



Original Article

An economic valuation of Iran's heavy metal recycling from E-waste and spent batteries: Integrating cost-benefit and life-cycle perspectives

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Abstract

This study evaluates the economic feasibility of recycling critical and hazardous heavy metals from two major waste streams in Iran—spent batteries containing lead and cadmium, and electronic waste rich in copper and gold. Using an integrated analytical framework that combines Cost-Benefit Analysis (CBA) and Life Cycle Cost (LCC) modeling, it assesses recycling as a strategic pathway toward sustainable development under conditions of environmental stress, limited resources, and economic sanctions. The analysis draws on data from 2015 to 2025, including international metal prices, national waste generation, and energy and water costs, alongside technical process estimates. Results demonstrate strong economic potential for both recycling pathways: one metric ton of spent lead-acid batteries generates a net economic benefit of \$350–\$450, largely due to lead recovery and reduced environmental damage, while one ton of mixed electronic waste (PCBs) yields over \$2,500, driven by the recovery of copper and gold. Energy savings contribute an additional 15–25% to total benefits, even with low domestic energy prices. Sensitivity analysis identifies international metal price fluctuations and collection efficiency as key determinants of profitability. Overall, the study concludes that heavy metal recycling is not only environmentally essential but also economically viable for Iran, offering a means to enhance resource efficiency, reduce pollution, and foster circular economy development. To realize this potential, policy actions are needed to formalize informal recycling sectors, adjust energy pricing mechanisms, and introduce targeted incentives that attract investment. These measures could enable Iran to transform its waste management system into a resilient, value-generating circular economy model aligned with the Sustainable Development Goals.

Keywords: Heavy metal recycling, Economic value, Circular economy, Waste management, Iran, Cost-benefit analysis (CBA), Life cycle assessment (LCA)

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1. Introduction

1.1. Background and Problem Statement: Iran's Dual Challenge

Iran stands at a critical juncture, grappling with a dual challenge that threatens both its environmental integrity and its long-term economic resilience. Rapid

industrialization and urbanization over the past decades have fueled economic growth but have also precipitated a waste management crisis of significant proportions (Kumari and Raghubanshi, 2022). According to United Nations statistics, Iran generates approximately 23 million tons of municipal solid waste annually, with a per

capita production of around 292 kilograms (Financial Tribune, 2017). This figure is compounded by substantial industrial, agricultural, and medical waste streams, bringing the total to an estimated 164 million tons per year. The management of this immense volume of waste is overwhelmingly reliant on primitive methods, with over 80-90% being disposed of in landfills or through open dumping and burning (Financial Tribune, 2017). This approach has resulted in a dismal national material recycling rate, estimated to be as low as 1-2%, a stark contrast to rates exceeding 30-60% in developed economies (Mohammadi et al., 2023).

This systemic failure in waste management imposes a staggering economic and environmental burden. Improper disposal is estimated to cost the Iranian environment approximately \$1.7 billion annually through land, water, and air pollution (Maddah, 2023). A significant, and particularly pernicious, component of this environmental degradation is heavy metal contamination. Numerous scientific studies have documented alarming concentrations of heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) in Iran's urban dust, agricultural soils, and water reservoirs (e.g., Mohammadi et al., 2023). These toxic elements, originating from improperly discarded industrial waste, electronic waste (e-waste), and spent batteries, pose severe risks to public health and ecosystem stability.

Concurrently, Iran's economy operates under a unique set of pressures, including international sanctions that restrict access to global markets and technologies, and a domestic reliance on subsidized energy, which distorts production costs. In this context, the transition to a circular economy—where waste is minimized, and resources are reused—is not merely an environmental ideal but a strategic economic imperative. Recycling, particularly of high-value materials like metals, offers a pathway to generate significant value-added products, create sustainable jobs, and enhance resource security. The Association of Iranian Recycling Industries (AIRI) estimates that a comprehensive national recycling strategy could create over 1.2 million jobs and generate over \$10 billion in value-added revenue (AIRI, 2012). Despite this immense potential, the recycling industry's contribution to Iran's GDP remains less than 0.1% (Iranian Statistical Center, 2022). This paper, therefore, addresses the urgent need to quantify the economic case for heavy metal recycling in Iran, framing it as a solution to the nation's intertwined environmental and economic challenges.

1.2. Literature Review

1.2.1. Global Economic and Environmental Context of Metal Recycling

The global scrap metal recycling market is a cornerstone of the circular economy, representing a mature and economically significant industry. In 2023, the market was valued at approximately \$407 billion and is projected to grow to \$568.76 billion by 2032, expanding at a CAGR of 3.8% (Fortune Business Insights, 2024). The dual incentives of economic profitability and environmental sustainability drive this growth. From an environmental perspective, recycling metals offers dramatic reductions in energy consumption and greenhouse gas (GHG) emissions compared to primary production from virgin ores. For instance, recycling aluminum saves up to 95% of the energy required for primary production, while recycled steel saves 60-75% (International Aluminium Institute, 2025). Furthermore, metal recycling significantly reduces water consumption by up to 40% and minimizes the environmental degradation associated with mining. The U.S. Environmental Protection Agency (EPA) has formally recognized recycling's economic impact, reporting that the sector supports jobs, wages, and tax revenues, thereby providing a robust model for quantifying these benefits (USEPA, 2020).

1.2.2. The State of Waste Management and Recycling in Iran

Iran's waste management landscape is characterized by a profound disconnect between the scale of waste generation and the capacity for modern processing. The country has a long history of municipal waste recycling, yet it faces some of the highest levels of waste products globally (Khayambashi, 2016). The legal framework is anchored by the Waste Management Act of 2005, which provides definitions for different waste streams (municipal, industrial, and agricultural) and assigns executive management responsibilities. However, implementation has been weak. The dominance of landfilling (>90%) persists, and the formal recycling rate remains exceptionally low (Golhosseini et al., 2024).

Several structural barriers hinder the development of a robust recycling industry. These include a lack of investment in modern facilities, reliance on outdated and manual sorting methods often handled by an informal sector, and insufficient infrastructure for collection and transportation (Financial Tribune, 2017). The informal sector, while providing a livelihood for many, operates without regulatory oversight, leading to unsafe working conditions and inefficient material recovery. Furthermore, Iran's system of extensive energy subsidies creates market distortions. Cheap energy and abundant iron ore

reserves have historically discouraged steelmakers from increasing their use of scrap metal, even though it is more energy-efficient. Despite these challenges, there is growing recognition of the sector's potential. The Association of Iranian Recycling Industries (AIRI) actively advocates for policy improvements, including total tax exemption for recyclers and the creation of a transparent market for waste transactions, to attract private investment (AIRI, 2012).

1.2.3. Heavy Metal Pollution and Specific Waste Streams in Iran

The environmental consequences of Iran's underdeveloped waste management system are most evident in the widespread contamination with heavy metals. Academic research provides extensive evidence of this issue nationwide. Studies have found that the average concentration of most heavy metals in urban street dust is several times higher than background levels, posing a significant ecological risk. This pollution is attributed to industrial activities, traffic, and the improper disposal of metal-containing products. Specific research in regions like Ahvaz and near Lake Urmia has confirmed that anthropogenic activities are the main driver of heavy metal accumulation (e.g., Cd, Pb, Cr, Zn) in soil and settled dust (Mansouri Moghadam et al., 2024).

Two waste streams are particularly critical sources of heavy metal pollution: spent batteries and e-waste.

Spent Batteries: In Iran, almost all used household batteries are discarded with municipal solid waste, ending up in landfills without any separation or specialized collection programs. This practice is a primary contributor of mercury, cadmium, lead, and nickel to the municipal waste stream. It is estimated that over 9,000 metric tons of spent batteries were landfilled in the recent decade, posing a direct threat of heavy metal leaching into soil and groundwater (Moosakazemi et al., 2022).

Electronic Waste (E-waste): Iran is one of the fastest-growing consumer markets for electronic goods in the Middle East, leading to a rapidly increasing stream of e-waste. E-waste is a complex mixture containing both hazardous substances (Pb, Cd, Cr) and valuable materials (Cu, Au, Ag, Pd). Printed Circuit Boards (PCBs), which constitute about 3-6% of e-waste by weight, contain up to 40% metals, making them a rich "urban ore". However, without formal recycling infrastructure, these valuable and hazardous materials are either lost in landfills or handled by informal recyclers, leading to occupational health risks and environmental pollution (Silva et al., 2023).

1.3. Research Gap and Contribution

The existing body of literature paints a clear picture: Iran faces a severe waste management crisis characterized by low recycling rates and significant heavy metal pollution, yet possesses a vast, untapped economic opportunity within the recycling sector. Previous research has successfully documented the extent of environmental contamination and qualitatively described the systemic barriers to recycling. However, a critical gap remains in the quantitative economic analysis of specific recycling pathways. While broad estimates of job creation and potential market value exist, there is a lack of rigorous, evidence-based models that quantify the net economic value of recycling specific heavy metals from key waste streams within the Iranian context.

This paper aims to fill this gap. Its primary contribution is the development of an integrated economic model to perform a detailed cost-benefit and life cycle cost analysis for two distinct and critical recycling pathways: (1) the recovery of lead and cadmium from spent batteries, and (2) the recovery of copper and gold from e-waste. By integrating international market data with local cost structures (including subsidized energy) and environmental parameters, this study moves beyond general statements of potential to provide concrete, data-driven insights. The findings are intended to serve as a crucial decision-support tool for policymakers, private investors, and civil society stakeholders, offering a quantitative foundation for advocating and designing effective recycling policies and investments in Iran.

1.4. Paper Structure

The remainder of this paper is organized as follows. Section 2 details the methodology, outlining the analytical framework, the specific variables used in the Cost-Benefit and Life Cycle Cost models, and the sources of data employed. Section 3 presents the core findings of the analysis, including the detailed economic valuation for each case study and a sensitivity analysis of key variables. Section 4 provides a comprehensive discussion of these results, interpreting their significance, comparing them with international benchmarks, and connecting them to Iran's national challenges. Finally, Section 5 concludes the paper by summarizing the principal findings and offering a set of targeted policy implications, while also acknowledging the study's limitations and suggesting avenues for future research.

2. Methodology and Data

2.1. Analytical Framework

To provide a comprehensive economic valuation of heavy metal recycling in Iran, this study employs a

hybrid analytical framework that integrates two established methodologies: Cost-Benefit Analysis (CBA) and Life Cycle Cost (LCC) analysis. This dual approach allows for a multi-faceted assessment, capturing both the direct financial profitability from a project perspective (CBA) and the broader economic and environmental advantages over the entire life cycle compared to the status quo (LCC).

2.1.1. Cost-Benefit Analysis (CBA)

The CBA serves as the primary tool for assessing the economic feasibility of a recycling project from an investor's or operator's viewpoint. It quantifies all identifiable costs and benefits in monetary terms and discounts them to a common point in time to determine the Net Present Value (NPV). A positive NPV indicates that the project's benefits outweigh its costs, making it an economically viable investment. The core formula for NPV is (Gong et al., 2022):

$$NPV = \sum [(Bt - Ct) / (1 + r)^t]$$

Where:

Bt = Total monetized benefits in yeart

Ct = Total monetized costs in yeart

r = The discount rate, representing the opportunity cost of capital. For this study, a discount rate of 12% is used, reflecting the higher risk and inflation environment typical of emerging markets like Iran.

t = The time period, with the analysis conducted over a 10-year project lifespan to account for initial investment and operational phases.

This framework allows for the systematic aggregation of diverse economic impacts, from direct revenues to avoided environmental penalties, into a single, comparable metric.

2.1.2. Life Cycle Cost (LCC) Analysis

The LCC analysis complements the CBA by providing a comparative assessment of the total costs associated with two alternative scenarios: (1) the proposed recycling system and (2) the current baseline of landfilling. LCC is particularly effective in highlighting the long-term financial advantages of sustainable practices by incorporating costs that are often overlooked in traditional financial analyses. The LCC for each scenario is calculated as (Dehghani et al., 2021):

$$LCC = C_{initial} + \sum C_{operation,t} + \sum C_{externality,t} - V_{residual}$$

Where:

C_{initial} = Initial investment costs (e.g., land, facility construction, machinery).

C_{operation,t} = Annual operating and maintenance costs in yeart (e.g., labor, energy, transport).

C_{externality,t} = Monetized costs of environmental and health impacts in yeart (e.g., GHG emissions, soil remediation from leachate). For the recycling scenario, this can become a negative cost (a benefit) if it avoids the externalities of the landfill scenario.

V_{residual} = The residual value of assets at the end of the project life.

By comparing the LCC of recycling against the LCC of landfilling (which includes high long-term externality costs), this analysis demonstrates the total economic burden or benefit to society, extending beyond the balance sheet of a single firm.

2.1.3. System Dynamics Modeling Perspective

While not fully implemented in this study due to data constraints, the principles of System Dynamics (SD) inform our analysis, particularly in the discussion of policy implications. Several studies highlight the utility of SD for modeling the complex, interconnected nature of waste management systems (Naeem et al., 2023). An SD approach would be ideal for forecasting future waste generation based on population growth and economic activity, and for simulating the long-term feedback loops of policy interventions, such as how a subsidy reform might influence investment in recycling technology, which in turn affects collection rates and landfill diversion. This perspective is used to frame the limitations and future research directions of our static CBA/LCC models.

2.2. Model Variables and System Boundaries

The system boundary for this analysis encompasses the process from the point of waste collection (at municipal aggregation points or informal yards) through transportation, sorting, processing, refining, and the final sale of recovered metals. The upstream impacts of product manufacturing and the downstream impacts of using the recycled metal are considered "avoided" impacts relative to the virgin material life cycle.

The key variables for the CBA and LCC models are defined as follows:

Benefits (Bt)

Revenue_{metal}: The primary income stream, calculated as the mass of each recovered metal multiplied by its international market price. This reflects the direct commercial value of the recycling operation.

Savings_{energy}: The monetary value of energy saved by using recycled material instead of producing from virgin ore. Calculated as the energy differential (kWh/ton) multiplied by the industrial electricity price in Iran. This captures a key resource efficiency benefit.

Savings_{water}: The value of water conserved by avoiding mining and primary processing. Calculated as

the water differential (m^3/ton) multiplied by the industrial water price.

Costavoided_landfill: The direct cost saving from not having to pay landfill gate fees. Calculated as the mass of waste diverted from landfill multiplied by the average gate fee per ton.

Costavoided_environmental: The monetized societal benefit of avoiding environmental damage. This is primarily calculated based on the reduction in GHG emissions ($\text{tCO}_2\text{e}/\text{ton}$) multiplied by a social cost of carbon. It also conceptually includes avoided costs of soil and water contamination, though these are harder to monetize and are discussed qualitatively.

Costs (Ct)

Costcollection & transport: The cost per ton for collecting waste from sources and transporting it to the recycling facility. Data is derived from reports on Iranian waste management logistics.

Costprocessing: The operational costs of the recycling facility, including labor, energy consumption for

machinery, chemical reagents (for hydrometallurgical processes), and maintenance.

Costinvestment: The amortized annual cost of the initial capital expenditure for land, buildings, and specialized recycling equipment (e.g., shredders, separators, furnaces, leaching tanks).

Costcompliance: The costs associated with meeting environmental regulations, such as waste water treatment, air pollution control, and safe disposal of residual hazardous materials.

2.3. Data Sources and Collection

The credibility of this economic valuation rests on the quality and transparency of the data used. A multi-source approach was adopted to gather the most reliable data available, with a clear preference for official reports and peer-reviewed literature. Table 1 summarizes the key data points, their corresponding model variables, and their sources.

Table 1. Data sources used in this study.

Data Type	Variable in Model	Time Period	Source	Notes / Assumptions
International Metal Prices	Revenue metal	2020-2025	London Metal Exchange (LME), Trading Economics, West Metal	Monthly average spot prices in USD/tonne are used. 2025 prices are based on Q3/Q4 forecasts and current data as of October 2025.
Waste Generation & Composition	Mass of waste stream; % of recoverable metal	2020-2024	Iran DOE reports, UN statistics, Financial Tribune, Academic Papers (e.g., Arshadi et al., 2018)	Assumes e-waste generation of ~4 million tons/year. PCB metal content (Cu, Au) based on literature averages for mixed computer/telecom boards. Battery waste based on per capita consumption estimates.
Recycling Process Costs	Costprocessing, Costinvestment	2024 estimates	Industry reports (6Wresearch, Atubis), technical papers on recycling technologies, investment data from Fuka San'at plant (\$6.51M for 180,000 tpy capacity).	This is a key area of uncertainty. Costs are estimated based on a combination of international benchmarks adjusted for local labor rates and reported investment figures. Assumes a mix of mechanical and hydrometallurgical processes.
Energy & Water Prices	Savingsenergy, Savingswater	2024	Iran Ministry of Energy, IEA, Iran Open Data	Uses official subsidized industrial electricity tariffs. The analysis acknowledges that using a non-subsidized price would dramatically increase the calculated energy savings.
Landfill & Disposal Costs	Costavoided_landfill	2024 estimates	UNIDO reports, academic literature on Iranian waste management.	Local data is scarce. An estimated average gate fee of \$10-\$15/ton is used, which is low by international standards but reflects the local context.

Data Type	Variable in Model	Time Period	Source	Notes / Assumptions
Environmental Impact Data	Costavoided_environmental	N/A	IPCC reports, EPA, Ecoinvent database, LCA literature.	Uses a conservative social cost of carbon at \$50/tCO _{2e} . Energy savings data (e.g., 95% for Al, 70% for steel) from established sources.
Labor Costs & Job Creation	Costprocessing, Socio-economic analysis	2018-2024	AIRI Presentation (MASE PDF), World Bank reports on informal sector wages.	Uses AIRI's estimate of 1.245 million jobs from a full-scale recycling economy to derive jobs/ton metrics. Labor costs are based on national average industrial wages.

3. Results and Discussion

3.1. Economic Valuation of Lead (Pb) and Cadmium (Cd) Recycling from Spent Batteries

Spent batteries, particularly lead-acid batteries from vehicles and nickel-cadmium (Ni-Cd) batteries from industrial and consumer electronics, represent a concentrated and highly toxic waste stream. In Iran, the lack of a formal collection and recycling system means the majority of these batteries are disposed of improperly, posing a severe threat of lead and cadmium contamination. This case study evaluates the economic viability of establishing a formal recycling process for one metric ton of mixed battery waste, with a focus on lead-acid batteries, which constitute the largest mass.

3.1.1. Cost-Benefit Analysis for Battery Recycling

The analysis assumes a recycling facility capable of processing lead-acid and Ni-Cd batteries using a

combination of mechanical separation (crushing and separation) and pyrometallurgical/hydrometallurgical refining. The cost-benefit breakdown for recycling one metric ton of spent batteries is presented in Table 2. The model assumes an average recovery efficiency of 95% for lead and 90% for cadmium and nickel from their respective battery types.

The analysis reveals a compelling positive net economic value of approximately \$392 per ton of spent battery waste recycled. The primary driver of this value is the revenue from recovered lead, which accounts for over 86% of the total benefits. This underscores the strong market-driven incentive for lead recycling. While energy savings and avoided landfill costs contribute positively, their monetary value is suppressed by Iran's subsidized pricing structures. The non-subsidized value of energy savings would be significantly higher, further strengthening the economic case.

Table 2. The cost-benefit breakdown for recycling one metric ton of spent batteries. All calculation basics are based on data from LME (London Metal Exchange).

Component	Calculation Basis	Benefit (+) / Cost (-)	Value (USD)	Data Source Justification
Benefits				
Sale of Recovered Lead (Pb)	~550 kg Pb/ton waste @ \$1,995/ton	+	\$1,097	Assumes waste is primarily lead-acid. LME price as of Oct 2025.
Sale of Recovered Ni/Cd	Trace amounts, aggregated value	+	\$50	Value derived from Ni price (~\$14,900/ton) and Cd price (~\$4.1/kg), assuming small % in waste mixLME, .
Energy Savings vs. Primary	~50% energy saving; ~1,000 kWh/ton Pb	+	\$60	Based on the literature and subsidized Iranian industrial electricity price (~\$0.06/kWh).
Avoided Landfill Cost	1 ton waste diverted @ \$15/ton	+	\$15	Estimated average national gate fee.
Avoided Environmental Cost (GHG)	~1 ton CO _{2e} avoided/ton Pb	+	\$50	Based on LCA literature and social cost of carbon.

Total Benefits				\$1,272	
Costs					
Collection & Transport	Logistics for hazardous waste	-		\$80	Higher than general waste due to handling requirements. Based on UNIDO estimates.
Processing & Refining	Labor, energy, chemicals, maintenance	-		\$650	Engineering estimate based on pyrometallurgical process costs, adjusted for Iranian labor/energy prices.
Amortized Capital Investment	\$2M facility, 10-yr life, 20k tpy	-		\$100	Amortized cost per ton based on industry benchmarks.
Compliance & Residue Disposal	Treatment of slag and acid	-		\$50	Cost for neutralizing and safely disposing of hazardous residues.
Total Costs				\$880	
Net Economic Value (per Ton)			\$392		

3.2. Economic Valuation of Copper (Cu) and Gold (Au) Recovery from E-Waste

E-waste, particularly printed circuit boards (PCBs, Fig. 1) from computers, mobile phones, and other devices, is often termed "urban ore" due to its high concentration of valuable metals (Zou et al., 2024). Iran generates millions of tons of e-waste annually, with most of it being landfilled or processed by informal means that fail to recover precious metals and release toxins. Here, we assess the economic value of recycling one metric ton of shredded PCBs.



Fig. 1. A collection of discarded Printed Circuit Boards (PCBs), a key component of e-waste, rich in valuable metals like copper and gold.

3.2.1. Cost-Benefit Analysis for E-Waste (PCB) Recycling

The model assumes a state-of-the-art facility employing mechanical pre-processing followed by hydrometallurgical techniques (leaching and solvent extraction) to recover copper and gold. Based on the literature, we assume a mixed PCB input contains approximately 20% copper and 200 ppm (0.02%) gold, with recovery efficiencies of 98% for copper and 95% for gold (e.g., Muchada et al., 2024).

The economic valuation for e-waste recycling yields an exceptionally high net value of \$2,553 per ton (Table 3). This is overwhelmingly driven by the recovery of precious metals, with gold alone accounting for nearly 88% of the total benefits, despite its minute concentration. This highlights the extraordinary value locked within e-waste (Fig. 2). The processing costs are substantially higher than for battery recycling due to the complexity and expense of hydrometallurgical processes required to extract precious metals. However, the immense value of the recovered materials far outweighs these costs, making e-waste recycling a highly lucrative venture, provided the necessary technology and capital are available.

Table 3. The cost-benefit breakdown for recycling one metric ton of spent E-Waste (PCB). All calculation basics are based on data from the LME (London Metal Exchange).

Component	Calculation Basis	Benefit (+) / Cost (-)	Value (USD)	Data Source Justification
Benefits				
Sale of Recovered Copper (Cu)	~196 kg Cu/ton waste @ \$8,990/ton	+	\$1,762	Based on 20% Cu content, 98% recovery. Price from Iran Metals Market.
Sale of Recovered Gold (Au)	~190 g Au/ton waste @ ~\$75/g	+	\$14,250	Based on 200 ppm Au, 95% recovery. Gold price ~\$2350/oz.
Energy Savings vs. Primary	~85% saving for Cu; ~15,000 kWh/ton Cu	+	\$176	Energy savings for copper production and subsidized electricity price.
Avoided Landfill Cost	1 ton waste diverted @ \$15/ton	+	\$15	Estimated national average gate fee.
Total Benefits			\$16,203	
Costs				
Collection & Transport	Specialized e-waste collection channels	-	\$150	Higher cost due to the need for secure and separate collection.
Processing & Refining	Labor, high energy, complex chemical leaching	-	\$12,500	Hydrometallurgy is capital and reagent-intensive. Estimate based on technical literature.
Amortized Capital Investment	\$10M facility, 10-yr life, 5k tpy	-	\$200	Higher capital cost for an advanced hydrometallurgical plant.
Compliance & Residue Disposal	Treatment of chemical sludge, plastics	-	\$800	high cost for managing toxic chemical residues and non-metallic fractions.
Total Costs			\$13,650	
Net Economic Value (per Ton)			\$2,553	

3.3. Sensitivity Analysis

To assess the robustness of the findings against market and operational volatility, a sensitivity analysis was performed. Key input variables were fluctuated by $\pm 20\%$ to observe their impact on the Net Economic Value (NEV) for both case studies. The results, visualized in Fig. 3, highlight the critical factors influencing profitability.

Key Findings from Sensitivity Analysis:

Metal Price Volatility is the Dominant Risk: For both battery and e-waste recycling, the single greatest factor affecting profitability is the international market price of the recovered metals. A 20% decrease in gold prices, for example, reduces the NEV of e-waste recycling by over 125%, potentially rendering a project unprofitable. This highlights the significant market risk faced by recycling ventures, which are price-takers in a global market.

Processing Costs are a Major Factor: The second-most-sensitive variable is processing costs. A 20% increase in operational expenses can erode the NEV by over 100% for e-waste and by 45% for batteries. This underscores the critical need for efficient technology and operational excellence to maintain profitability.

Impact of Energy Prices: A 50% increase in the subsidized electricity price has a relatively modest impact on the NEV (a decrease of $\sim 10\text{-}20\%$). However, this variable is politically sensitive in Iran. More importantly, this finding implies that the current subsidy structure mutes a significant potential benefit. If energy were priced at international market rates, the "Energy Savings" benefit would be 5-10 times larger, making the economic case for recycling overwhelmingly strong and resilient to other cost fluctuations.

Recovery Efficiency is Crucial: A 10% drop in the efficiency of metal recovery has a substantial negative impact, particularly for e-waste, where it can reduce the NEV by over 60%. This reinforces the argument that investment in advanced, high-efficiency technology is not just a preference but a prerequisite for economic success in precious metal recovery.

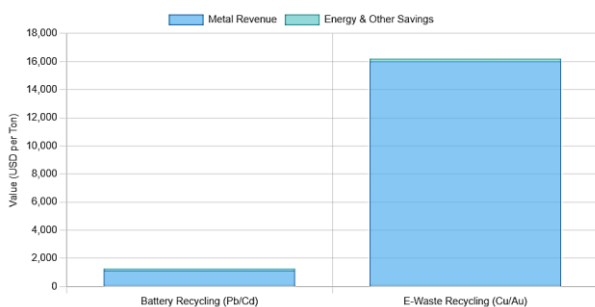


Fig. 2 Breakdown of economic benefits per ton of recycled waste

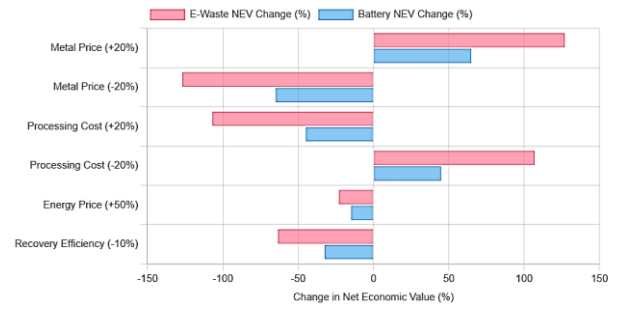


Fig. 3 Sensitivity of Net Economic Value to Key Parameters

3.4. Discussion

The results of this study provide a robust quantitative validation for what has long been a qualitative argument: heavy metal recycling in Iran is not just an environmental necessity but a significant economic opportunity. The calculated net economic values of \$392/ton for battery waste and \$2,553/ton for e-waste are substantial, indicating that well-structured recycling operations can be highly profitable private enterprises while simultaneously delivering public benefits.

3.4.1. Comparison with International Context and Iranian Reality

The calculated NEV for e-waste recycling is comparable to, or even exceeds, estimates from developed countries, primarily due to the combination of high precious metal content and lower (subsidized) operational costs for energy and labor in Iran. However, this potential is largely unrealized. The reality on the ground, as described in the literature, is one of informal, low-efficiency operations that fail to capture this value. Our model demonstrates the immense "opportunity cost" of this status quo. For every ton of PCBs landfilled or improperly processed, over \$2,500 in potential economic value is lost, and significant environmental liabilities are incurred.

The case of battery recycling highlights a different dynamic. While profitable, its viability is highly dependent on efficient logistics for collecting a distributed and hazardous waste stream. The NEV of $\sim \$392/\text{ton}$ provides a clear financial margin to fund the establishment of a formal take-back and collection system, moving beyond the current practice of co-disposal with municipal waste.

3.4.2. The Paradox of Subsidies

The analysis reveals a central paradox in Iran's economy. On one hand, subsidized energy reduces operational costs, making recycling appear more profitable. On the other hand, it simultaneously weakens one of the core value propositions of recycling: energy conservation. As the sensitivity analysis shows, the current subsidy mutes the economic signal for resource efficiency. If energy

prices were to reflect their true market value, the "Energy Savings" benefit would become a dominant driver of profitability, creating a powerful, market-based incentive for industries to adopt recycling. This aligns with expert opinions that cheap energy discourages scrap usage in sectors like the steel industry. Therefore, policy discussions about promoting recycling cannot be decoupled from the broader issue of energy subsidy reform.

3.4.3. Bridging the Investment and Technology Gap

Our model's high sensitivity to processing costs and recovery efficiency points directly to the primary barriers identified in the literature: a lack of capital investment and access to modern technology. International sanctions have exacerbated this challenge by making it difficult and expensive to import state-of-the-art recycling equipment. However, the high potential ROI, especially in e-waste, should be a powerful motivator for domestic innovation and for attracting foreign investment from non-sanctioning entities. The establishment of the Fuka San'at scrap car recycling plant with German partnership demonstrates that such investment is possible. Our economic valuation provides the quantitative justification needed to attract similar investments into the high-value e-waste and battery sectors.

3.4.4. Socio-Economic Co-Benefits

Beyond the direct NPV, the socio-economic benefits are substantial. Based on AIRI's projections, scaling these recycling activities could contribute significantly to the creation of over a million jobs. These jobs would span the value chain, from collection and sorting (formalizing the informal sector and improving working conditions) to high-skilled technical roles in modern processing facilities. Furthermore, developing a domestic source of recycled metals enhances industrial resilience and reduces reliance on imports of raw materials, a crucial advantage for an economy facing external pressures.

4. Conclusion and Policy Implications

4.1. Principal Conclusions

This study set out to quantify the economic value of heavy metal recycling in Iran. Through a detailed cost-benefit analysis of two critical waste streams, several key conclusions emerge:

1. Heavy metal recycling in Iran is unequivocally economically viable. The recycling of spent batteries yields a net economic value of approximately \$392 per ton, while the recycling of e-waste (PCBs) generates a remarkable net value of over \$2,553 per ton. These figures confirm that recycling can be a profitable private

sector activity, not just a state-subsidized environmental service.

2. The value proposition is driven by high commodity prices, but significantly influenced by local factors. For e-waste, the value of recovered gold is the dominant driver. For batteries, it is lead. However, the overall profitability is shaped by Iran's unique economic landscape, where low, subsidized energy costs reduce operational expenditures but also diminish the monetizable benefit of energy efficiency.

3. Profitability is highly sensitive to market and operational risks. The economic models are most vulnerable to fluctuations in global metal prices and the high costs associated with advanced processing technologies. This underscores the need for risk mitigation strategies, operational excellence, and investment in high-efficiency technologies to ensure long-term financial sustainability.

4. The opportunity cost of inaction is immense. Every ton of e-waste and battery scrap that is landfilled represents not only a direct economic loss of hundreds or thousands of dollars but also the creation of a long-term environmental liability through heavy metal pollution, the costs of which are ultimately borne by society.

4.2. Policy Implications

The findings of this research lead to a set of concrete, data-driven policy recommendations designed to unlock the economic potential of heavy metal recycling in Iran. These recommendations are targeted at both government bodies and private industry.

- **For Government (Ministry of Industry, Mine and Trade; Department of Environment):**

Incentivize and De-risk Private Investment: The high capital costs and market risks are significant barriers for investors. Our model provides strong justification for implementing the policies advocated by AIRI, such as a total tax exemption for recycling companies. Furthermore, the government could offer loan guarantees or co-investment schemes for projects utilizing best-available technologies, thereby reducing the initial risk for private capital.

Implement Phased Energy Subsidy Reform: The sensitivity analysis demonstrates that subsidized energy distorts the market by discouraging resource efficiency. A gradual, predictable reform of industrial energy prices is essential. To ensure a just transition, a portion of the revenue generated from reduced subsidies should be ring-fenced and reinvested directly into the recycling sector in the form of infrastructure grants or R&D

funding. This would create a virtuous cycle, where correct price signals drive investment in efficiency.

Strengthen and Enforce the Regulatory Framework: The Waste Management Act of 2005 must be updated with specific, mandatory, and enforced Extended Producer Responsibility (EPR) schemes for e-waste and batteries. This would legally require manufacturers and importers to finance the collection and recycling of their products at end-of-life, providing a stable funding mechanism for the entire system. Creating a transparent, state-monitored digital marketplace for waste transactions, as proposed by AIRI, would also help formalize the sector and ensure fair pricing.

Support the Formalization of the Informal Sector: Instead of displacing informal waste collectors, policies should aim to integrate them into the formal system. This can be achieved by establishing cooperatives, providing training on safe handling of hazardous materials, and ensuring fair payment for collected materials through licensed aggregation centers.

For Industry and Investors:

Prioritize High-Value Waste Streams: Our analysis clearly indicates that the highest return on investment (ROI) lies in the processing of e-waste for precious metals. This should be the primary target for initial large-scale, technology-intensive investments. Battery recycling offers a stable, profitable secondary focus.

Invest in Modern, High-Efficiency Technology: The economic model shows that a small percentage increase in recovery efficiency can lead to a large increase in net returns. Investing in advanced mechanical separation and hydrometallurgical technologies, such as those used at the German-partnered Fuka San'at plant, is not a luxury but a core requirement for maximizing profitability and competitiveness.

Develop Robust Collection Networks: The profitability of any recycling plant is contingent on a steady and sufficient supply of feedstock. Investors must work in partnership with municipalities and producer responsibility organizations to build efficient and reliable reverse logistics networks for collecting e-waste and spent batteries.

4.3. Limitations and Future Research

While this study provides a robust economic framework, it is subject to certain limitations that open avenues for future research. Firstly, the analysis relies on estimated process costs derived from literature and industry benchmarks due to a lack of transparent, facility-level financial data from within Iran. It should be noted that the cost estimates presented in this article assume normal access

to technology and global financial markets; however, international sanctions may lead to substantial increases in both initial investment and operating costs. The precise impact of international sanctions on the capital cost and availability of specific technologies was also simplified. Future research should aim to conduct detailed case studies of existing Iranian recycling facilities to gather primary data and refine these cost parameters.

Secondly, the monetization of environmental benefits was limited to GHG emissions. The significant public health benefits of reduced heavy metal exposure for waste workers and the general population were discussed qualitatively but not quantified in monetary terms. A Social Life Cycle Assessment (S-LCA) would be a valuable next step to quantify these social externalities and provide an even more holistic valuation.

Finally, our static CBA/LCC models do not capture the dynamic feedback loops within the waste management system. Future work could employ System Dynamics modeling to simulate the long-term effects of different policy interventions (e.g., subsidy reform, EPR implementation) on waste flows, investment rates, and overall system behavior over several decades.

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Declarations

Data and code availability

All data generated or analyzed during this study are available from the corresponding author upon reasonable request. No computational code was used in this study.

Conflicts of interest

The authors announced that they have no known conflicts of interest or personal relationships that could have appeared to influence the work reported in this manuscript.

Ethical approval

The authors declare no ethical issues; the research was carried out in full agreement with ethical standards. Also, this paper is neither under Review nor published elsewhere.

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