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Optimising Reverse Supply Chains for Resource Recovery: Insights from ICRIER Sampada WSUT- Linear Programming Model

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Contents

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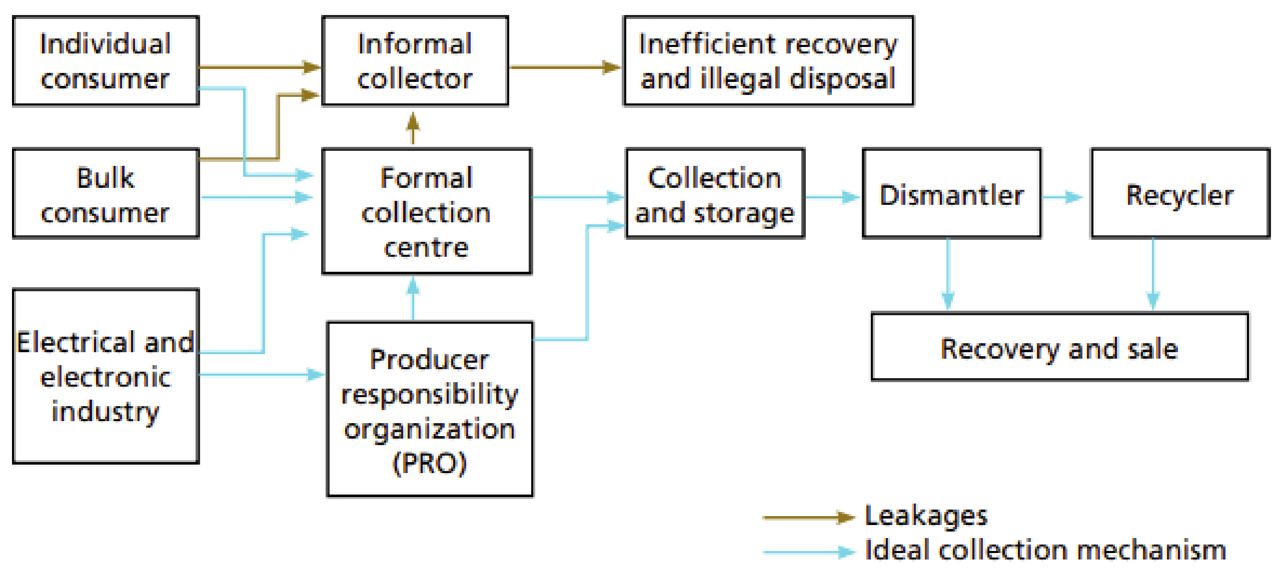
1. What are 'Reverse Supply Chains' in the E-waste Context?

The reverse supply chain contributes to resource conservation, thus helping to recover several embedded critical minerals from the e-waste. Electronic devices contain valuable materials such as gold, silver, copper, and rare earth elements. When e-waste is improperly discarded, these resources also vanish. Through efficient recycling processes, the reverse supply chain can recover these precious materials, reducing the need for new mining and lowering the environmental impact associated with raw material extraction. This not only conserves resources but also supports the economy by supplying raw materials for new electronic products.

Figure 1: Ideal collection flow and leakages in e-waste management in India



(Source: CSE, 2020)

2. Entities in the E-waste Supply Chain

According to the various rules and regulations governing e-waste management in the country, numerous entities are engaged in the management of the same. Through critical analysis in Goldar et al. (forthcoming) , the following key entities have been identified:

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- **Collectors and Transporters:** The informal sector is majorly involved in the collection of e-waste in India. The collectors in the formal sectors are part of the recyclers or the manufacturers under the purview of the Extended Producer Responsibility (EPR) who collect e-waste through, door to door-to-door collection facilities, their take-back service, or drop-off facilities at their centers. Following the collection of e-waste from consumers, the collectors sort these into different categories and prepare them for being transported to the recycling facilities. Thereafter, the transporters ensure timely, safe and efficient movement of e-waste from the collection points to the recycling facilities.

- **Dismantlers:** These entities are involved in the dismantling operations either manually or semi-manually (material shredder or material separator). They meticulously disassemble electronic devices to retrieve valuable components and materials, including metals, plastics, and precious metals such as gold and silver. The dismantling operations are labour-intensive, but with efficient sorting and aggregation of e-waste during the process, the quality, and quantity of the material being recycled can be improved.

- **Recyclers:** Recyclers adopt mechanical and chemical processes to extract valuable materials from e-waste (copper, gold, silver, etc.). The most commonly used technologies in the market include pyrometallurgy, hydrometallurgy, or a combination of both. The extracted materials undergo further purification processes to produce high-quality raw materials for manufacturing new products. Thus, by employing suitable recycling methodologies, recyclers aid in diverting e-waste from landfills, preserving resources, and mitigating the environmental repercussions of recycling.

As discussed in Goldar et al. (forthcoming), the study focuses on Maharashtra and Karnataka to identify the entities involved in e-waste management in these states. Based on the findings from the two states it can be said that the collection of e-waste is mostly carried out by the informal sector. The absence of skill gradation hampers their involvement in dismantling and recycling operations. The formal recyclers even though registered with the respective state pollution control board, lack suitable infrastructure for dismantling and advance recycling. With a basic recycling facility, they pose a threat to the environment and the health of the workers.

3. Research Question and Hypothesis

a. Identifying Critical Entities Involved in the Recycling Supply Chain

Identifying critical entities involved in the recycling supply chain for certain key states includes entities at the base of the pyramid (involved in collection) to the top (involved in material recovery). The critical entities identified include collectors/transporters, dismantlers, and recyclers are discussed in detail in a forthcoming working paper (Goldar et al., forthcoming).

b. Evaluating the Contribution of Individual Supply Chain Entities Using Value-Added, Cost of Recovery and Recovery Rates as the Metric of Contribution, among others.

The contribution of individual supply chain agents has been assessed using value-added, cost of recovery and recovery rates. The ICRIER ***Sampada 2.0*** model has been used to gauge both the direct and indirect impacts of existing and potential waste management technologies.

c. What could be the Optimal Policy Instrument to Incentivize the Sector- Producer/Technology Subsidies or Consumer Subsidies or Mandates?

The study has identified the challenges faced by each of the entities involved in the supply chain and suggests solutions that could be used as inputs by policymakers.

4. Modelling and Database Creation

a. Modelling of Circular Economy

Leontief (1970, 1972) introduced an environmentally extended IO model (EIO) which modified the conventional IO framework to account for pollution emissions. A significant limitation of this model was its assumption of a one-to-one relationship between pollutants (waste) and their abatement methods (waste treatment), which do not align with empirical observations. To overcome this limitation, Nakamura and Kondo (2002) presented a generalized version of it, called the Waste Input-Output (WIO) model, for Life Cycle Analysis (LCA) of waste management issues. This *hybrid* LCA model, which combined IOA with an engineering process model, can handle any combination of waste type and treatment, provided they are technically feasible. This is achieved through a mapping exercise, facilitated by an allocation matrix (or S-matrix), which assigns waste types to various waste treatment methods. Since the factors determining the elements of the S-matrix change slowly over time, it can serve as a convenient mechanism for representing alternative policy scenarios that guide the allocation of waste to alternative treatment methods. Thus, it provides a technically sound and robust approach for analysing the direct and indirect impacts of various policy options.

Kondo and Nakamura (2005) developed a linear programming (LP)-based decision analytic extension of the WIO model, named the waste input–output linear programming (WIO-LP) model. It provides a framework for choosing an 'optimal' waste management and recycling strategy from among alternative feasible ones based on some objective function(s). This framework is used to evaluate the effects of alternative waste management strategies (such as recycling of waste materials) on a chosen measure of eco-efficiency. The framework is capable of accommodating any engineering-feasible waste management technology. In their analysis, the authors consider two eco-efficiency measures, CO_2-efficiency and landfill-efficiency (defined as the ratio of GDP to CO_2 emission, and the ratio of GDP to landfill consumption, respectively) as their objective functions to minimize. But additional ones may be included for development of a more robust and holistic framework.

Lenzen and Reynolds (2014) proposed a Waste-Supply Use Table (WSUT) extension of Nakamura and Kondo's WIO Table (WIOT) by integrating the S-matrix or allocation matrix into the WIOT. WSUT extension for the WIO framework incorporates the flexible features of the (monetary) SUT concept, allowing waste data to be represented both by waste type and by waste treatment method simultaneously in one table. This promotes a comprehensive understanding of the full range of activities associated with waste generation and processing within the economy. The WIO model by Nakamura and Kondo, and its variants (such as the WIO-LP model and the WSUT extension by Lenzen and Reynolds) serve as versatile tools that provide useful insights by modelling the impacts of policy or consumption behaviours on waste generation and flows across sectors. The present paper thus uses the WSUT framework to create the ICRIER Sampada 2.0 and incorporates a linear programming model to understand the role technology shifts could play in improving recovery rates and adding to waste management costs.

b. Basics of ICRIER *Sampada 2.0*

- **Waste Supply-Use Table Framework**

A schematic of the WSUT is presented in Table 1. As can be observed, there are three parts to the table - (a) standard monetary input-output table elements, that can be distinguished between intermediate consumption and ($T_{11} \in R^{N1\times N1}$,) final demand ($f \in R_{N1\times NF}$) and gross output ($x_1 \in R_{N1\times 1}$) (b) waste generation by intermediate sectors ($W_{31} \in R_{N3\times N1}$), waste treatment sectors ($W_{32} \in R_{N3\times N2}$) and final demand sectors ($WF \in R_{N3\times NF}$), and finally, (c) waste treated by the N_2 waste treatment methods ($W_{23} \in R_{N2\times N3}$). The vectors x_1, x_3, and x_2 are the total output of N_1 goods and services sectors, N_3 waste types, and N_2 waste treatment methods for the economy.

Table 1: Schematic for the Waste supply-use table (in units)

	Intermediate demand sectors 1....N_1	Waste treatment sectors 1...N_2	Waste types 1...N_3	Final demand Sectors 1...N_f	Gross Output
Intermediate supply sectors 1....N_1	T_{11} (INR Lakhs)	T_{12} (INR Lakhs)		f (INR Lakhs)	x_1 (INR Lakhs)
Waste treatment Sectors 1...N_2			W_{23} (Mtpa)		x_2 (Mtpa)
Generation of waste by type 1....N_3	W_{31} (Mtpa)	W_{32} (Mtpa)		W_F (Mtpa)	x_3 (Mtpa)

(Source: Based on Lenzen and Reynolds (2014))

The WSUT in balanced form is written as

$$\begin{pmatrix} T_{11} & T_{12} & 0 \\ 0 & 0 & W_{23} \\ W_{31} & W_{32} & \end{pmatrix} \begin{pmatrix} 1_1 \\ 1_2 \\ 1_3 \end{pmatrix} + \begin{pmatrix} f \\ 0 \\ W_f \end{pmatrix} 1_F = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \qquad \textbf{(Equation 1)}$$

This can also be expressed in the coefficient form as below:

$$\begin{pmatrix} A_{11} & A_{12} & 0 \\ 0 & 0 & S_{23} \\ G_{31} & G_{32} & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} + \begin{pmatrix} f \\ 0 \\ W_f \end{pmatrix} 1_F = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \qquad \textbf{(Equation 2)}$$

where input coefficient matrices are defined as $A_{11} = T_{11}\hat{x}_1^{-1}$, $A_{12} = T_{12}\hat{x}_2^{-1}$, $G_{31} = W_{31}\hat{x}_1^{-1}$, and $G_{32} = W_{32}\hat{x}_2^{-1}$. It needs to be highlighted here that the matrix S_{23} (ù $R_{N2\times N3}$) is the same as Nakamura and Kondo's (2002) allocation matrix. The elements of S_{23} refer to the share of waste type *j* that is treated by treatment method *i*, and are normalized according to $\sum_j S_{23}(i,j) = 1$.

The Leontief inverse of the WSUT is thus formulated as follows:

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} I - A_{11} & -A_{12} & 0 \\ 0 & I & -S_{23} \\ -G_{31} & -G_{32} & I \end{pmatrix}^{-1} \begin{pmatrix} f \\ 0 \\ W_f \end{pmatrix} 1_F \qquad \textbf{(Equation 3)}$$

Each of the elements of the above-partitioned matrix are discussed below.

- **Monetary Input-Output (Matrices T_{11} and f)**

The construction of the WSUT for the baseline year 2021-22 is based on the national Input-Output Transaction Table (IOTT) prepared by Chaudhuri et al. (2024). However, given that the 37 sectors in the ICRIER ***Sampada*** *2.0* model are not aligned with those included in the aforementioned paper, the input structure that was used follows the input mix as adopted by Pohit and Pratap (2023) having the base of 2018-19. The IOTT accounts for inter-industry demand, final demand and output values in monetary terms.

- **Waste generation in India (Matrices W_{31} and W_F)**

WIO calculations utilize nationwide waste generation data, specifically sourcing information from the annual reports provided by the Central Pollution Control Board (CPCB) for the fiscal year 2020-21. This paper classifies waste into five types: Municipal Solid Waste (MSW), hazardous waste, e-waste, bio-medical waste and plastic waste. The waste generation of the stated waste types is collected from national inventories. Compiling waste generation data, Table 2 provides the total waste generated by each waste type on an annual basis, measured in Metric Tons or MTA.

Table 2: Annual waste generation (in MTA)

Waste Type	Dry Waste	Wet Waste	Inert waste	Hazardous waste	E-waste waste	Bio-Medical waste	Plastic waste
Waste Generated	17624588	22660184	10071193	12354686	1601155	252977	3743948

(Source: Authors' Construction)

- **Waste Generation by Waste Technology (Matrix W32)**

After waste generation, data was collected for the amount of waste being treated by waste types. Table 3 furnishes data on the quantities of different types of waste treated annually. The same has been sourced from the CPCB annual reports, reflecting waste management and treatment efforts in India.

Table 3: Amount of waste treated by waste type across the country (in MTA)

Waste Type	Dry Waste	Wet Waste	Inert waste	Hazardous waste	E-waste waste	Bio-Medical waste	Plastic waste
Waste Generated	5538972	9231620	3692648	12354686	320231	178339	1006231

(Source: Authors' Construction)

In the realm of waste management, it is customary to define waste based on its proportions of combustible elements, moisture, and residual matter. These aspects hold significance within waste management, profoundly influencing how specific waste treatment procedures function. This study puts forward the notion of estimating the ash content released from the treatment technologies by looking at it from a pragmatic angle of waste treatment.

- **Allocation Matrix (Matrix S_{23})**

The allocation matrix offers a convenient way to depict alterations in the distribution of waste among various treatment techniques. Nevertheless, the allocation pattern is largely influenced by factors such as institutional regulations, including environmental laws. The accuracy of the WSUT analysis relies on the assumption that matrix S_{23} remains constant. As long as particular regulations dictate how certain wastes are assigned to different treatment methods, the relevant components of matrix S_{23} would remain steady throughout the duration of the regulations.

Nonetheless, changing the allocation pattern requires the introduction of alternative treatment methods, which require a considerable amount of time. The components of matrix S would alter gradually and would, at the very least, not be substantially responsive to shifts in existing economic conditions, like the output levels in various sectors. Thus, given the exogenous nature of matrix S, it is a convenient tool for representing alternative policy scenarios with regard to the allocation of waste to different treatment methods. Table 4 below provides the allocation matrix used in the present study.

Table 4: Waste Allocation Matrix (in MTA)

		Waste Types						
		Dry MSW	**Wet MSW**	**Inert MSW**	**Hazardous waste**	**E-waste**	**Biomedical waste**	**Plastic waste**
Waste Treatment	**Incineration**	553897	461581	0	1030381	32023	151588	105654
	Composting	0	3692648	0	0	0	0	0
	Landfill	14301205	18505955	7855604	8050314	1409017	74638	2838341
	MRF	2769486	0	738530	3273992	160116	26751	799954
	C&D Waste Management	0	0	1477059	0	0	0	0
Total Waste		17624588	22660184	10071193	12354686	1601155	252978	3743949

(Source: Authors' Construction)

- **Linear Programming (LP) for Waste Technologies**

Parallel to the WSUT construction, a linear programming model for waste technologies was also developed. As discussed earlier, reverse supply chains in India are characterized by certain key entities operating with different technologies, scale of operations and skill levels. This composition of waste technologies represents a particular bundle of value addition, recovery rates and costs of recovery. However, optimising this composition based on a specific metric provides the choice of technologies that are best suited for a particular objective, i.e. minimising recycling costs or maximising recovery rates.

For the present analysis, seven technologies were chosen among three broad stages of resource recovery:

a) Collection/Transportation - tendering process with IT companies, and door-to-door and drop-down collection from individuals

b) Dismantling – material shredder, material separators, manual dismantling

c) Recycling (or material recovery) – hydrometallurgical processes, pyrometallurgical processes.

All these technologies were optimized based on their cost per tonne, value-added shares and recovery rates. This led to the derivation of corner solutions as particular technologies were found to be most suitable for each of the three stages. This was fed into the model in the form of an Alternative Scenario.

5. Scenario Description – Base Year 2021-22

Following the optimisation carried out in the previous step, two scenarios were created with differing market shares for waste management technologies.

- **Baseline Scenario:** This was created assuming the following market shares for the mentioned technologies. All costs and revenue streams were calculated keeping the following composition in mind as given in Table 5 below:

Table 5: Market Shares for Technologies Assumed in the Baseline Scenario

	Collector/Transporter		Dismantling			Recycling	
	Tendering process with IT companies	Door-to-door and drop-down	Material shredder	Material Separator	Manual Dis-mantling	Hydromet-allurgy	Pyrometal-lurgy
Market Share	40%	60%	55%	30%	15%	30%	70%

(Source: Authors' Construction)

- **Alternative Scenario:** As stated earlier, the corner solution of technology selection was used to create the Alternative Scenario. The associated cost differences and recovery rates were incorporated into this model as given in Table 6 below

Table 6: Market Shares for Technologies Assumed in Alternative Scenario

	Collector/Transporter		Dismantling			Recycling	
	Tendering process with IT companies	Door-to-door and drop-down	Material shredder	Material Separator	Manual Dis-mantling	Hydromet-allurgy	Pyrometal-lurgy
Market Share	-	100%	-	100%	-	100%	-

(Source: Authors' Construction)

6. Results from Model Runs

The WSUT-LP combination is powerful as it allows the analysis to look into both the direct and indirect impacts of technology changes. Looking first at the direct, indirect and total waste generation, in tonnes per INR crore, it can be observed that the manufacturing sector has the largest direct and total waste generation amongst various intermediate sectors. Note that the direct effects from the manufacturing sector already incorporate figures for recycling. Without recycling, the direct waste generation effects would be much higher. This is followed by the services sector, for direct waste generation and total waste generation effects as shown in Table 7. Despite the varying values of the latter, it is interesting to note that in most cases the indirect effects may be quite significant as well.

Table 7: Total Waste Generation Effects in Aggregated Intermediate Sectors (tonnes per crore Rupees)

Sectors	Direct Efects	Indirect Efects	Total Efects
Agriculture	0.78	0.60	1.38
Mining	2.72	0.00	2.72
Forestry	0.31	0.26	0.57
Manufacturing	6.84	3.84	10.68
Construction	0.91	0.14	1.05
Utilities	2.61	1.35	3.96
Transport	0.80	0.49	1.29
Services	4.46	3.42	7.88

(Source: Authors' Construction)

In the case of India, landfill (Lf) is the dominant treatment method in terms of tonnes treated. The results in Table 8 indicate that landfill generates smaller direct and total waste tonnages compared to the various recycling treatments. It appears that material recycling facilities exhibit a higher degree of "inefficiency" when considering both direct and total waste generation impacts. This is because, when treating a metric ton of waste, these facilities yield a larger quantity of waste products. However, this observation is misleading, as the recycled materials (such as plastics, glass, metals, etc.) undergo additional processing, becoming useful resources in subsequent cycles. From a technical perspective, recycling through these seemingly inefficient methods could be interpreted as macroeconomically converting one type of waste into larger quantities of other types, rather than genuine 'treatment'.

Table 8: Total Waste Generation Effects in Waste Treatment Sectors (tonnes per tonnes treated)

Treatment Methods	Direct Efects	Indirect Efects	Total Efects
Incineration	0.05400	0.00536	0.05936
Composting	0.00000	0.00006	0.00006
Landill	0.00000	0.00012	0.00012
MRF	1.00000	0.25322	1.25322
C&D Waste Management	0.04000	0.00393	0.04393

(Source: Authors' Construction)

Looking at the results from an economic stimulus point of view, provides interesting insights. The phrase 'economic stimulus' refers to the monetary value associated with treating an extra ton of waste through each specific method (Reynolds, et. al, 2014). While it is true that waste management as an activity is not carried out to create economic stimulus, insofar as it is related to demand creation for materials, labor, energy, and machinery, it leads to positive impacts on the economy.

Another way of looking at it could be that these 'costs' enable the choice of treatment approaches that generate useful products or material resources through recycling, instead of merely disposing of waste in landfills. Given these two positive aspects, coupled with increased employment, consumption, and lower environmental loads, signifies a stimulus.

Based on the costs, MRF provides the highest total economic activity per tonne treated. As indicated in Table 9, for every tonne of waste disposed of via material recovery stimulates INR 0.00010 crore direct, or INR 0.00033 crore in total economic activity. Taking the direct and indirect costs or stimulus together shows that recycling provides a larger economic stimulus than the conventional option of landfill per tonne of waste treated. This also indicates that there is room to improve the economic stimulus associated with waste treatment by diverting waste from landfill to recycling.

Table 9: Economic Stimulus Per Tonne Treated in Waste Treatment Sectors (INR crore per tonne treated)

Treatment Methods	Direct Efects	Indirect Efects	Total Efects
Incineration	0.00013	0.00011	0.00024
Composting	0.00005	0.00004	0.00009
Landill	0.00011	0.00010	0.00020
MRF	0.00010	0.00033	0.00043
C&D Waste Management	0.00006	0.00006	0.00012

(Source: Authors' Construction)

- **Comparison between Scenarios**

It is expected that the transition from the Baseline to the Alternative scenario would bring about two critical impacts: (a) it would lead to higher quantum of recoveries, and (b) result in larger costs for waste management. The computation of direct impacts shows that the Alternative Scenario could result in higher waste management costs for the economy to the extent of 28.3 percent as compared to the Baseline. In terms of enhanced recovery, this leads to an increased recovery of 10 percent compared to the Baseline. Note however, that this increased recovery is in terms of quantum. Looking specifically at the last stage, i.e., material recovery, hydrometallurgical recycling offers a significant advantage over pyrometallurgy in that it allows for the recovery of high-purity valuable metals such as Nickel, Cobalt, Manganese and Lithium with recovery rates exceeding 99 percent, minimal impurities, and lower energy consumption. In contrast, pyrometallurgical methods typically yield these metals at around 93 percent purity, with higher energy requirements. The former would thus be of much higher value on a relative scale when looked at from a value per tonne perspective.

Two additional points need to be highlighted here:

(a) As has been discussed in the previous section, the total impact of waste management processes is much higher than what the direct impacts would lead us to believe. When these direct impacts are pre-multiplied with the total multipliers calculated above, a small change in recovery and economic stimulus (discussed earlier) could lead to a large impact in the economy.

(b) There would be feedback loops that could occur with respect to the monetary side of the WSUT as well. Higher recoveries (via recycling carried out by industry) could reduce material consumption of virgin material by industries. This would have an impact in terms of the profitability of operations as well. An analysis utilizing unit-level data from the Annual Survey of Industries (ASI) for the year 2019-20 shows that that an increasing share of recycled inputs in materials consumed is negatively related to the cost of production. Specifically, a 1 percent increase in the share of recycled inputs results in a 0.05 percent reduction in production costs. When focusing on recycled material sourced from e-waste, the impact is even more pronounced, i.e., a 1 percent increase in the share of recycled e-waste inputs reduces production costs by 0.15 percent.

7. Policy Lessons

Recycling of critical minerals has been observed as one of the important aspects of the clean energy transition. For instance, in 2021, the International Energy Agency (IEA) estimated that by 2040, recycled quantities of copper, lithium, nickel, and cobalt from spent batteries could reduce combined primary supply requirements for these minerals by around 10 percent (IEA, 2021).

With a strong manufacturing base, India can develop the technology needed to recycle the Critical Raw Materials (CRMs) and thereby shape its role in CRM recycling on a global scale. Encouraging new recycling technologies for CRMs will not only push toward a circular economy but will also contribute to India's efforts to become self-reliant in their sourcing.

Therefore, it is imperative to re-evaluate and optimise the approach toward e-waste recycling. Here are a few suggestions to enhance the current system:

- Investment in the infrastructure development of the collection centers and transport network is necessary because if the quantum of waste collected is low, it becomes economically unviable. This often leads to leakage towards the informal sector. To further improve the collection efficiency, collectors can provide financial incentives for consumers to return their e-waste through schemes such as take-back deposits, etc.

- There is a need to create market access for recyclers. The government should focus on establishing platforms and opportunities for recyclers to access both domestic and international markets for recycled materials.

- Procurement policies that prioritise products containing recycled materials need to be implemented, as these policies would help create a steady demand for recycled e-waste components. Additionally, standards and certifications for the quality and reliability of recycled products need to be established.

By implementing these measures, India can move towards a more sustainable and effective e-waste management system that leverages the strengths of both formal and informal sectors. While this model attempts to quantify from a static perspective, future work will focus on enhancing the dynamic capabilities thereby offering a more comprehensive framework

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