A Circular Light Bulb Economy: Framework for Sustainable End-of-Life Management of Modern Light Bulb

1. Abstract

This paper presents a framework that focuses on transitioning from a linear light bulb economy to a circular light bulb economy by developing a closed-loop system of reuse. The conceptual framework is based on a pilot study conducted in India and strengthened by **a** comprehensive review and analysis of relevant literature. Accordingly, the proposed paradigms are a result of best practices identified during the pilot study. The results demonstrate the financial viability of the pilot study conducted over a period of three years. Additionally, the results provide evidence of the impact of the circular economy on economic growth, employment opportunity, and reduction in environmental waste. The discussion also identifies the barriers to the adoption of a circular economy framework including the role of attitude towards the environment and the skill gap in labor.

2. Keywords

Compact fluorescent lamp, Light emitting diode, circular economy, linear economy, end-of-Life

3. Introduction

Absence of Scientific Methods of Disposal in a Linear Economy

The modern light bulb, namely the Compact Fluorescent lamp and the Light Emitting Diode, has unequivocally replaced the incandescent bulb from households across the globe. The efficiency, longevity, and versatility of operation make the modern light bulb an economical lighting solution. Once the bulb turns faulty, however, the environmental cost of its disposal, in terms of resource depletion and toxicity potential (Table 1 and 2), outweighs all its potential benefits during operation. Today, consumer light bulbs which reach their end-of-life are collected by scrap dealers who crush them to extract valuable materials [6]. This unscientific method of metal extraction creates waste for incineration or landfill. Both LED and CFL bulbs have high metal composition and therefore, possess high toxicity potential when dumped in landfill. The metals include aluminum, copper, gold, lead, silver, zinc, and mercury (present in CFL bulb only [1].

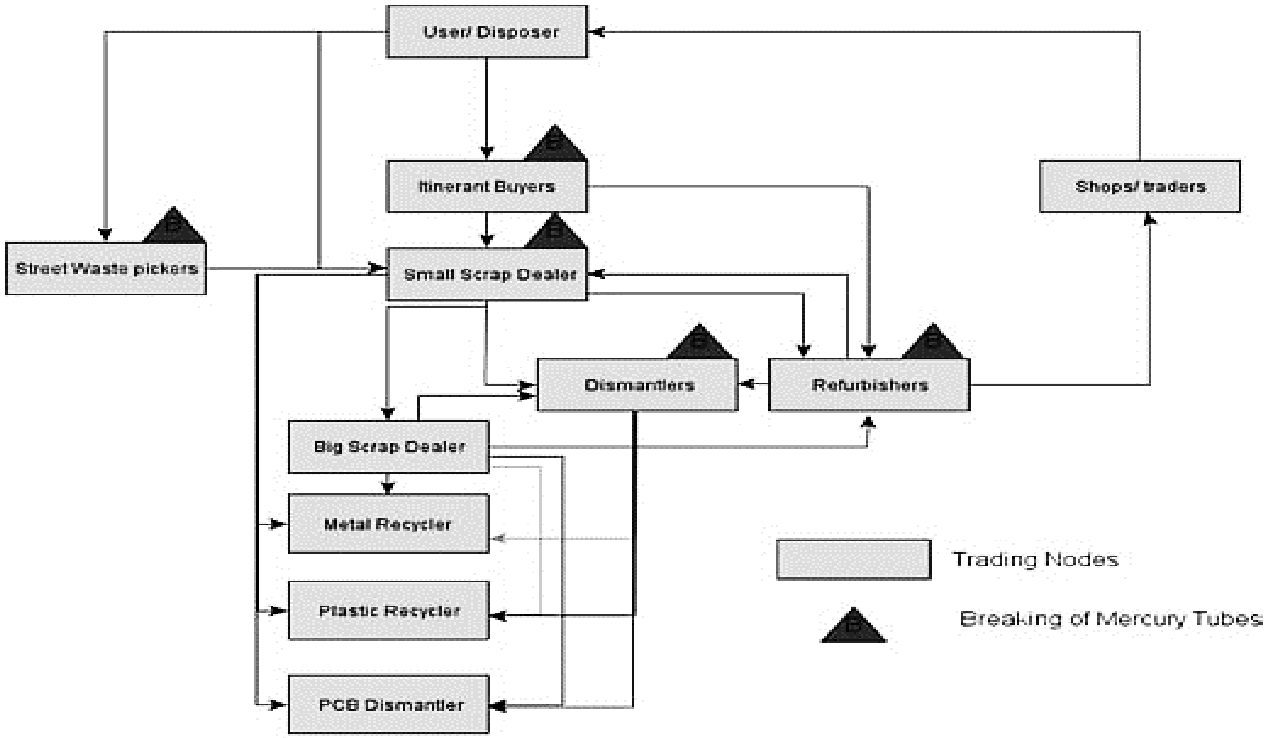


Figure 1: Flow of CFL bulb in a linear light bulb economy [6]

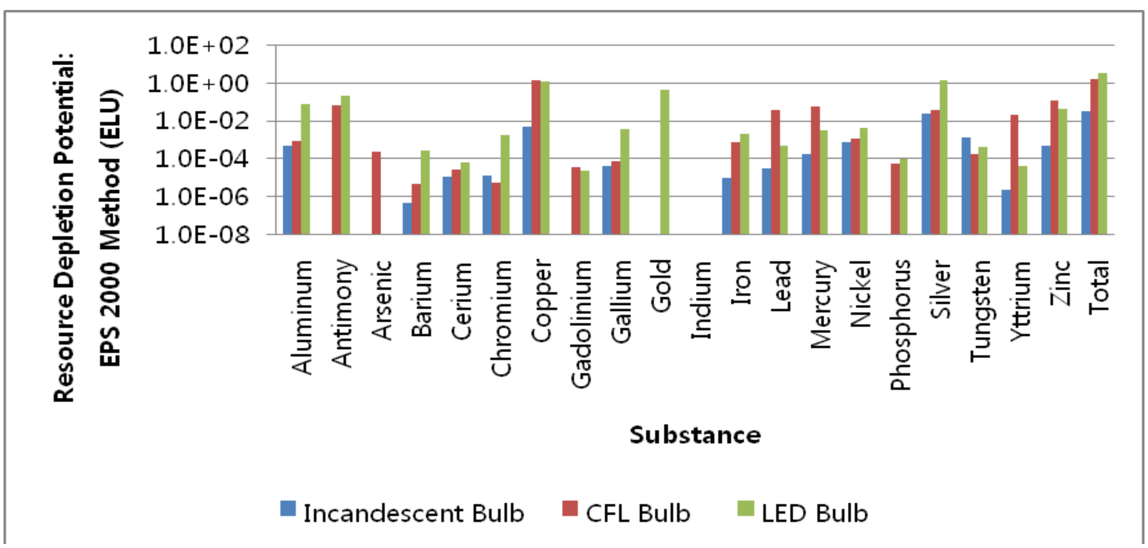


Figure 2: Resource depletion potentials of the incandescent, CFL, and LED bulbs (on a per-bulb basis) derived based on the EPS 2000 method. Unit: Environmental Load Unit (ELU) [1]

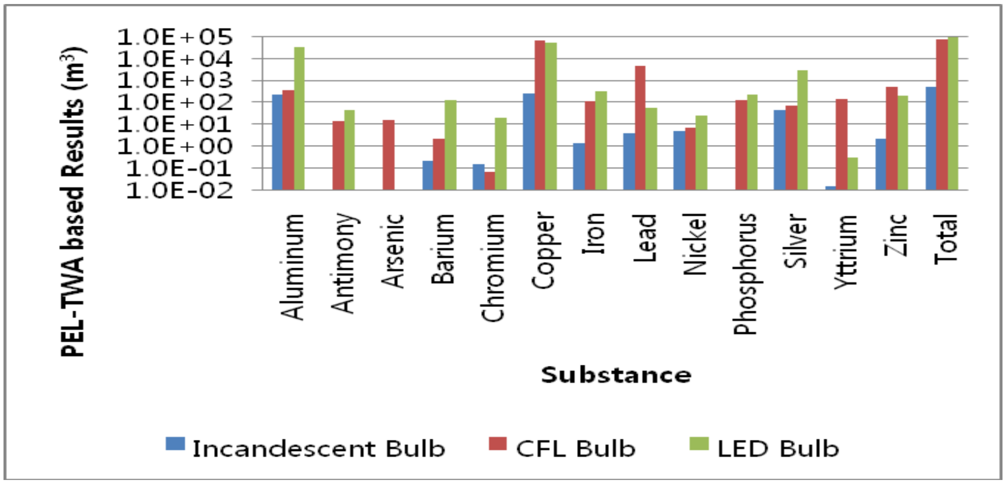


Figure 3: Toxicity potentials of the incandescent, CFL, and LED bulbs as determined based on the PEL-TWA method. The unit represents the volume of the fresh air needed to dilute the hazard from the substance under the exposure limit. Unit: m3 [1]

A CFL bulb tube contains approximately five milligrams of mercury (Hg), a neurotoxin which cannot be recycled, in addition to phosphorous and inert gases [2]. When the glass tube of a CFL bulb is broken, the mercury contained in the tube may come in direct contact of people by inhalation. The mercury leaches from broken CFLs in dissolved or vapor form and gets converted into methylmercury, which intrudes into the food chain by means of biomagnification. The vapor leaching from broken CFL tube can continue for weeks and even months, and the discharge rate varies from one manufacturer to another [3]. LED bulbs, on the other hand, contain lead, another neurotoxin which exhibits significant cancer potential upon human exposure. Copper, also found in some LED bulbs, has the ability to poison aquatic life if allowed to leach in water bodies.

In the absence of any formal end-of-life management system for waste electronic goods in place, developing countries like India, Pakistan, and Bangladesh face high risk from heavy metals entering the food chain.

Definition of Circular Economy

A circular economy is one built on the pillars of innovation in all stages of the product lifecycle. It involves the development of robust materials and components, new business models, and zero-waste end-of-life management systems and processes. A circular economy framework is designed with the objective of maximizing economic value across the product lifecycle. All other derived benefits apart from economic value creation, such as environmental benefits, are ancillary [8]. This approach is fundamentally different from other ecological methodologies such as cradle to cradle, biomimicry or the Natural Step which are aimed at effective use natural resources. [4] Since the circular economy is driven by economic motivation, it is a more pragmatic approach than other ecological methodologies.

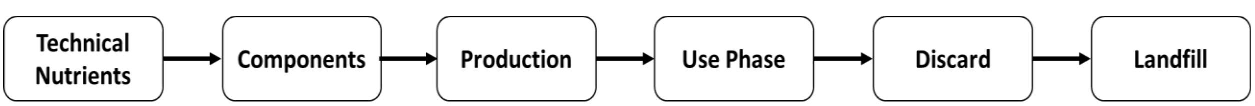


Figure 4: Linear Economy Framework

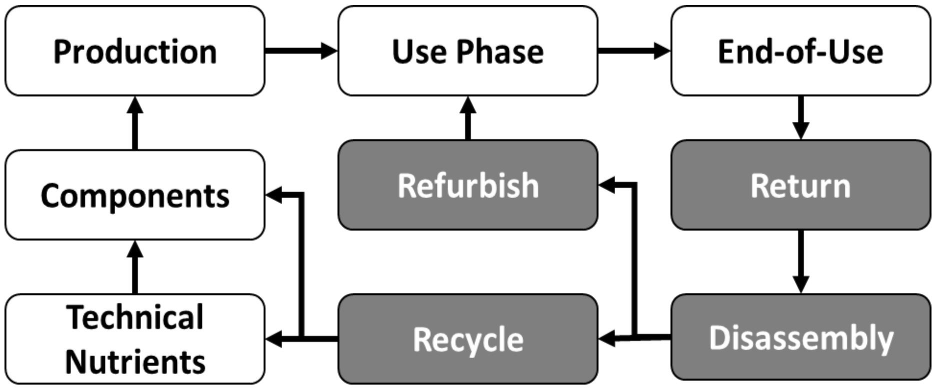


Figure 5: Circular Economy Framework

Product Design:
Historically, light bulbs are infamous for introducing planned obsolescence to consumer electronics. The selection of components and the overall product design is aimed at one singular objective- the lowest cost for a given level of features and quality. Many modern light bulb manufacturers intentionally obscure the part numbers of individual components in a light bulb or discontinue spare parts supply in the open market within months of product launch. These measures significantly reduce the potential for reuse of light bulb by means for repair and refurbishment.

In contrast, products for the circular economy need to be designed and engineered to last as long as technically feasible. Their design philosophy should maximize the use of components and materials that allow reuse even after the product itself is not operational. Innovative product designs support the repairability of the product instead of discarding after first use.

Few design developments in modern LED bulbs to improve recycling benefits are listed.
1. Elimination of Aluminum heat sink with efficient design geometry
2. Combined Light bulb housing and lens
3. Ultrasonic Welding for bonding in place of glue resin
4. Use of recycled ABS plastic generated from electronic waste
5. Implementing modularity in product design

Business Model:
Traditional sales model operates on the concept of selling products to consumers. The product-based sales model provides no incentive to the manufacturer to ensure product performance, as per original claims, during the life of the product. The consumer at the end of life of the product discards the product due to the absence of any repair infrastructure. A service-based sales model (Product-as-a-Service or PaaS) operates on the concept of pay for use and pay for performance. PaaS ensures circularity in the business model. This model has seen increased adoption rates in recent years by major light manufacturers including Philips. The National Union of Students Library in the UK rents the lighting equipment from Philips and pays a flat energy bill for agreed use as per the contract. The lighting contract requires Philips to compensate the Library in case

the energy bill exceeds the agreed amount. The contract provides incentive Philips to maintain the operation and efficiency of fixtures at an optimum level throughout the duration of the contract (15 years) [5]

Type of Cycle	Circular Business Model	Short Description of the Model
1. Short cycle	Pay per use Repair Waste reduction Sharing platforms Progressive purchase	One-time payment to use product or service Product life extension by repair services Waste reduction in the production process Products and services are shared among consumers Pay periodically small amounts before purchase
2. Long cycle	Performance based Take back management Next life sales Refurbish and resell	Long term contract and responsibility with producer Incentive to ensure product gets back to producer Product gets a new life Product gets a new life after adjustments
3. Cascades	Upcycle Recycling (waste handling and repurpose) Collaborative production	Materials are reused and their value is upgraded Materials are cascaded and reused, recycled or disposed Cooperation in the production value chain leading to closing material loops
4. Pure cycles	Cradle to cradle Circular sourcing	Product redesign to 100% closed material loops Only sourcing circular products or materials
5. Demateria-lized services	Physical to virtual Subscription based rental	Shifting physical activity to virtual Against a low periodic fee, consumers can use a product or service
6. Product on demand	Produce on order 3D printing Customer vote (design)	Only producing when demand is present Using 3D printing to produce what is needed Making customers vote which product to make

Table 1: Circular Business Model [7]

Impact Assessment of Circular Light Bulb Economy

The success of transitioning from a Linear Light Bulb economy to a Circular Light Bulb economy should be measured by a combination of methods to reflect the full potential of a Circular Light Bulb economy both in terms of economic and ecologic benefit. Key assessment parameters recommended for adoption are listed.

1. Reduction in the ecological footprint of the entity
2. Increased earnings by the adoption of new business models
3. Increased earnings by use of recycled materials
4. Increased earnings by the recovery of materials

4. Research Elaborations

The pilot study to implement a circular light bulb economy, based on above fundamentals, was carried out in Khora Village in Ghaziabad, a satellite city located in northern India from 2014 to 2016. The study consisted of the following stages:

a. Need Assessment: Primary field research consisting of needs and demand assessment was carried out in community markets and households across the national capital region including Ghaziabad. An analysis was drawn over light bulb usage and disposal patterns based on data through series of informal discussions and questionnaire ground surveys. The sample size of the survey included 56 CFL collectors and 1300 CFL consumers. The CFL collectors consisted of traders who purchased CFLs from waste handlers and sold them to refurbishers, door to door waste collectors, segregators, and refurbishers. The CFL consumers sample size had equal representation from households, offices, and retailers. The results highlighted an acute lack of awareness about the hazards associated due to improper disposal of light bulbs. The results of the ground survey are listed.

1. 63% of the respondents were unaware of the presence of mercury in the CFLs and its hazardous impact
2. 98% of the waste handlers removed the electronic parts by breaking the glass tube of the CFL
3. 42% of the respondents were reluctant to switch over to LED bulbs owing to the high cost
4. 80% of the waste handlers were willing to join the pilot study if monetary incentives were provided

b. Capacity Development: Technical modules were prepared in Graphic/Text/AV formats for trainees keeping in mind their minimal educational background. Trainees from highly diverse backgrounds were recruited and trained in the skill of light repairing. Trainees successful in completing their course were awarded certificates. The course was conducted in a total of 28 sessions. Each session, spanning for 2 hours, had a theory component of 1.5 hours followed by a practical class of half an hour duration. At the end of every 2 weeks, a test was conducted which would either be an objective pen-paper test or a practical demonstration. The course was concluded by a final oral test and a full practical demonstration.

Course Curriculum:

- Fundamentals of Electrical and Electronics Engineering
- Overview of Compact Fluorescent Lamp and Light Emitting Diode technology
- Study of CFL/LED circuitry and defect analysis
- Key procedures utilized in manufacturing and repairing of CFL/LED
- Lighting Design basics
- Introduction to book keeping and basic accounting
- Business development and marketing

Activities	W 1	W 2	W 3	W 4	W 5	W 6	W 7	W 8	W 9	W 10	W 11	W 12	W 13	W 14
Technical Theory and Business Economics	■	■	■	■	■	■	■	■						
Soldering and Punching Machine						■	■	■	■					
LED/CFL Driver									■	■				
LED/CFL assembly										■	■	■	■	■

LED/CFL Refurbishment														

Table 2: The Gantt chart shows the plan of activities spread over a period of 14 weeks.

c. Supply Chain Linkage: Tie-ups were made with local area maintenance contractors for procurement of faulty and discarded light bulbs in bulk. Collections of faulty and spent bulbs from other establishments such as schools, offices, and hospitals were also carried out every month. On the sales end, the partnerships were made with retailers for sale of repaired bulbs. The retailers showed acceptability towards the concept due to the anticipated increase in their earnings. Post setting up of a closed-loop supply chain, the newly trained micro-electricians repaired spent light bulbs in their shops.

d. Awareness Building: To mitigate the lack of awareness in the community identified during the field surveys, a marketing campaign was developed. It utilized popular means of mass media to encourage LED and CFL usage and generate awareness on the hazards of improper light bulb disposal. The pilot study was featured on reputed print mediums and radio channels.

Challenges and Risks	Mitigation
Skill Gap	Finding trainees with right entrepreneurial mindset is key. Mindset of younger trainees can be molded with relevant guidance and handholding,
Employment Insecurity	The pilot study team collaborated with industry partners to seek employment for trained and qualified individuals.
Warranty claims	The pilot study team reviewed quality of sourced raw materials and refurbished products.
Lack of awareness about safe disposal and recycling of Light bulbs	The pilot study team conducted awareness campaigns to generate awareness amongst the community members in collaboration with local leaders.

Table 3: Challenges faced, and mitigation techniques identified during the pilot study on Circular Light Bulb Economy

5. Findings

The detailed schedule of major costs for setting up of a light bulb repairing center during the period 2014-16 is presented below. The three major categories of cost include fixed costs, semi-fixed costs, and operating costs.

The one-time annual capital expenditure costs are known as fixed costs. The fixed costs are independent of the annual production capacity of the repairing center. The recurring costs which have both fixed and variable components are known as semi-fixed costs. The semi-fixed costs include utility charges and facility rent that are fixed up to a threshold production level. The operating costs are the recurring costs dependent on the level of production of the repairing center. The operating costs include staffing costs and material costs.

Table 4: Fixed Costs in 2014

Component	**Price per unit (INR)**	**Quantity**	**Cost (INR)**
Soldering Machine	500.00	2.00	1,000.00
Punching Machine	650.00	2.00	1,300.00
Electrical Equipment (Miscellaneous)	1,000.00	2.00	2,000.00
Furniture	10,000.00	1.00	10,000.00
Total (A)			**14,300.00**

Table 5: Semi fixed Cost in 2014

Component	**Price per unit (INR)**	**Quantity**	**Cost (INR)**
Shop/Workshop-Rented (250sq.ft)	30/sq ft	250sq ft.	90,000.00
Electricity Charges	8.00	15 x 25 x 12	36,000.00

Water Charges	300.00	12.00	3,600.00
Security Deposit (Accommodation)	7,500.00	2.00	15,000.00
Total (B)			**1,44,600.00**

Table 6: Operating Costs in 2014

Component	**Price per unit (INR)**	**Quantity**	**Cost (INR)**
Assembling Cost	15.55	70 X 25 x 12	3,26,550.00
Packaging & Labelling	2.00		42,000.00
Warranty Repair	1.05		22,050.00
Manpower (Self+1)	6,000.00	1 x 12	72,000.00
Binding Material	250.00	50.00	12,500.00
	Total (C)		4,75,100.00

Total Expenditure (A+B+C)			**6,34,000.00**
Gross Revenue	35.00	70x 25x 12	7,35,000.00
Net Profit			1,01,000

Table 7: Fixed Costs in 2015

Component	**Price per unit (INR)**	**Quantity**	**Cost (INR)**
Soldering Machine	500.00	3.00	1,500.00
Punching Machine	0.00	0.00	0.00

Electrical Equipment (Miscellaneous)	1,000.00	3.00	3,000.00
Furniture	0.00	0.00	0.00
Total (A)			4,500.00

Table 8: Semi fixed Cost in 2015

Component	**Price per unit (INR)**	**Quantity**	**Cost (INR)**
Shop/Workshop-Rented (250sq.ft)	30/sq ft	250sq ft.	90,000.00
Electricity Charges	8.00	15 x 25 x 12	36,000.00
Water Charges	300.00	12.00	3,600.00
Security Deposit (Accommodation)	0.00	0.00	0.00
Total (B)			1,29,600.00

Table 9: Operating Costs in 2015

Component	**Price per unit (INR)**	**Quantity**	**Cost (INR)**
Assembling Cost	15.55		4,66,500.00
Packaging & Labelling	2.00	100 X 25 x 12	60,000.00
Warranty Repair	1.05		31,500.00
Manpower (Self+2)	6,000.00	2 x 12	1,44,000.00
Binding Material	250.00	50.00	12,500.00
Total (C)			7,14,500.00

Total Expenditure (A+B+C)			**8,48,600.00**
Gross Revenue	35.00	100x 25x 12	10,50,000.00
Net Profit			2,01,400.00

Table 10: Fixed Costs in 2016

Component	**Price per unit (INR)**	**Quantity**	**Cost (INR)**
Soldering Machine	500.00	3.00	1,500.00
Punching Machine	0.00	0.00	0.00
Electrical Equipment (Miscellaneous)	1,000.00	3.00	3,000.00
Furniture	0.00	0.00	0.00
Total (A)			4,500.00

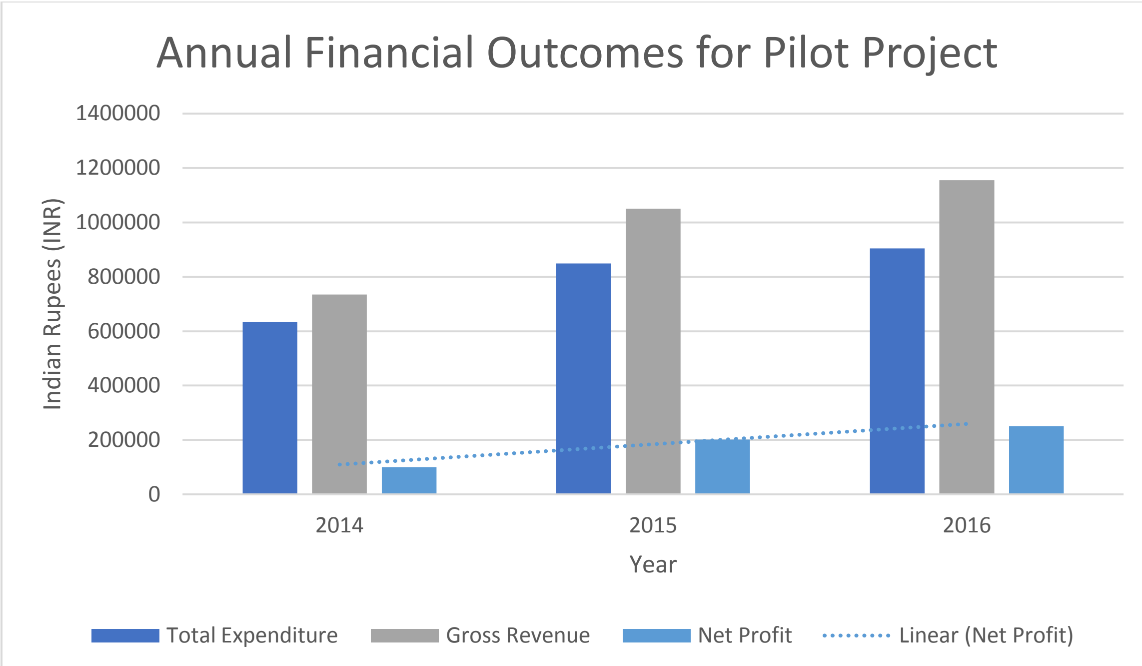
Table 11: Semi fixed Cost in 2016

Component	**Price per unit (INR)**	**Quantity**	**Cost (INR)**
Shop/Workshop-Rented (250sq.ft)	30/sq ft	250sq ft.	90,000.00
Electricity Charges	8.00	15 x 25 x 12	36,000.00
Water Charges	300.00	12.00	3,600.00
Security Deposit (Accommodation)	0.00	0.00	0.00
Total (B)			1,29,600.00

Table 12: Operating Costs in 2016

Component	Price per unit (INR)	Quantity	Cost (INR)
Assembling Cost	15.55	110 X 25 x 12	5,13,150.00
Packaging & Labelling	2.00		66,000.00
Warranty Repair	1.05		34,650.00
Manpower (Self+2)	6,000.00	2 x 12	1,44,000.00
Binding Material	250.00	50.00	12,500.00
Total (C)			7,70,300.00
Total Expenditure (A+B+C)			**9,04,400.00**
Gross Revenue	35.00	110x 25x 12	11,55,000.00
Net Profit			2,50,600.00

Figure 4: Annual Financial Outcomes of a 3-year pilot study on Circular Light Bulb Economy



Social Impact: Repaired light bulbs are an affordable alternative for low- and medium-income groups. The pilot project was able to impact 3522 people directly and 95960 people indirectly. Environmental Impact: Over 35,338 Kgs of reduction in greenhouse gas emissions. Over 900 Kgs of discarded CFL and LED bulb waste was been repaired, reducing 728mg of mercury emissions

Economic Impact: Each micro electrician repairs about 100 bulbs a day earning between INR 150-300. They can earn about INR 9000 a month –about 3 times the average local income. Annual savings of Rs 2,12,535 in electricity bills over the lifetime of the LED bulbs by cutting down on electricity bills as compared to consumption by an incandescent bulb. Associated estimated power saving was 29,565kWh annually over the lifetime of the bulbs.

6. Conclusions

The modern light bulb is increasingly replacing the inefficient incandescent bulb in developing countries. Although this trend strongly supports the energy security measures in these countries, the extent of damage from unscientific disposal nullifies the benefits accrued out of this transition. The analysis of results from the pilot study shows that the Circular Light Bulb Economy is economically viable and scalable for developing economies in order to combat the environmental impact from unsafe disposal. The model implemented during the pilot study can be replicated with minor adjustments to account for the prices of components and labor rates. Challenges, however, that remain in the implementation of this model include awareness level and attitude of stakeholders towards safe disposal as well as lack of skilled manpower to carry out refurbishment of modern light bulbs.

7. References

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