India, 2023) to validate the findings and contextualize the observed energy loss due to DORL.

While prior studies have demonstrated the effectiveness of automated and sensor-based lighting systems in reducing energy consumption, they have largely overlooked the operational challenges in rural and semi-urban areas. Our results highlight that, in the absence of automation, human error and inadequate maintenance are primary contributors to energy wastage. This finding aligns with the observations of Strielkowski *et al.* [7] regarding the importance of operational practices in achieving energy efficiency. In addition, studies involving motion-detection-based lighting (Abdullah *et al.* [17]), GPS-based controls (Kadirova and Kajtsanov [19]), and cloud-based remote monitoring (Pachamanov and Kassev [10]) have also shown that automation minimizes human intervention and reduces operational errors. This supports the need for centralized solutions such as ACS and VMC in rural environments where manual switching is still predominant.

5.1. Comparative analysis

Our findings align with Prasad *et al.* [8] and Jebaseeli *et al.* [9], who reported similar inefficiencies in public lighting and demonstrated that improper switching and lack of monitoring contribute significantly to energy wastage. The case study by Ozadowicz and Grela [4] also supports the feasibility of implementing automated control mechanisms such as ACS and VMC, though it highlights that rural deployment requires additional operational support. Furthermore, studies by Sorif *et al.* [5] and Suseendran *et al.* [15] showed that integrating intelligent control systems and sensor-based automation leads to consistent reductions in unnecessary lamp operation. These comparisons reinforce that the DORL problem observed in this study is consistent with documented challenges in other regions, especially where manual switching practices still dominate.

5.2. Proposed strategies and implications

The implications of these findings have two main takeaways. First, fixing issues with defective or outdated road lighting (DORL) can quickly reduce how much energy is used and cut down on greenhouse gas emissions. This helps India move closer to its sustainability goals. Second, the proposed ACS and VMC solutions offer practical paths to local governments and utility providers to upgrade street lighting [5]. These improvements don’t need major changes to existing infrastructure, making it easier to adopt. The approach used in this study can also be applied in other regions to identify and address DORL-related losses. Plus, ACS and VMC can be added to ongoing rural electrification and smart city projects, helping save energy across different areas. Future research should focus on piloting these solutions, evaluating their long-term effectiveness, and exploiting the integration of renewable energy sources with automated control systems.

5.2.1. Practical challenges of astronomical clock switches and village-wise master controllers systems

Although ACS and VMC systems provide an effective pathway to reduce DORL-related energy loss, their implementation in rural areas may face several practical challenges. First, the long-term maintenance and calibration of ACS units require trained personnel, which is often limited in rural and semi-urban mandals. Improper calibration or battery failure may cause switching errors, reducing the expected benefits. Second, reliability issues may arise due to dust accumulation, voltage fluctuations, and exposure to harsh weather conditions, which can affect the accuracy of astronomical timers and sensing components. Third, VMC-based centralized control systems depend on communication networks and consistent power quality, both of which may be unstable in remote areas, leading to delayed switching or loss of monitoring capability. Additionally, previous case studies in rural lighting automation have reported challenges such as insufficient technical support, delayed repairs, and lack of periodic inspections, all of which may limit the sustained performance of these systems. These practical considerations highlight the need for a strong maintenance framework, trained operators, and reliable communication infrastructure to ensure the long-term success of ACS and VMC deployments.

5.3. Limitations

While this study provides useful insights into the problem of DORL, it also has certain limitations that should be acknowledged. First, the field investigation was carried out in one mandal of Tirupati District. Although this mandal is representative of many rural mandals in Andhra Pradesh, variations in local administration, maintenance practices, and infrastructure conditions may exist in other regions. Second, the study relied on manual observations, which may introduce measurement uncertainties such as human error, timing variations, and temporary load fluctuations during the survey period. To minimize this, each location was visited multiple times, but some degree of observational bias cannot be fully eliminated. Third, the state-wide extrapolation presented in this work is based on the assumption that similar operating conditions exist across other mandals in Andhra Pradesh. This provides an estimate of the possible scale of energy loss, but the values should not be interpreted as exact statewide measurements. Finally, seasonal factors, weather-related variations, and differences in switching behaviour across regions were not included in this study, which may influence the overall DORL patterns.

6. CONCLUSION

The project site considered within the CM constitutes about 18 VCs, and about 80 SV. The ADD of RLs is from 6 PM to 6 AM while the NADD of RLs is from 6 AM to 6 PM. During the FR and data analysis, it was found that a total of 417 road lights with a combined capacity of 12.73 kW were switched on during NAAD. This led to daily electricity usage of 153 kWh, adding up to about 55.757 MWh annually. After visiting all the villages and speaking with residents and local representatives, it became clear that this energy is being wasted mainly due to poor switch control and lack of attention. This waste is estimated to result in AACL of around 4.8 tonnes of oil equivalent (toe) and causes roughly 47.4 tonnes of CO_2 emissions every year.

Two strategies were proposed to solve the above-mentioned problem. As strategy-1, install automatic control systems for individual roads, groups of roads, or wherever feasible. These systems would reduce the need for manual switching and improve efficiency. However, they require reliable operation and a skilled maintenance team. In addition, to have an effective and sustainable impact, it is recommended to install the proposed VMC integrated SPD System as a strategy-2, through which centralized actions can be taken to control RLS and take necessary corrective actions against fail RLs.

In this paper more emphasis on identifying the AAC loss due to DORL through FR is presented. From the outcomes of the FR carried out within the CM, i.e., in one mandal out of 34 mandals within the Tirupati locality of Andhra Pradesh, India, it has been assessed that RLs around 13.2% were found operational during NAAD, accounting to an annual electrical vitality loss about 55.75 MWh. However, as there are about 713 mandals consisting of about 17928 villages within the entire state of Andhra Pradesh, it is estimated that annually about 39,750 MWh of electrical vitality gets wasted due to DORLs. Hence the research findings and proposed remedial measures can contribute to a significant change in minimizing the unaccounted electrical vitality loss due to DORL. This study highlights the significant contribution of DORL to energy loss and carbon emissions in rural India. By quantifying the problem and proposing scalable solutions, our findings provide actionable insights for both academic research and policymaking. These insights support the development of targeted interventions for local energy planning and public infrastructure management.

Addressing DORL through automation and improved operational practices can yield substantial energy and cost savings, contributing to national sustainability goals. The proposed solutions—ACS and VMC—offer practical pathways for modernizing public lighting infrastructure without requiring large-scale overhauls. Future work should focus on piloting these solutions in diverse settings, evaluating their long-term impact on energy efficiency and sustainability, and exploring integration with renewable energy sources and smart control systems.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon request.

REFERENCES

[1] I. Stellios, K. Mokos, and P. Kotzanikolaou, “Assessing smart light enabled cyber-physical attack paths on urban infrastructures and services,” *Connection Science*, vol. 34, no. 1, pp. 1401–1429, Dec. 2022, doi: 10.1080/09540091.2022.2072470.

[2] R. Alvarez, F. Duarte, D. Frenchman, and C. Ratti, “Sensing Lights: The Challenges of Transforming Street Lights into an Urban Intelligence Platform,” *Journal of Urban Technology*, vol. 29, no. 4, pp. 25–40, Oct. 2022, doi: 10.1080/10630732.2022.2082825.

[3] Y. S. Hang, N. Jali, L. S. Ping, C. W. Shiang, S. K. Jali, and L. P. Chin, “Energy Saving And Safety Street Lighting System,” in *2022 IEEE International Conference on Artificial Intelligence in Engineering and Technology (IICAIET)*, Kota Kinabalu, Malaysia: IEEE, Sep. 2022, pp. 1–6, doi: 10.1109/IICAIET55139.2022.9936779.

[4] A. Ozadowicz and J. Grela, “The street lighting integrated system case study, control scenarios, energy efficiency,” in *Proceedings of the 2014 IEEE Emerging Technology and Factory Automation (ETFA)*, Barcelona, Spain: IEEE, Sep. 2014, pp. 1–4, doi: 10.1109/ETFA.2014.7005345.

[5] S. M. Sorif, D. Saha, and P. Dutta, “Smart street light management system with automatic brightness adjustment using bolt IoT platform,” in *2021 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS)*, Toronto, ON, Canada: IEEE, Apr. 2021, pp. 1–6, doi: 10.1109/IEMTRONICS52119.2021.9422668.

[6] M. Balsky and T. Terrich, “Light trespass in street LED lighting systems,” in *2020 21st International Scientific Conference on Electric Power Engineering (EPE)*, Prague, Czech Republic: IEEE, Oct. 2020, pp. 1–4, doi: 10.1109/EPE51172.2020.9269248.

[7] W. Strielkowski, T. Veinbender, M. Tvaronavičienė, and N. Lace, “Economic efficiency and energy security of smart cities,” *Economic Research-Ekonomska Istrazivanja*, vol. 33, no. 1, pp. 788–803, Jan. 2020, doi: 10.1080/1331677X.2020.1734854.

[8] R. Prasad, “Energy Efficient Smart Street Lighting System in Nagpur Smart City using IoT-A Case Study,” in *2020 Fifth International Conference on Fog and Mobile Edge Computing (FMEC)*, Paris, France: IEEE, Apr. 2020, pp. 100–103, doi: 10.1109/FMEC49853.2020.9144848.

[9] E. A. E. Jebaseeli, D. Susitra, and Sundaram, “Energy saving in street lighting system,” *Journal of Physics: Conference Series*, vol. 1770, no. 1, pp. 1–9, Mar. 2021, doi: 10.1088/1742-6596/1770/1/012039.

[10] A. Pachamanov and K. Kassev, “Rehabilitation and Remote Control of Municipalities Street Lighting,” in *2019 Second Balkan Junior Conference on Lighting (Balkan Light Junior)*, Plovdiv, Bulgaria: IEEE, Sep. 2019, pp. 1–4, doi: 10.1109/BLJ.2019.8883673.

[11] P. Mohanty, U. C. Pati, and K. Mahapatra, “Self-powered intelligent street light management system for smart city,” in *2021 IEEE 18th India Council International Conference (INDICON)*, Guwahati, India, 2021, pp. 1-6, doi: 10.1109/INDICON52576.2021.9691575.

[12] E. Anthopoulou and L. Doulos, “The effect of the continuous energy efficient upgrading of LED street lighting technology: The case study of Egnatia Odos,” in *2019 Second Balkan Junior Conference on Lighting (Balkan Light Junior)*, Plovdiv, Bulgaria: IEEE, Sep. 2019, pp. 1–2, doi: 10.1109/BLJ.2019.8883662.

[13] S. M. Qaisar, W. M. Alzahrani, F. M. Almojalid, and N. S. Hammad, “A vehicle movement based self-organized solar powered street lighting,” in *2019 IEEE 4th International Conference on Signal and Image Processing (ICSIP)*, Wuxi, China: IEEE, Jul. 2019, pp. 445–448, doi: 10.1109/SIPROCESS.*2019*.8868384.

[14] A. M. Al-Smadi, S. T. Salah, A. A. Al-Moomani, and M. S. Al-Bataineh, “Street Lighting Energy-Saving System,” in *2019 16th International Multi-Conference on Systems, Signals & Devices (SSD)*, Istanbul, Turkey: IEEE, Mar. 2019, pp. 763–766, doi: 10.1109/SSD.2019.8893160.

[15] S. C. Suseendran, B. N. Kishore, J. Andrew, and M. S. B. Praba, “Smart Street lighting System,” in *2018 3rd International Conference on Communication and Electronics Systems (ICCES)*, Coimbatore, India: IEEE, Oct. 2018, pp. 630–633, doi: 10.1109/CESYS.2018.8723949.

[16] N. Yashaswini, N. Raghu, S. Yashaswini, and G. P. Kumar, “Automatic street light control by detecting vehicle movement,” in *2018 3rd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)*, Bangalore, India: IEEE, May 2018, pp. 847–850, doi: 10.1109/RTEICT42901.2018.9012376.

[17] A. Abdullah, S. H. Yusoff, S. A. Zaini, N. S. Midi, and S. Y. Mohamad, “Smart Street Light Using Intensity Controller,” in *2018 7th International Conference on Computer and Communication Engineering (ICCCE)*, Kuala Lumpur, Malaysia: IEEE, Sep. 2018, pp. 361–365, doi: 10.1109/ICCCE.2018.8539321.

[18] A. K. Saymbetov *et al.*, “Intelligent Energy Efficient Wireless Communacation System for Street Lighting,” in *2018 International Conference on Computing and Network Communications (CoCoNet)*, Astana, Kazakhstan: IEEE, Aug. 2018, pp. 18–22, doi: 10.1109/CoCoNet.2018.8476893.

[19] S. Y. Kadirova and D. I. Kajtsanov, “A real time street lighting control system,” in *2017 15th International Conference on Electrical Machines, Drives and Power Systems (ELMA)*, Sofia, Bulgaria: IEEE, Jun. 2017, pp. 174–178, doi: 10.1109/ELMA.2017.7955426.

[20] O. Singh and T. S. Sisodia, “Solar LED street light system with automatic scheme,” in *2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)*, Chennai, India: IEEE, Aug. 2018, pp. 3415–3419, doi: 10.1109/ICECDS.2017.8390094.

[21] B. Samy and I. Adly, “Wireless street lighting system using ZigBee cluster library,” in *2017 Japan-Africa Conference on Electronics, Communications and Computers (JAC-ECC)*, Alexandria, Egypt: IEEE, Dec. 2017, pp. 132–135, doi: 10.1109/JEC-ECC.2017.8305795.

[22] B. Abinaya, S. Gurupriya, and M. Pooja, “Iot based smart and adaptive lighting in street lights,” in *2017 2nd International Conference on Computing and Communications Technologies (ICCCT)*, Chennai, India: IEEE, Feb. 2017, pp. 195–198, doi: 10.1109/ICCCT2.2017.7972267.

[23] J. T. Kim and T. Hwang, "Feasibility study on LED street lighting with smart dimming systems in Wooi Stream, Seoul," *Journal of Asian Architecture and Building Engineering*, vol. 16, no. 2, pp. 425–430, May 2017, doi: 10.3130/jaabe.16.425.
[24] N. K. Jha and A. Biswal, "Advanced Street Lights," *International Journal of Engineering Research & Technology*, vol. V5, no. 01, pp. 704–707, Jan. 2016, doi: 10.17577/ijertv5is010594.
[25] M. Dey, T. Akand, and S. Sultana, "Roadside power harvesting for auto street light," in *2015 3rd International Conference on Green Energy and Technology (ICGET)*, Dhaka, Bangladesh: IEEE, Sep. 2015, pp. 1–5, doi: 10.1109/ICGET.2015.7315113.

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