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Systematic lamp replacement for energy efficiency improvement: a comparative luminous-efficacy analysis

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ABSTRACT

Achieving energy efficiency and establishing energy conservation for driving future energy is one of the prime concerns of any nation. Besides, the lighting system, one of the major contributors of energy consumption set ahead in fixing the aforesaid concerns to the extent possible. When looking at environmental benefits and energy saving opportunities, among several available luminaries, LEDs stand far superior to standard tubular fluorescent lamps (TFL). However, the power consumption pattern differs by its manufacturing constraints which are notified to the consumers through the star ratings and energy efficiency labels. Energy savings can be achieved by systematically replacing the conventional TFLs by means of energy efficient LED lamps (EEL). This paper focuses on the practicality of use concerning the scheme of lamp replacement to achieve better energy efficiency. To carry out these isometrics, Bureau of Energy Efficiency (BEE) approved TFL and LED lamps of different brands and star ratings were used. In line with methodology discussed in the manuscript, it is obvious that by replacing 36 W and 28 W standard TFLs through appropriate EELs, the respective annual energy savings of about 11-16 kWh and 7 kWh can be achieved. The results highlight that replacing the lamps randomly can be futile; however, a strategic process in the selection and proximate replacement ensures an optimal level of efficiency. This leads to an increased lumen output, longer lamp life, or both, which ultimately saves an appreciable amount of energy. The prospective research may focus on inter EEL replacement isometrics to achieve microtic energy efficiency.

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1. INTRODUCTION

Achieving energy efficiency has become a critically focused global concern as a part of addressing environmental sustainability and achieving energy conservation. Different illuminating technologies, viz. incandescent lamps to LED lamps have been introduced in the market so as to provide adequate lighting to the occupants of any accommodation. Incandescent lamp serves as a general lighting source with the best colour rendering index and established power factor, for which a separate stream of research focuses to achieve. However, on the rear side, it consumes relatively high power to produce desired illumination in comparision to second generation lamp technologies, viz. fluorescent lamps. Further, with advancement in LED technology, even fluorescent lamps are being superseded by the LED lamps in view of their luminous efficacy and enhanced durability.

In line with this, it can be stated that the lighting systems, which represent a significant share of overall energy consumption, offer a major opportunity for improvements in energy efficiency by replacing the traditional lighting sources like incandescent and fluorescent lamps by means of energy-efficient lamp technology options such as LED lamps. However, as a current practice, the existing traditional lamps are being replaced by LED lamps arbitrarily. As a consequence, the design requirement is getting overlooked, leading to either inadequate or surplus illumination irrespective of their desired energy efficiency, while prior studies focus on lamp technology improvements, they rarely address systematic replacement strategies that ensure optimal illumination and energy savings. Unlike previous works, this study introduces a structured methodology using isometric analysis to bridge this gap. On the contrary, the content of the study presented in this manuscript examines systematic lamp replacement opportunity as a strategic method for boosting energy efficiency complying with the desired illumination. By analyzing the energy consumption patterns of various lighting systems through isometric analysis, the research assesses the potential energy savings and environmental advantages of switching to high-efficiency lighting solutions. Isometric analysis provides a structured way to compare the performance of different lamp technologies based on power usage, luminous efficiency, lifespan, and cost-effectiveness.

The goal of the presented research is to demonstrate how a carefully planned and systematically implemented lamp replacement strategy can result in significant energy savings, lower greenhouse gas emissions, and support sustainable energy management. The study evaluates real-world data and case studies to assess the effectiveness of this approach in different application settings. Based on these findings, it offers practical recommendations for businesses, municipalities, and households seeking to enhance their lighting infrastructure while reducing operational costs and environmental impact.

2. LITERATURE REVIEW

The replacement of tubular fluorescent lamps by LED lamps represents a significant opportunity to achieve energy savings, enhance performance, and reduce environmental impact across various sectors. While challenges such as initial costs and compatibility issues exist, the benefits of LED technology outweigh these concerns in the long run. Continued research, innovation, and policy support are essential to facilitate the widespread adoption of LED lighting and realize its full potential in creating a more sustainable and efficient lighting infrastructure.

Widartha *et al*. [1] examined how smart-lighting systems can save energy by automatically adjusting brightness using sensors and daylight information. Their study showed that combining sensor inputs with simple control rules can reduce energy consumption while keeping indoor lighting comfortable for users. Aliparast and Onaygil [2] conducted a field study in an office environment to evaluate energy-efficient LED lighting. They found that well-designed LED systems can improve visual comfort, support human-centred lighting needs, and still lower energy usage. The results highlight the benefits of adopting efficient LED setups in indoor spaces. Khayam *et al.* [3] examined the current state of lighting technology adoption in Indonesia, highlighting challenges and advancements in sustainable lighting solutions.

Recent studies have extensively explored energy-efficient lighting technologies, yet their findings vary in scope and application. Castilla *et al.* [4] examined lighting's impact on cognitive performance in educational environments, demonstrating that optimized illuminance and color temperature can simultaneously reduce energy consumption and improve learning outcomes—a perspective absent in earlier reviews. Mitali *et al.* [5] provided a comprehensive review of energy storage systems, discussing various technologies and their applications in sustainable energy solutions. In contrast, Padmasali *et al.* [6] focused on LED luminaire reliability under accelerated conditions, highlighting degradation factors such as lumen maintenance and color stability, which are critical for long-term performance but do not address system-level energy optimization.

Al-Ghaili *et al.* [7] reviewed lighting system designs for different building types, emphasizing ICT-based smart solutions for energy savings, but lacked experimental validation. Beucker *et al*. [8] assessed the global potential and environmental impact of building energy management systems (BEMS), emphasizing their role in reducing energy consumption. Wallich [9] explored advancements in lighting technology, highlighting the benefits of a newly developed lightbulb with improved efficiency and longevity. Mills and Schleich [10] examined factors influencing consumer awareness and purchasing behavior of energy-efficient appliances, shedding light on policy and market implications.

Papantoniou *et al*. [11] introduced adaptive lighting controllers utilizing smart sensors to enhance energy efficiency in buildings. Cook [12] analyzed high-efficiency lighting in industrial and commercial buildings, outlining strategies for reducing power consumption while maintaining optimal lighting conditions. Aslanoğlu *et al*. [13] conducted an international survey on residential lighting usage, analyzing consumer behavior and energy consumption patterns during winter. Yun *et al*. [14] assessed the energy-saving potential of LED lighting systems, emphasizing their role in reducing electricity consumption in indoor environments. Ahn *et al*. [15] investigated the impact of LED lighting on cooling and heating loads in office buildings, demonstrating its potential to enhance energy efficiency. Park and Lee [16] explored consumer perceptions and behaviors regarding energy-efficient lighting, providing insights into market adoption and policy implications. Singh *et al*. [17] evaluated the application of LED lighting in greenhouse environments, highlighting its benefits for energy-efficient agricultural practices.

Cheng and Cheng [18] conducted a general study on replacing traditional lighting devices with LEDs, presenting technical and economic feasibility considerations. Khan and Abas [19] conducted a comparative study on various energy-saving light sources, evaluating their efficiency, lifespan, and environmental impact. Nakano *et al*. [20] explored the key determinants of energy savings in Indonesia, focusing on the adoption of LED lighting in Bogor and its impact on electricity consumption. The U.S. Department of Energy outlined a multi-year research and development plan for solid-state lighting, emphasizing advancements in LED technology and efficiency improvements [21].

The International Energy Agency (IEA) provided an in-depth analysis of global energy efficiency trends and outlooks up to 2040, highlighting the role of lighting technology in reducing energy demand [22]. Osram Inc. conducted a life cycle assessment comparing incandescent bulbs, compact fluorescent lamps (CFLs), and LED lamps, underscoring the environmental benefits of LED technology [23]. The U.S. Environmental Protection Agency provided online resources on energy star-certified light bulbs, guiding consumers in selecting energy-efficient lighting options [24]. Similarly, the Australian Government published an online guide on energy savings through efficient lighting choices, promoting sustainable practices in residential and commercial settings [25].

The United Nations Environment Programme highlighted the impact of buildings on climate change, presenting strategies for sustainable energy consumption in construction and infrastructure development [26]. The Bureau of Energy Efficiency (BEE) provided details on its standards and labeling program, offering guidelines for energy efficiency certifications and testing procedures for lighting products in India [27]. Additionally, the European Commission discussed the promotion of energy-efficient products within the EU, reinforcing policies aimed at reducing energy consumption in households and industries [28].

Overall, the aforesaid research collectively contributes to our understanding of the energy-saving potential of LED lighting by offering insights from various geographical regions and sectors. The findings also highlight the importance of policy initiatives and consumer awareness in promoting the adoption of energy-efficient technologies. In addition, previous studies have shown that energy efficiency labels influence consumer behavior and preferences, leading to increased demand for energy-efficient lamps (EEL).

In India, households and institutions are using fluorescent tube lights. Banning a particular technology is policy-oriented decision. But implementation may take years in practical scenarios. Awareness must be created from root level for the consumers. This paper is intended to create the same. The aforesaid research aims in presenting the technology, but not the systematic way of practical implementation, so as to establish the ease of technology adoption. If a conventional lamp is replaced by an energy efficient lamp, careful consideration must be given to the efficacy, because even a minute deviation in the capacity may not come with the desired lumen output. Hence, a proper methodology is desired to have optimum technology-to-technology balancing, which is being addressed in the presented research.

3. LAMP REPLACEMENT ISOMETRICS: METHODOLOGY

The methodology for lamp replacement is illustrated in Figure 1. The process begins by selecting the specific occupancy where the lamp replacement is to be carried out. Based on the nature of the occupancy, the required illumination (E) level is determined, and the existing conventional lamps serving that space are identified. After establishing the desired illuminance, the number of suitable EEL is evaluated by considering their available capacities and star ratings. The different EEL options are then compared, and the set that meets the required illuminance while providing maximum light output, longer lamp life, and lower energy consumption is selected as the replacement option.

The methodology adopted in this study ensures both reproducibility and practical relevance. The approach is based on isometric analysis. This method provides a structured comparison of lamp technologies by considering illumination, energy consumption, and star ratings.

Step-by-Step procedure involved in the methodology is furnished below:

i) Define illumination requirements – determine the required lux level for the given room dimensions based on IS standards.
ii) Calculate room index – compute room index (K) using (1).

$$K = \frac{L \times W}{H \times (L + W)} \quad (1)$$

Where L is length in metres, W is width in metres, and H is mounting height in metres.

iii) Select existing conventional lamp – identify the existing TFL used and acquire its specifications (wattage, lumen output).

iv) Identify the candidate LED lamp – identify and collect necessary technical records of the LED lamps, including star ratings from BEE-approved sources.

v) Compute required number of lamps – use the following expression as in (2).

$$N = \frac{E \times Area}{Lumens \times CUF \times MF} \tag{2}$$

Where CUF is coefficient of utilization factor and MF is maintenance factor.

vi) Calculate energy consumption – use the following expression as in (3).

$$E = \frac{W_T \times H \times D}{1000} \tag{3}$$

Where E is energy consumption in kWh, H is hours of use, and D is noo. of days.

vii) perform isometric analysis – compare relative combinations based on energy savings, lumen output, and lamp life.

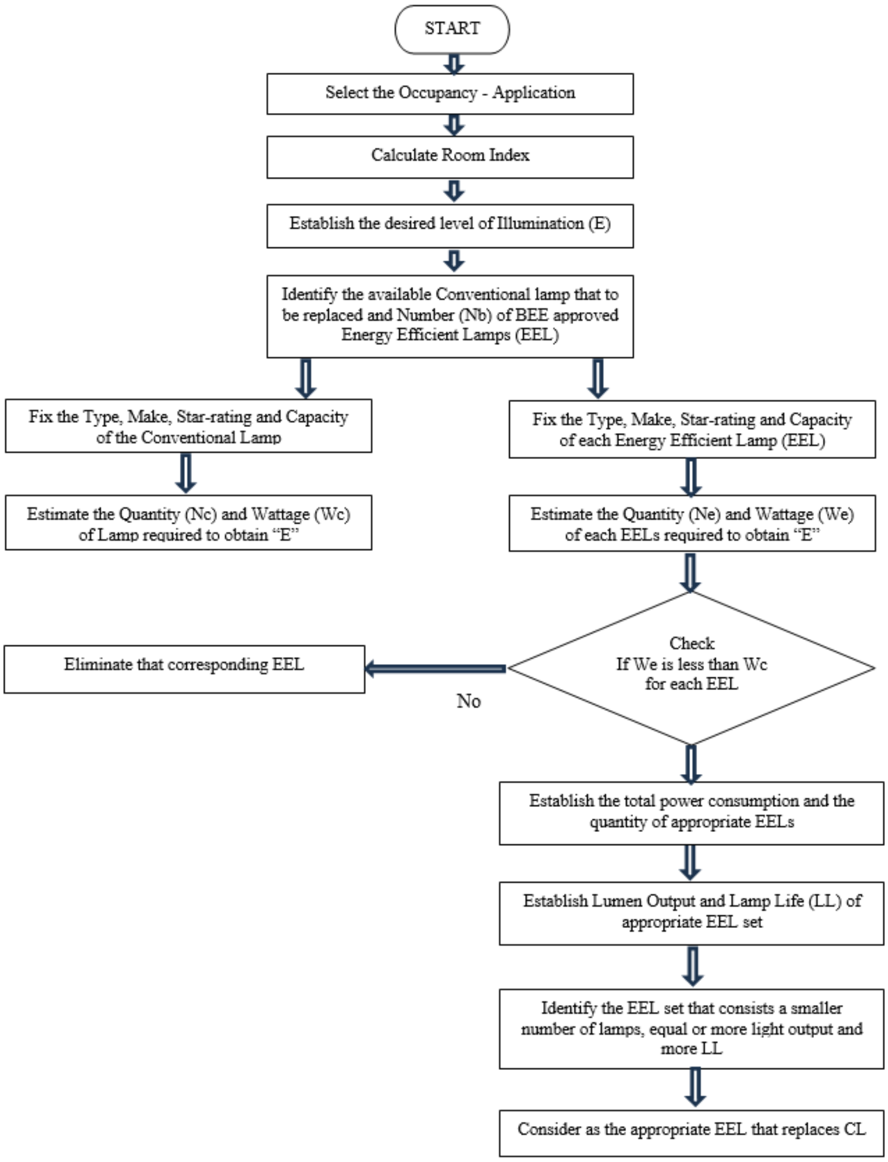

Figure 1. Methodology for lamp replacement isometrics

4. COMPARATIVE ANALYSIS OF STAR RATED LUMANARIES

Bureau of Energy Efficiency (BEE) - Standards and Labeling Program (S&L scheme) was commenced by the Hon'ble Minister of Power, Govt. of India in the May month of the year 2006. It is presently summoned for variety of energy consuming equipments/appliances. As per BEE, in order to participate and acquire star labeling, all the products produced by the manufacturers must apply and undergo the standard testing in relevant BEE empanelled Labs with respect to the appliances. Based on the test results obtained, the concern appliances will be given star rating and make it eligible for labelling, or else it will be disqualified. Even now, incandescent lamps are being used in most of the villagers and urban areas, keeping in view the budget of below poverty line households, particularly in India. The following pictures as furnished in Figure 2 confirm the same.

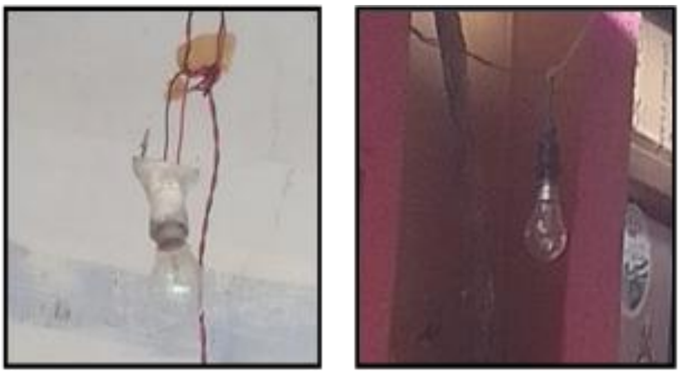

Figure 2. Incandiscent lamps being used by Indian households

It is to be understood that incandescent lamps are the ones which consume power satisfactorily with unity power factors (UPF), unlike LEDs which are creating power quality issues and is becoming a cause for increasing the compensatory budget indirectly. Hence, incandescent lamps cannot be left as they are. Research must progress to make it consume less power, rather than banning it. To compare the performance of various star rated LED lamps, LED lamps of 10 W and 23 W ratings produced by one of the reputed Indian manufacturers are considered. With this make only 1-star, 2-star, and 3-star rated 10 W LED lamps, and 2-star and 3-star rated 23 W LED lamps are available in the market.

The detailed specifications of the available star rated 10 W and 23 W LED lamps are furnished in Tables 1 and 2, respectively. The graphical representation of various performance features of available star rated 10 W LED Lamp and 23 W LED lamp are depicted in Figures 3 and 4, respectively. From Figures 3 and 4, it is clear that the rated luminous efficiacy increases with the increase in star rating. From Table 1 and Figure 1, it can be understood that the relative performance of 2-star and 3-star rated LED lamps with respect to 1-star rated LED lamp is better by 4.39 and 15.38%, respectively. From Table 2 and Figure 2, it can be understood that the relative performance of 3-star rated LED lamps with respect to 2-star rated LED lamps is better by 16.66%.

The total number of 10 W and 23 W LED lamps required and corresponding circuit watts for a considered three number of rooms with same dimensions of 5 m × 3 m × 2.5 m and desired illumination of 300 Lux, coefficient of utilization factor of 0.54 and maintenance factor of 0.95 are furnished in Tables 3 and 4, respectively. From Table 3, it is clear that as compared to 1-star rated LED lamp of same wattage the number of 10W LED lamps (30 numbers for 1-star) required is relatively less by about 10% and 20% with 2-star (27) and 3-star (24) rated LED lamps. And also, from Table 3 and Figure 2 it is clear that as compared to 1-star rated LED lamp of same wattage the average monthly energy consumption (45 kWh for 1-star) for total operating hours of 150 is also relatively less by about 10% and 20% with 2-star (40.5 kWh) and 3-star (36 kWh) rated LED lamps.

From Table 4, it is clear that the number of 23W LED lamps (20 numbers for 1-star) required is relatively less by about 20% with 3-star (16) rated LED lamp as compared to 2-star rated LED lamp of same wattage. Also, from Table 4 and Figure 3, it is clear that the average monthly energy consumption for total operating hours of 150 is also relatively less by about 20% with 3-star rated LED lamps (55.2 kWh) as compared to 2-star rated LED lamp (69 kWh) of same wattage. From Tables 3 and 4, it is clear that the total connected circuit watts get reduced with increase in star rating of the concern lamp.

Table 1. Specifications of various star rated 10W LED lamps

Description	1-star	2-star	3-star
Model number	12LSK10DH B303- Family	7LSK10HB01	12LSK10DH B601- Family
Wattage of lamp	10	10	10
Equivalent incandescent lamp (wattage) as per BEE	75	75	75
Light output (lumens)	910	950	1050
Light (hours)	25000	25000	25000
Rated luminous efficacy (lm/W)	91	95	105

Table 2. Specifications of various star rated 23W LED lamps

Description	1-star	2-star	3-star
Model number	-	19LSI23HB3 01	19LSI23HB6 01
Wattage of lamp	-	23	23
Equivalent incandescent lamp (wattage) as per BEE	-	160	200
Light output (lumens)	-	2010	2415
Light (hours)	-	25000	25000
Rated luminous efficacy (lm/W)	-	90	105

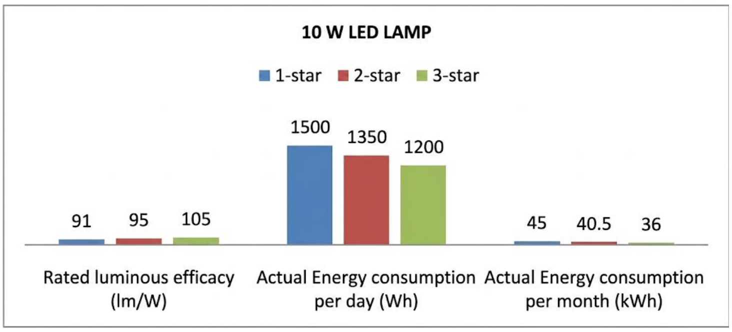

Figure 3. Various performance features of 10 W LED lamp

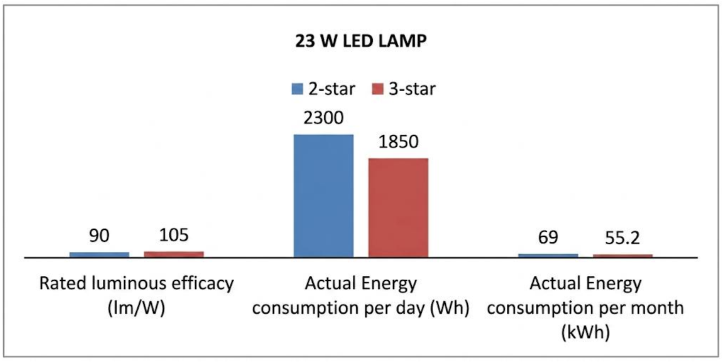

Figure 4. Various performance features of 23 W LED lamp

Table 3. Estimation of total 10 W LED lamps and circuit watts

Description	1-star	2-star	3-star
Quantity of 10 W LED lamps required per room	9.64	9.23	8.35
Quantity of 10 W LED lamps required per room (rounded)	10	9	8
No. of similar rooms considered (for understanding)	3	3	3
Total no. of LED lamps required (rounded)	30	27	24
Total connected wattage	300	270	240
Operating hours	5	5	5
Actual energy consumption per day (Wh)	1500	1350	1200
Actual energy consumption per month (kWh)	45	40.5	36

Table 4. Estimation of total 23 W LED lamps and circuit watts

Description	1-star	2-star	3-star
Quantity of 23W LED lamps required per room	-	4.24	3.63
Quantity of 23W LED lamps required per room (rounded)	-	5	4
No. of similar rooms considered (for understanding)	-	4	4
Total No. of LED lamps required (rounded)	-	20	16
Total connected wattage	-	460	368
Operating hours	-	5	5
Actual energy consumption per day (Wh)	-	2300	1850
Actual energy consumption per month (kWh)	-	69	55.2

5. OPTIMAL LAMP REPLACEMENT: RESULTS AND DISCUSSIONS

To reduce the electrical vitality consumption and establish energy efficiency, it is required to replace the high-power consuming lamp with the lamp or combination of lamps that produce same amount of illumination as that of the former lamp. The most common type of lamps which are being used for indoor illumination is 36 W and 28 W TFL lamps. The specifications of these TFL lamps are furnished in Table 5.

Specifications of different categories of LED lamps which could produce the light output, either individually or in combination same as that of the lamps as considered in Table 5 and are approved by BEE are furnished in Tables 6 to 9. From Tables 6 to 9, it is clear that the LED lamps that could produce the integral light output to match the considered conventional TFL lamps are 30 W, 25 W, 23 W, 20 W, 15 W, 14 W, and 9 W. These lamps are being released with different brand names viz. Crompton, Halonix, BPL, Orient, Gold Medal, Syska and Philips, and with different star ratings.

Table 5. Specifications of conventional TFL lamps

Brand	OSRAM	OSRAM
Type of lamp	TFL	TFL
Wattage of lamp	28	36
Life in hours	19000	20000
Light output (lumens)	2800	3350
Rated luminous efficacy (lm/W)	100	93

Table 6. Specifications of LED lamps (>10 W)

Brand	Crompton		Halonix		BPL
Wattage of lamp	30	23	25	25	25
Star rating	2	3	2	3	3
Light output (lumens)	3150	2415	2500	2625	2650
Ratedluminous efficacy(lm/W)	105	105	100	105	106

Table 7. Specifications of LED lamps (>10 W)

Brand	Orient	Goldmedal	
Wattage of lamp	20	15	14
Star Rating	5	2	3
Light output (lumens)	2700	1410	1470
Rated luminous efficacy(lm/W)	135	94	105

Table 8. Specifications of LED lamps (<10 W)

Brand	Orient		Halonix		Syska	
Wattage of lamp	9	9	9	9	9	9
Star rating	5	3	4	3	2	3
Light output (lumens)	1215	1035	1150	945	900	1080
Rated luminous efficacy(lm/W)	135	115	128	105	100	120

Table 9. Specifications of LED lamps (<10 W)

Brand	Syska		Philips		
Wattage of lamp	9	9	9	9	9
Star rating	2	1	4	3	2
Light output (lumens)	945	810	1080	950	825
Rated luminous efficacy(lm/W)	105	90	120	106	92

The options for replacement of conventional 36 W and 28 W TFL lamps with suitable combinations of LED lamps as furnished in Tables 6 to 9 are presented in Tables 10 and 11, respectively. The energy savings that can be achieved through corresponding lamp replacement options are furnished in Tables 12 and 13, respectively. From Tables 10 and 12, it is clear that one number 36 W Osram make TFL lamp can be replaced by either one number of 30 W Crompton make LED lamp (option-1) or three numbers Orient make 5-star rated 9W LED lamps (option-2) or three number Halonix make 4-star rated 9W LED lamps (option-3). With option-1, though light output is relatively less (3150 lumens) with respect to the reference 36 W TFL lamp (3350 lumens), there is power savings about 6 W and an annual energy savings about 11 kWh considering 1825 annual operating hours. With options-2 and 3, though light output is relatively more (3645 lumens and 3450 lumens) with respect to the reference 36 W TFL lamp (3350 lumens), there is power savings about 9 W and annual energy savings about 16 kWh considering 1825 annual operating hours.

The pictorial representation of the options for replacing 36 W TFL and corresponding power and energy savings that can be achieved through various lamp replacement options is depicted in Figures 5 and 6, respectively. From Figure 5 and relevant Table 10, it is clear that as the wattage and quantity of lamps required for the considered occupancy is relative and equally less with the options II (ORIENT 5*) and III (HALONIX 4*), they can be considered as the best choice as replacing lamps. The same can be confirmed by referring Figure 6 and relevant Table 12, from which it is clear that even the power and energy consumption by opting these options is relatively and equally less.

Table 10. Lamp replacement options for 36 W TFL lamp

Replacement options	Make (star rating)	Life in hours	Wattage	Qty
I	CROMPTON	25000	30	1
II	ORIENT (5*)	25000	9	3
III	HALONIX (4*)	25000	9	3

Table 11. Lamp replacement options for 28W TFL lamp

Replacement options	Make (star rating)	Life in hours	Wattage	Qty
I	GOLD MEDAL (3*)	25000	14	2
II	ORIENT (5*)	25000	9	3
III	HALONIX (4*)	25000	9	3
IV	HALONIX (2*)	25000	7	4
V	WIPRO (4*)	25000	7	4
VI	WIPRO (3*)	25000	12	2

Table 12. Energy savings through lamp replacement options for 36 W TFL lamp

Replacement options	Light output per lamp	Total light output	Saving in power consumption(W)	Energy saving per annum (say 1825 hrs) in kwh
I	3150	3150	6	11
II	1215	3645	9	16
III	1150	3450	9	16

From Tables 11 and 13, it is clear that one number 28 W Osram make TFL lamp can be replaced by either two number of gold medal make 3-star rated 14 W LED lamp (option-1) or three numbers orient make 5 star rated 9 W LED lamps (option-2) or three numbers Halonix make 4 star rated 9 W LED lamps (option-3) or four numbers of Halonix make 2-star rated 7 W LED lamps (option-4) or four numbers Wipro make 4 star rated 7 W LED lamps (option-5) or two numbers Wipro make 3- star rated 12 W LED lamps (option-6). Exact light output can be matched with option-4. With option-6, though light output is relatively less (2520 lumens) with respect to the reference 28 W TFL lamp (2800 lumens), there is power savings about 4 W and an annual energy savings about 7 kWh considering 1825 annual operating hours.

Exact power consumption can be matched with options-1, 4, and 5 because of which there will be not any relative energy savings. However, the life of the lamp will get extended. With options-1, 2, 3, and 5, light output is relatively high. With options 2, 3, and 6 there will be power savings about 1 W, 1 W, and 4 W respectively and annual energy savings about 2 kWh, 2 kWh, and 7 kWh respectively. From Tables 10 and 12 it is evident that the lifespan of 36 W and 28 W TFL lamp is 20,000 hours and 19,000 hours, respectively, but the lifespan of LED lamps irrespective of their ratings is 25,000 hours.

The pictorial representation of the options for replacing 28 W TFL and corresponding power and energy savings that can be achieved through various lamp replacement options is depicted in Figures 7 and 8, respectively. From Figure 8 and relevant Table 13, it is clear that with option VI (WIPRO 3*) the relative power and annual energy savings that can be achieved is high, but it is at the cost of reduced light output. However, from Figure 7 and relevant Table 11, it is clear that as the wattage and quantity of lamps required for the considered occupancy is relatively less with the options IV (HALONIX 2*) and V (WIPRO 4*), they can be considered as the best choice though the net energy savings that can be achieved is nil. It is so because of their extended life span.

Table 13. Energy savings through lamp replacement option

Replacement options	Light output per lamp	Total light output	Saving in power consumption (W)	Energy saving per annum (say 1825 hrs) in kwh
I	1470	2940	0	0
II	1215	3645	1	2
III	1150	3450	1	2
IV	700	2800	0	0
V	840	3360	0	0
VI	1260	2520	4	7

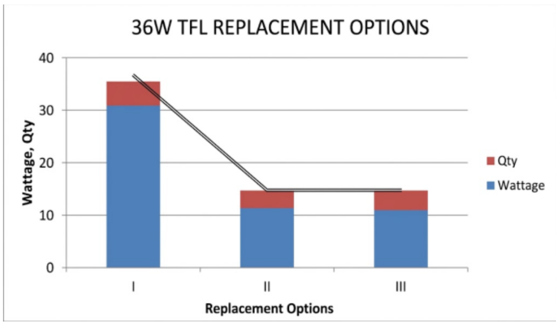

Figure 5. Options for replacing 36 W TFL lamps

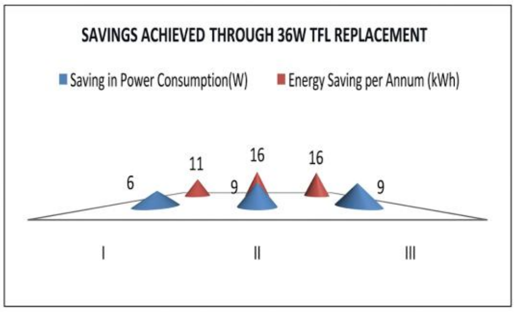

Figure 6. Power and energy savings achieved through 36 W TFL replacement

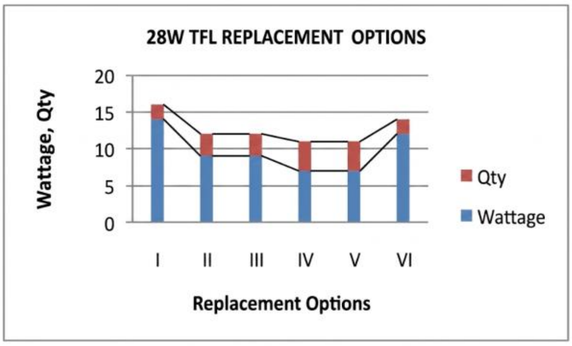

Figure 7. Options for replacing 28 W TFL lamp

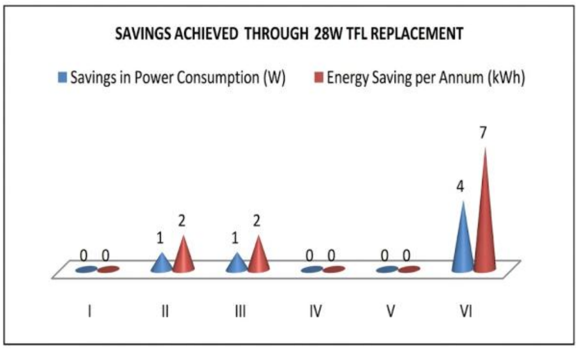

Figure 8. Power and energy savings achieved through 28 W TFL replacement

6. ECONOMIC ANALYSIS AND ENVIRONMENTAL IMPACT

Economic analysis: The cost of LED lamps and TFLs are enquired and compared to determine economic feasibility and adaptability in the real time practice. For instance, replacing a 36 W TFL (average cost ₹120) with three 9 W LED lamps (average cost ₹250 each) results in an investment of ₹750. With an estimated annual energy savings of about 16 kWh and at an average monetary equivalent of ₹6/kWh, total annual monetary equivalent of savings that can be achieved is ₹96 per combination, leading to a simple payback period of approximately 7.81 years.

Environmental impact: Every unit of electricity saved reduces CO_2 emissions by approximately 0.82 kg/kWh (as per Indian grid emission factor). Therefore, for the aforesaid case, i.e. by replacing a 36 W TFL by means of three 9 W LED lamps, with possible annual energy savings of about 16 kWh, the total CO_2 emissions that can be reduced is about 13.12 kg. And in line to this if 100 numbers of 36 W TFLs are proposed to be replaced by appropriate LED lamps, then the total reduction in CO_2 emissions that can be achieved is 1312 kg, which is an appreciable figure.

7. CONCLUSION

It is to confirm that, the data considered for the study is sourced from BEE empanelled Labs with respect to the concerned appliances. As per BEE, Ministry of Power, Govt. of India; in order to participate and acquire star labeling, all the products produced by the manufacturers must apply and undergo the standard testing in relevant BEE empanelled Labs. Based on the obtained test results, the concern appliances will be given star rating and make it eligible for labeling or else it will be disqualified. It is also to confirm that this study doesn't depend on manufacturer results, but the trusted BEE empanelled testing Labs. Hence, the data presented is verified and reliable.

The process of designing or operating a system or facility to consume less energy while maintaining the same level of performance is known as energy efficiency. The best energy savings can be obtained via the appropriate substitute isometrics. The artificial lighting sector is crucial in ensuring appropriate illumination of the internal and external parts of not just domestic structures, but also commercial and industrial ones; thus, considerable energy savings can be achieved if old conventional lamps such as TFL are replaced with energy-efficient ones such as LED lamps. In order to compare the performance of various star rated LED lamps, LED lamps of 10 W and 23 W ratings produced by one of the reputed Indian manufacturers are considered. The total number of 10 W and 23 W LED lamps required and corresponding circuit watts for a considered three number of rooms with same dimensions and desired illumination are evaluated. By comparative analysis it is apparent that, with respect to 1- star (2-star) rated 10 W (23 W) LED lamp the relative performance of 2-star and 3-star rated (3-star) 10 W (23 W) LED lamps is better by 4.39 and 15.38% (16.66%), respectively. Also, the number of 10W (23 W) LED lamps required and the average monthly energy consumption is relatively less by about 10% and 20%, respectively (20%).

In the manuscript presented, 36 W and 28 W TFL lamps which are most commonly used conventional lamps for indoor illumination are considered for replacement with EELs. With reference to the methodology presented for systematic lamp replacement, LED lamps of different capacities, star ratings and make available in the market are considered and isometric analysis was performed. The results are so fertile that by replacing 36 W and 28 W standard TFLs by means of appropriate EELs, the respective annual energy savings of about 11-16 kWh and 7 kWh can be achieved. A 36 W TFL can be replaced by 3 numbers 5-star or 4- star rated 9 W LED lamps while a 28 W TFL can be replaced by either 3 numbers 5-star rated 9 W LED lamps or 2 numbers 3-star rated 12 W LED lamps or 4 numbers 4-star rated 7 W LED lamps. It is also obvious that the lamp life of TFL lamp is too less in comparision to the LED lamp. If a lamp combination with relatively less light output is selected, then though there is a slight compromise on light output, the lamp life will get extended. Besides, if a lamp combination with relatively high light output is selected, then in addition to the increased illumination, the lamp life also gets extended. Through proper isometrics, the lamp combinations can be finalized so as to achieve energy efficiency by reducing energy consumption and establishing green electricity.

This study is limited to indoor lighting scenarios and does not account for outdoor or industrial lighting conditions. The findings can guide manufacturers and dealers in promoting star-rated LED lamps and help policymakers design incentive schemes for systematic lamp replacement. Stakeholders such as building contractors and facility managers can use these insights to plan energy-efficient retrofits aligned with BEE standards. Further studies can explore inter-EEL replacement isometrics, integration with smart lighting controls, and cost-benefit analysis across diverse building types. Research can also examine consumer behavior and policy frameworks to accelerate adoption of energy-efficient lighting technologies.

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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 supports the findings of this study are available from the corresponding author, [SJ], upon request.

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