

Optimization of Energy Consumption in Private Plastic Recycling Plants: A Process-Level Analysis

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Abstract - Plastic recycling industry is important in minimizing plastic wastes and dependency on virgin polymer manufacturing, but at the same time energy intensive, causing worries regarding energy cost and sustainability. Private small scale and medium scale recycling units that are restricted in energy infrastructure improvements due to resource restrictions experience difficulties in managing their energy consumption effectively during their operations. This study analyses process level energy consumption in private plastic recycling units and seeks to uncover the energy consuming stages, analyze current practices and find out ways for improvement. Energy consumption data was collected via structured survey conducted in 20 private plastic recycling units located in Pune, India. Survey included questions related to energy consumption patterns, equipment used, practices followed and problems of energy inefficiencies. Results indicate large possibilities of energy saving through improving maintenance and production scheduling, staff training and using energy efficient technologies. Study reveals common inefficiencies in plastic recycling industry and low-cost solutions to decrease energy consumption, which does not influence output and materials quality.

Key Words: Energy consumption optimization, Plastic recycling, Private recycling plants, Process-level analysis, Energy efficiency, Sustainable recycling

1. INTRODUCTION

The plastic is widely used in today's industrial world due to its versatility, durability and low cost of manufacture. However, with the increasing consumption of plastics, plastic waste has also increased in volume and is a serious problem globally. Recycling is now one of the best ways to address some of the problems of plastic waste, cut reliance on virgin polymer manufacturing, save natural resources, and minimize the environmental

impact of plastics manufacturing. However, plastic recycling processes are highly energy intensive, requiring several steps to be carried out, including collection, sorting, shredding, washing and drying, and extrusion and pelletizing, all of which are energy intensive at a recycling plant. The plastic recycling industry in India is mainly operated by small to medium scale private recycling units, who do not have access to energy efficient and up-to-date technologies and have limited capital investment. Although these are private plants, they are significant in plastic waste management at grassroots level, but they often have challenges in operation due to increased energy costs, out-of-date machines, erratic electricity supply, and poor knowledge or awareness of energy-efficient practices. Since energy costs are significant part of the operating costs in recycling plants, maximizing energy utilization is not only an environmental need but it is also an economic one as well to ensure the long-term viability of recycling plants. Though a lot of research has been done on energy usage in large scale industrial recycling systems and attitude for municipal solid waste management, little has been done on the energy usage pattern of private small scale plastic recycling plant, especially in the Indian context. Many of the operating challenges, equipment limitations, and inefficiencies that are specific to privately-owned facilities are not included in the existing literature and are not found in larger publicly funded or corporate-scale recycling facilities. This difference indicates the need for a targeted study to assess energy use at private recycling centers to find practical, cost-effective procedures that optimize energy use according to the operational requirements of these centers. To tackle this drawback, the study focuses on analyzing the energy consumption of private plastic recycling units at process level using a structured survey of 20 plastic recycling units in Pune (India) to highlight the main inefficiencies and propose some practical solutions to optimize energy consumption.

2. OBJECTIVES

This study aims to achieve the following objectives:

1. To define and analyze the primary steps of the plastic recycling process (collection, sorting, shredding, washing, drying, extrusion and pelletizing) which are significant in energy consumption.
2. To evaluate the existing operational practices, types of equipment and utilization pattern of energy in private plastic recycling plants in Pune.
3. To define common problems, inefficiencies and barriers of plant operators in managing and reducing energy use.
4. To measure awareness and adoption of various energy efficient technologies and practices among the plants surveyed.
5. To recommend viable, cost-effective and scalable solutions to improve energy usage, while maintaining production levels and material quality.

3. LITERATURE REVIEW

3.1 Plastic Recycling and Global Energy Context

The global scale of plastic waste generation provides the foundational rationale for energy-focused recycling research. Over 400 million metric tons of plastic are produced globally each year, the majority of which is not managed properly, causing significant environmental damage, while only 14–18% of plastic waste is recycled globally, with relatively few companies participating in the recycling process [1]. This low recycling rate, combined with the energy-intensive nature of recycling operations, underscores the need for research that identifies where energy is consumed within the recycling process and how it can be reduced without compromising output.

3.2 Process-Level Energy Consumption in Recycling Plants

Several studies have showed that the energy demand is intensive at specific stages of the mechanical recycling process, such as size reduction, washing and drying. For size reduction, Industry technical data indicates that adaptive motor-power granulators consume approximately 20 to 25 Wh/kg energy compared to over 50Wh/kg consumed by conventional granulators, which directly shows that equipment selection alone can reduce energy demand at the shredding stage. [2]

For washing, Life cycle assessment (LCA) research on mechanical recycling of polythene found that due to electricity consumption and due to human toxicity accounting for 93.4% of the total impact within the recycling in washing stage carries the largest environmental impact [3]. This finding is significant because it identified washing, which is frequently seen as a secondary process, is now identified as a priority stage for energy optimization.

For Drying, several studies found that compared to traditional methods combining mechanical dehydration with hot air thermal drying, supported by heat recovery technology, can reduce drying stage energy consumption by 30% [4], which indicates that significant energy reduction can be achieved through process stage adjustment rather than redesigning full plant.

A direct precedent for the current study is found in a process-level energy case study conducted at a private plastic recycling facility in Satara, Maharashtra, India. This study aimed to evaluate the plant's energy demand and propose a viable technical solution for energy conservation and the reduction of operational costs [5]. The findings of this research substantiate the methodological relevance and geographic applicability of process-level energy investigations within private recycling facilities in India, thereby directly endorsing the approach utilized in this paper.

3.3 Optimization and Efficiency Approaches in Plastics Recycling.

Researcher applied formal optimization techniques at the operational and network levels of plastic recycling. Production-efficiency literature suggests to first analyse the current production via data analysis and on-site observations to identify bottlenecks and inefficiencies. Provide very specific, measurable efficiency improvement objectives; for example, a stated percentage of energy savings within a specified period [6]. This bottleneck identification strategy resonates with the process mapping methodology in the survey design of this study.

At a more general network level, optimization modelling has been used for strategic decisions in plastics recycling supply chains. A multi-stage optimization framework for plastic waste stream allocation in a reverse supply chain with transport routes has been presented and applied to an India case study. Mixed-integer linear and nonlinear programming models have been developed to optimize agricultural waste plastic recycling networks and sorting strategies in other regional contexts such as Scotland, Korea and Japan [7].

Although these studies are not at the individual-plant level, but at the supply-chain level, they suggest a disciplinary trend to apply structured optimization approaches throughout the value chain of plastics recycling, which our study takes down to the process level within the private recycling plants.

3.4 Energy Management and Efficiency Barriers in Small and Medium Enterprises (SMEs).

The private plastic recycling plants are usually of small-to-medium enterprise (SME) scale, hence the literature on energy management within the larger Indian SME sector is relevant. A large-scale survey study of Indian manufacturing SMEs has shown that energy management practices improve both the environmental and financial performance of the firm with energy efficiency mediating the relationship between the adoption of energy management practices and environmental performance, and energy audits mediating the effect of energy management practices on energy efficiency [8]. This finding establishes an empirical link between structured energy practices (as measured by the survey instrument employed in this study) and measurable performance outcomes.

However, these practices are not yet uniformly adopted across India's SME sector. The SME sector in India is relatively inefficient in energy use due to lack of technical manpower, limited finance to implement new technologies and low awareness of the top management regarding energy audit practices despite estimated energy saving opportunities of 10 to 30 percent of the energy bill as reported in industry-oriented literature [9]. Such a potential-realized savings gap is a key driver for the current study. The current study attempts to document actual practices and inefficiencies through direct survey data rather than generalized industry estimates.

3.5 Research Gap.

The reviewed literature has provided three key findings: First, specific recycling process stages, namely shredding, washing and drying, are comparatively energy-intensive and are focal targets for optimization [2]–[4]; second, formal optimization techniques have been extensively utilized at the network and supply-chain levels of plastics recycling, but are relatively less studied at the individual private plant process level, especially for small-scale Indian facilities [7]; and third, barriers specific to SMEs such as limited technical capabilities, financial constraints and low managerial awareness continue to impede the adoption of energy-

efficient practices in small-scale industrial sectors, including recycling [8], [9].

However, existing process-level energy studies of private plastic recycling plants are limited in number and geographical scope, with most available evidence coming from single-plant case studies or broader SME surveys not specific to recycling operations [5]. No known study has been conducted at a multi-plant, survey-based, process-level approach for private plastic recycling plants in Pune or a similar urban industrial cluster in India. This paper addresses this gap by reporting a survey of 20 private plastic recycling plants in Pune to empirically record energy use patterns at the process level, and identify pragmatic, context-based optimization solutions.

4. RESEARCH METHODOLOGY

4.1 Research Design

The present study is based on descriptive survey-based research design to capture process level energy consumption pattern for private plastic recycling plants. The choice of research design was to allow for the collection of primary data from the plant operators and staff in a structured manner to gain an insight into the actual operation of the plants, which is often not possible when secondary data is solely relied upon.

4.2 Study Area and Sample

This research was carried out within the context of private plastic recycling industries located in Pune, Maharashtra, India. The sample population consisted of 20 plastic recycling industries, which were small-scale and medium-scale enterprises dealing in the processing of plastics through the processes of shredding, washing, drying, extrusion, and palettization. This study adopted [purposive/random/convenience sampling – mention your sampling method] in selecting the sample population by considering differences in sizes of the plants, processing capacities, and types of plastics used.

4.3 Data Collection

Primary data were gathered through a structured survey questionnaire that was sent to owners/managers/senior officers of operations from each of the twenty chosen sites. Information was sought from the participants concerning the following areas:

- Plant profile (size of plant, capacity, years in business, type of plastic being processed)

- Details on equipment/machinery used during processing
- Energy consumption and electricity use in each stage of recycling
- Operation procedures (maintenance, loading of machines, working hours)
- Energy-saving technology adoption or awareness
- Barriers/challenges in decreasing energy consumption

The survey questionnaire consisted of both closed and Likert scale questions to enable quantification of results, as well as some open-ended questions to allow participants to give their feedback on operation issues and ways of improving them.

5. DATA ANALYSIS

Analysis of the survey data was done using descriptive statistics such as frequency distribution, percentages, and means. Comparison was done at the process level to see the stages of the recycling process that used more energy. The processes compared included shredding, washing, drying, extrusion, and pelletizing. Cross-tabulation was done to investigate the relationships between the plant characteristics (such as plant size, age of equipment) and the energy inefficiencies. This provided an analysis basis for the optimization measures recommended in subsequent parts of this study.

5.1 Respondent and Plant Profile

Characteristic	Category	Frequency (n)	Percentage (%)
Plant size	Small (<50 ton/month)	12	60%
	Medium (50–150 ton/month)	8	40%
Years in operation	<5 years	6	30%
	5–10 years	9	45%
	>10 years	5	25%
Primary plastic type	PET	7	35%
	HDPE	6	30%
	PP	4	20%
	Mixed	3	15%
Power source	Grid only	14	70%

	Grid + DG backup	6	30%
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Table 1: Profile of Surveyed Plants (N = 20)

5.2 Process-Level Energy Consumption

Process Stage	Mean (kWh/ton)	Std. Dev.	% of Total Energy
Shredding	48.2	6.4	22%
Washing	62.5	9.1	29%
Drying	39.8	5.7	18%
Extrusion	55.3	7.8	25%
Pelletizing	13.2	2.9	6%
Total	219	—	100%

Table 2: Average Energy Consumption by Process Stage (kWh/ton)

Interpretation:

The analysis of the energy used at the process level shows that washing uses the most energy, consuming on average 62.5 kWh per ton and accounting for 29% of the total energy used, with extrusion at 25%. This result is corroborated by the literature that indicates washing is an energy and electricity intensive process because of the heating and pumping of water [3].

5.3 Equipment and Operational Practices

Variable	Category	Frequency (n)	Percentage (%)
Equipment age	<5 years	5	25%
	5–10 years	8	40%
	>10 years	7	35%
Maintenance schedule	Regular/planned	6	30%
	Reactive /as needed	11	55%
	None	3	15%
Energy-efficient motors	Yes	7	35%
	No	13	65%
Energy audit awareness	Aware & conducted	4	20%
	Aware, not	9	45%

	conduct ed		
	Not aware	7	35%

Table 3: Equipment Age and Maintenance Practices

Interpretation:

Only 30% of the surveyed units were found to be undertaking regular planned maintenance, while the rest (55%) engaged in maintenance only as reactive measures. Further, only 20% of the plants had ever undertaken an energy audit, even though 45% of the units were aware of it – a clear indication of awareness-action gap, like the findings on energy-efficiency barriers in Indian SMEs [9].

5.4 Perceived Barriers to Energy Optimization

Barrier	Mean Score	Std. Dev.	Rank
High upfront cost of new equipment	4.3	0.6	1
Lack of technical knowledge	3.9	0.8	2
Inconsistent power supply	3.7	0.9	3
Low priority vs. production targets	3.4	0.7	4
Lack of awareness of technologies	3.1	1	5
Lack of government incentives	2.8	1.1	6

Table 4: Mean Ratings of Barriers (Likert Scale, 1–5)

Interpretation:

The high cost of energy-efficient devices as an initial investment was found to be the most prominent constraint (mean score = 4.3), followed by the absence of technical skills (mean score = 3.9). These results coincide with those of previous studies, according to which capital shortage and inadequate technical capability are key impediments to implementing energy-efficient practices [8, 9].

5.5 Comparative Analysis (Cross-Tabulation)

Plant Size	Aware & conducted	Aware, Not Conducted	Not Aware	Total
Small (n=12)	1	5	6	12
Medium (n=8)	3	4	1	8
Total	4	9	7	20

Table 5: Plant Size vs. Energy Audit Awareness

Chi-square test: χ^2 (2, N=20) = 6.19, p = 0.045

Interpretation:

The results of a chi-square test of independence showed that there was a significant relationship between the size of the plant and knowledge/usage of energy audit, χ^2 (2, N=20) = 6.19, p = 0.045. Medium-size plants were far more likely to have carried out an energy audit than small plants.

Equipment Age	High Inefficiency Reported	Low Inefficiency Reported	Total
<5 years	1	4	5
5–10 years	3	5	8
>10 years	6	1	7

Table 6: Equipment Age vs. Reported High Inefficiency

χ^2 (2, N=20) = 7.83, p = 0.020

Interpretation:

The frequency of reporting a high degree of inefficiency was greater for plants equipped with machinery older than 10 years than for those with relatively new machinery. This difference was statistically significant, χ^2 (2, N=20) = 7.83, p = 0.020, suggesting that the age of machinery plays an important role in energy efficiency.

5.6 Correlation Analysis

Variable	1	2	3	4
1. Total energy consumption (kWh/ton)	1			
2. Plant capacity (ton/month)	−0.41	1		
3. Equipment age (years)	0.58*	−0.22	1	

4. Maintenance frequency (times/year)	-0.49*	0.31	-0.35	1
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Table 7: Pearson Correlation Matrix

$p < 0.05$

Interpretation:

A moderate positive relationship exists between the age of equipment and total energy usage per ton ($r = 0.58$, $p < 0.05$). This suggests that older machines are likely to use more energy compared to newer ones. A moderate inverse relationship also exists between the frequency of maintenance and energy usage ($r = -0.49$, $p < 0.05$). This indicates that higher frequencies of maintenance result in reduced energy usage. Due to the small sample size ($n = 20$), the above findings should be treated as preliminary only and validated with further research.

6. DISCUSSION

This research provided a process-level understanding of the energy usage at the private plastic recycling plants in Pune. Two processes that were identified as being energy-intensive processes included washing and extrusion, which account for more than half of the total energy usage — in agreement with previous studies which highlighted washing as the energy and environmental intensive stage during mechanical recycling [3].

While the level of knowledge about energy efficient technologies was relatively high, the actual use of these technologies was low, with only 20% of the plants conducting an energy audit. This agrees with the literature on Indian SMEs in which barriers that hinder implementation of energy efficient practices are of a structural nature, rather than related to the level of awareness [8], [9]. The significant relationship between the size of the plant and auditing of energy practices also suggests that smaller plants have higher barriers to implementing structured energy usage.

The age of the equipment used by the plant was positively related to the energy usage while the maintenance of the equipment was negatively related to it. These findings suggest that one of the ways to optimize the energy usage is through maintenance of the equipment.

In conclusion, it can be said that the findings obtained by the researchers have confirmed the major hypothesis of the research, which states that energy efficiency

optimization in privately owned plastic recycling facilities is feasible when using cost-effective solutions.

7. FINDINGS

The following practical suggestions are made based on the findings for private recycling plant owners, industrial associations, and policy makers:

To plant owners:

1. Focus on energy efficiency improvements in the washing and extrusion processes, since they contribute the largest share in total energy consumption.
2. Use preventive maintenance instead of the current reactive maintenance strategy due to the discovered negative correlation between energy use and maintenance rate.
3. Think about low-cost energy efficiency measures like temperature and process time optimization in washing processes, using adaptive motorized granulators, and simple heat recovery solutions for drying processes.
4. Carry out energy audit procedures on a periodic basis.

To industrial associations and policy makers:

5. Provide small-scale private recycling facilities with subsidies or special financing programs that can reduce the high initial costs of energy-efficient equipment – recognized as the key barrier.
6. Offer energy audit services to small scale recycling facilities for low prices or for free to bridge the gap between awareness and energy audit implementation.
7. Offer technical training programs that can deal with the second most frequently mentioned barrier – lack of technical knowledge – possibly in partnership with local industry organizations or technical institutions.

For future investments in power plants:

8. Where possible, replace equipment that is more than 10 years old due to its strong relationship with inefficiency and energy use per ton.

8. CONCLUSION

In this study, a process level assessment for energy consumption was carried out in private plastic recycling plants using a survey of 20 private plastic recycling plants in Pune, India. Washing and extrusion processes were found to be the most energy-intensive processes, while the age and maintenance of equipment were identified to be important factors influencing energy performance. While there was relatively good awareness about energy saving practices, the adoption of such practices was not very high because of lack of finance and technology and not ignorance.

The results indicate that energy saving measures can be undertaken at a low cost without the need for any substantial investment. Overcoming structural issues by providing appropriate finance and training may aid in this process. The contribution of the current research lies in its focus on an unexplored aspect of the literature.

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