Western Digital

White Paper

Advanced Recycling and Rare Earth Recovery at Scale

A blueprint for rare earth recovery that enhances supply chains and planetary resilience.

April 2025

Overview and Problem Statement

Traditionally, End of Life (EoL) hard disk drive storage devices have gone through recycling processes that extract some materials from the product. However, a typical storage device contains numerous elements from the periodic table, including rare earth elements (REEs) such as Neodymium, Praseodymium and Dysprosium that are used in various components within the storage device due to their magnetic properties. Current recycling processes recovered few materials at lower yields and recovered no rare earths. We are reporting a rare earth material capture program successfully launched at scale in the United States from destroyed, shredded hard drives.

Western Digital, in collaboration with Microsoft, Critical Materials Recycling (CMR), and PedalPoint Recycling (PP), have converted ~47,000 pounds of end-of-life hard disk drives (HDD), solid state drives (SSD), and caddies, into critical and valuable metals for the United States (U.S.) supply chain. Rare Earth Oxide (REO) recovery occurred entirely in the U.S. The process results in a 95% reduction in climate changing gases when aggregated over all elements recovered compared to equivalent product of those elements from virgin mining. The data and methodology supporting this reduction are fully described in this paper. The project accelerates domestic production of (1) high purity REOs of Neodymium (Nd), Praseodymium (Pr), and Dysprosium (Dy); and (2) value-added metals such as Gold (Au), Silver (Ag), Palladium (Pd), Copper (Cu), Aluminum (Al), and Steel. The system's key advantage is close integration of *HDD manufacturing and use with advanced physical separation and chemical processing.* Figure 1 depicts the flow of materials within the U.S. The pilot study established clear and robust business processes for involved organizations and demonstrated impressive metal re-capture rates. The entire pilot is tightly centered on the U.S. and represents an expansion of existing capabilities.

This multi-party pilot has demonstrated that an economically viable ecosystem of socially and environmentally responsible EoL management is possible through a combination of careful segregation and selective chemistry. Further, the process can provide increased sustainable resources with possible ~90% high yield elemental and rare earth recovery. The process is highly efficient, yielding ~80% by mass of the feedstock (which includes caddies and expoxy resins) to valuable metals. The carbon footprint analysis of this pilot shows 95% less climate changing gases compared to the equivalent virgin material mining.

The virgin mining (primary production) of REEs especially is a process that can be environmentally and socially detrimental. This new process when scaled worldwide can return a significant amount of recovered rare earths to the recycled pool drastically reducing the need for primary production.

This project is also significant because the feedstock, hard disk drives (HDD), will continue to grow globally as Artificial Intelligence drives the demand for data storage. According to IDC, total data production between 2023-28 will grow at a 24% CAGR, a total of 393.9 ZB data by 2028. A majority of this will be supported by HDDs (approximately 6.57 billion HDD) [1]. Thus, there will be a steady feed stock for domestic *secondary* production (recycling), which offers many advantages over *primary* production (from ore).

Current commercial-scale baseline technology for metals includes primary production (from ore) or secondary production of metal from scrap and salvage (recycling) [2]. Primary production of most metals has significant biodiversity impacts because of land use change [3], [4], emissions of climate changing gases, and water consumption [5][6], [7]. Secondary production generally causes less environmental damage than primary production [8], [9]. Most primary production (>85%) of (REEs) occurs outside of the U.S. [10], [11] and the current domestic recycling rate for REEs is very low (<10%) [12]. The demonstration project thus addresses the twin threats of planetary decline and supply chain vulnerability.

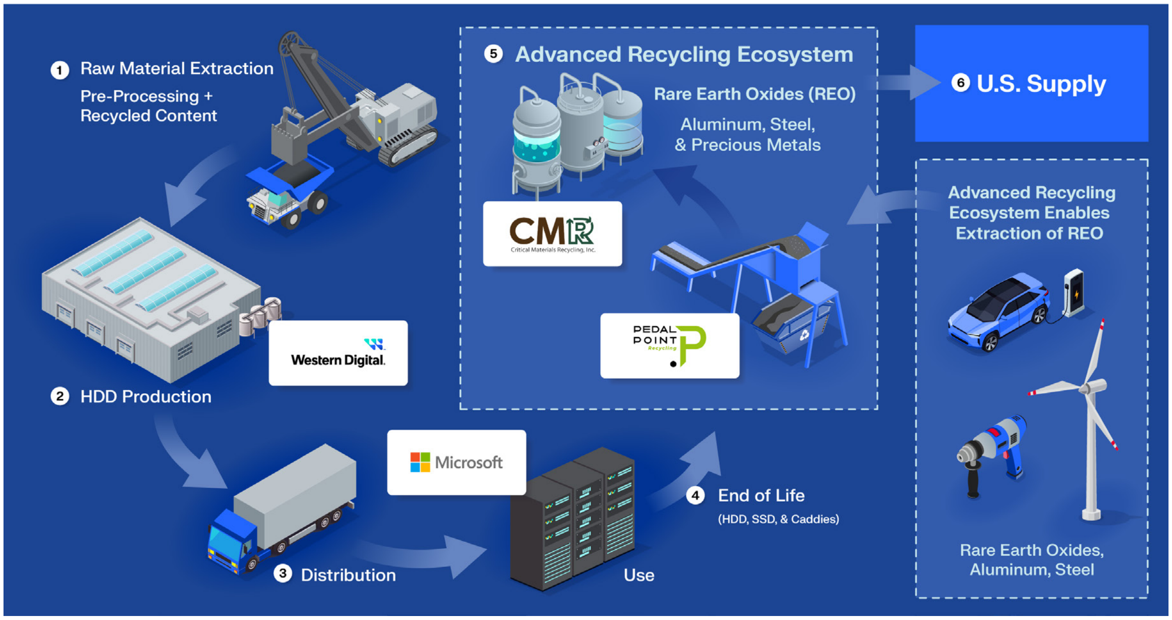

Figure 1: HDDs produced by Western Digital and in use at Microsoft data centers are then shredded and sorted at PedalPoint Recycling before undergoing acid-free dissolution at CMR where rare earth oxides are extracted, then returned to the U.S. supply pool. The advanced recycling process these partners created has been emulated by other industries to extract rare earths from their hardware, returning even more materials to the U.S. supply.

Study Scope

The demonstration was completed over a period of approximately 18 months, beginning in 2023. Two blends of materials were collected from Microsoft Datacenters (IA, VA, TX): 1) shredded HDD and caddies and 2) shredded HDD, SSD, and caddies. These were transported to a PP facility (Il) and then processed and separated into fractions: printed circuit board (PCB), Aluminum, and Ferrous. The Ferrous fraction was shipped to CMR (IA), for recovery of REO. The remaining Steel was then shipped from CMR back to the same PP facility. The PCB fractions were shipped to a smelter (South Korea) for recovery of precious metals such as Au, Cu, Ag and Pd. The Steel returns and the Al fraction were shipped to a Steel and Al processor (NC). Figure 2 illustrates the material process flow within and between processes. Although some processes were outside of the U.S., all metals, including Cu, Au, Ag and Pd remained within a proprietary PP refining network.

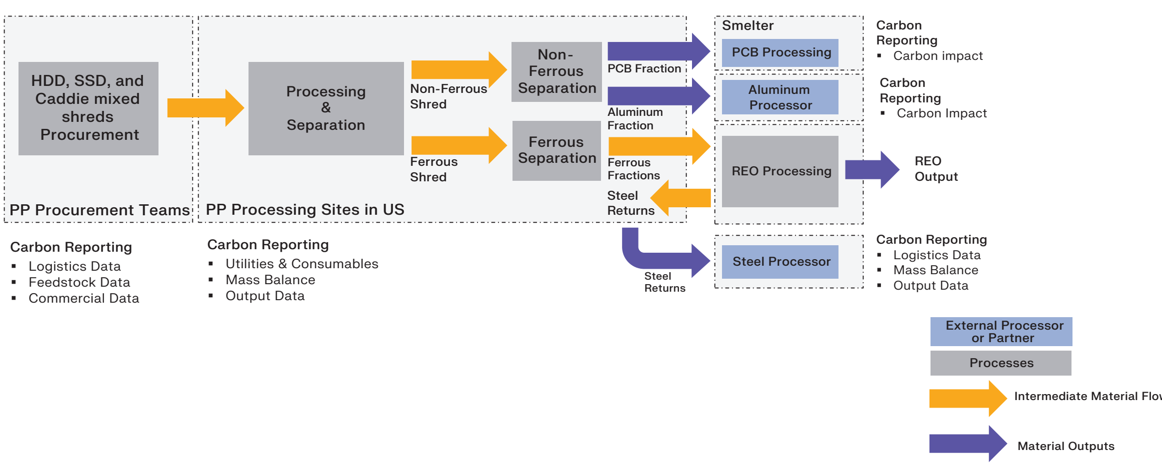

Figure 2: Details of material fractions, and processing and transport by PP and CMR.

At PP, mechanical processing steps (such as harvesting the board from the HDD and separating Ferrous from non-Ferrous material after shredding) help increase the recovery yield and purity. The Ferrous material is shipped to CMR for processing for REEs and then shipped to a domestic smelter for Ferrous material returned to the U.S. market. Non-Ferrous material is shipped to a U.S. smelter for Al recovery and re-introduction to the U.S. market.

The chemical basis of the acid-free dissolution (ADR) recovery of REEs has been described in detail [9]. Instead of high temperatures and/or harsh chemicals such as strong acids, ADR utilizes selective leaching via a copper salt solution. This selective leaching makes the technology ideal for low-concentrated rare earth feedstocks, where magnet isolation is not feasible, but it is also extremely efficient (>98%) for concentrated feedstocks, such as scrap magnet or magnet swarf. HDDs, for example, contain as little as 1 wt. % REEs.

ADR recovers >90% of the REEs from an HDD feedstock to produce a >99.5% pure REO **(Figure 3)**. Compared with current REO refining processes, ADR has much lower potential human health impacts which is an important benefit to workers and the broader community. This impact is driven by the selective leaching and avoidance of harsh chemicals, such as high concentration strong acids and high temperature/pressure techniques.

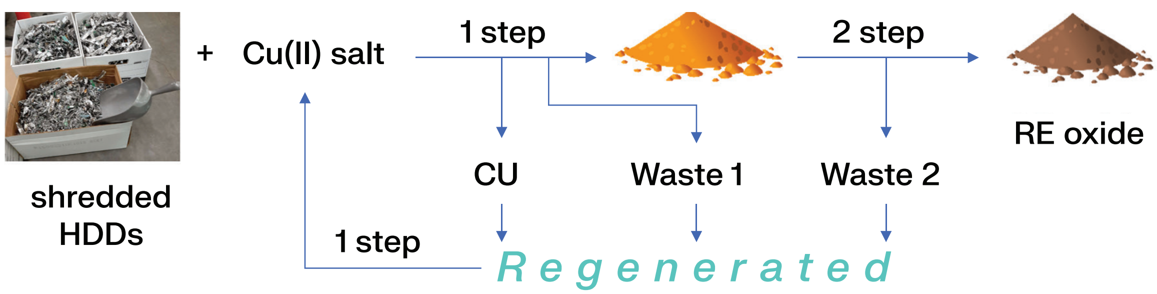

Figure 3: CMR's patented ADR process utilizes a copper salt for the selective leaching of REEs from dilute feedstocks such as shredded HDDs. The process produces a >99.5% pure REO with a recovery efficiency of >90%.

Life Cycle Assessment (LCA) Methodology

A process-based life cycle assessment (LCA) was applied to evaluate the difference in environmental impact between the demonstrated recycling system (Scenario 1; Fig. 4) and conventional primary production outside of the U.S. (Scenario 2; Fig. 5). The LCA was conducted with a functional unit of 1000 kg of shredded material.

Throughout the study, all organizations collaborated closely to collect high quality primary data for Scenario 1, such as transportation distances and modes, precise weights for each shipment, and natural gas and electricity consumption. Primary data helps ensure the accuracy of the LCA outcomes, including estimated environmental impacts. Modeling Scenario 2 included secondary data sources such as LCA databases and published values.

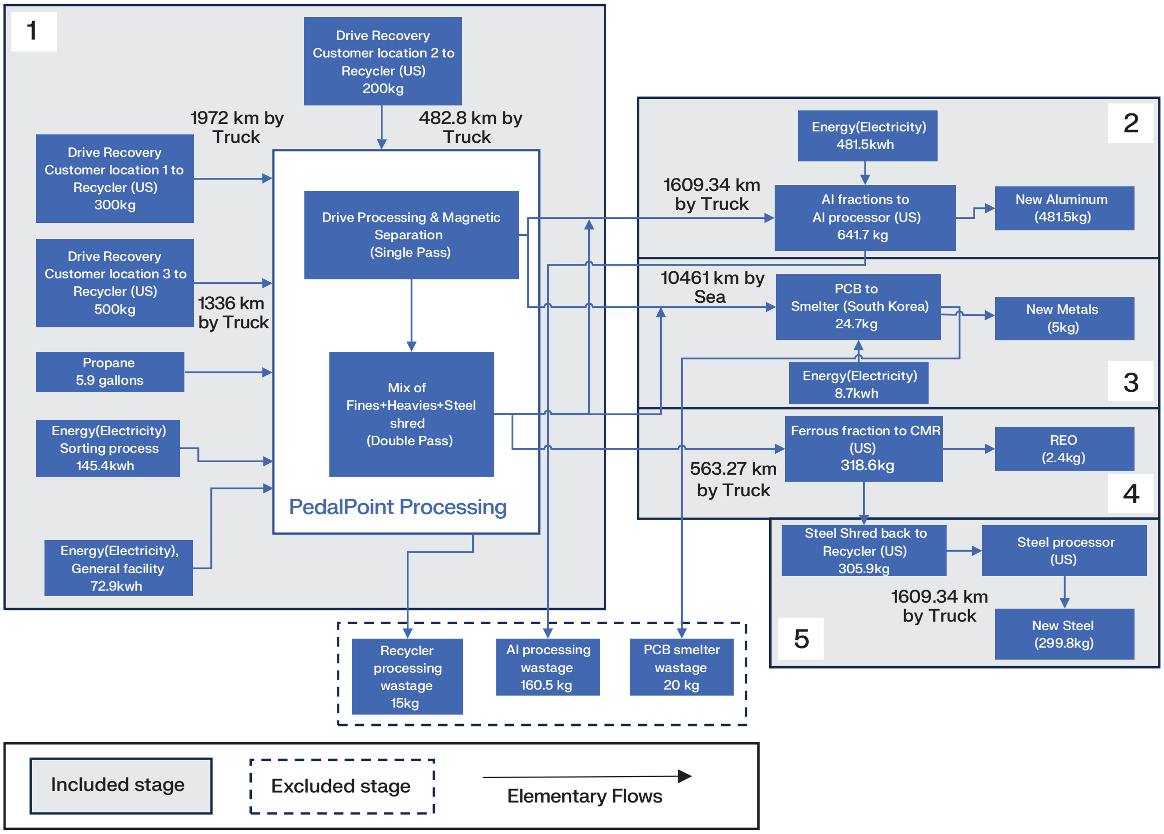

Figure 4: The system boundaries for Scenario 1. All processes shown within the grey boxes were included in the LCA for Scenario 1, and the overall system was divided into 5 processes. The processing of waste materials from each process is excluded from the study due to data unavailability.

Scenario 2 (Conventional material production): Emissions for the material production are calculated based on secondary sources.

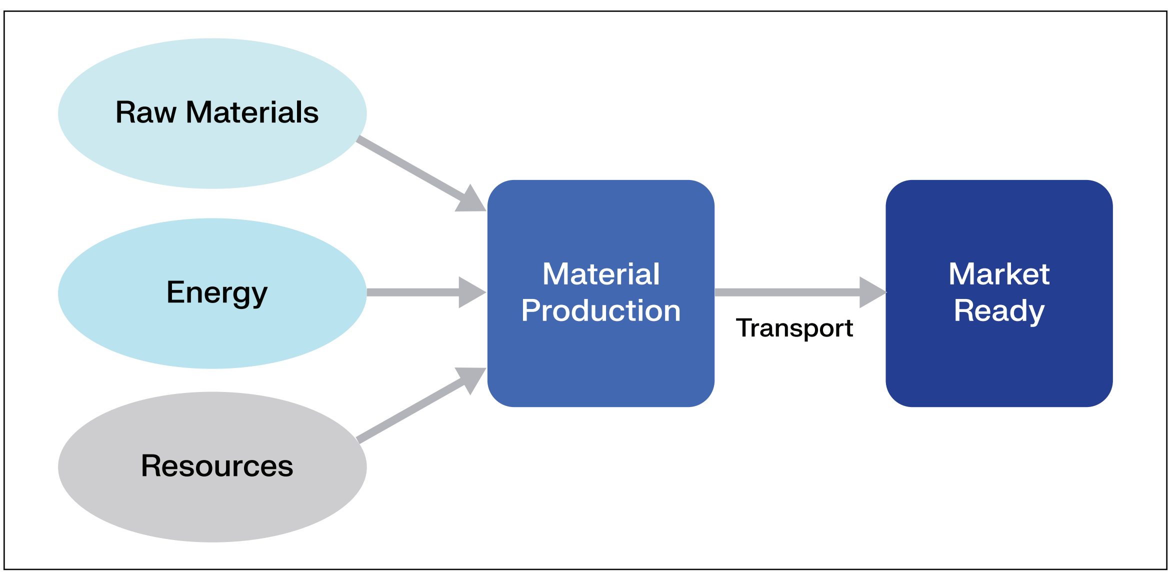

Figure 5: The system boundary for Scenario 2, primary production of each material, includes ore extraction and processing outside of the U.S. Specific processes will depend on the metal (REO, Cu, Al, or Steel).

Scenario 1:

Sphera LCA database 2024 was the source of all data for Tables 1 and 2.

Table 1: Energy and Resources

Energy & Utility	Region of Unit Process	Dataset Name or flow
Electricity	USA	Electricity grid mix
Electricity	South Korea	Electricity grid mix
Propane	USA	Liquefied Petroleum Gas (LPG) (70% propane; 30% butane)

Table 2: Transport and Fuel

Transport & Fuel	Region of Unit Process	Dataset Name or flow
Road	Global	Truck, Euro 6, 28 - 32t gross weight / 22t payload capacity
Sea	Global	Container ship, 5,000 to 200,000 dwt payload capacity, deep sea
Diesel fuel	USA	Diesel mix at filling station
Heavy fuel oil	USA	Heavy fuel oil at refinery (0.3wt.% S) Sphera

Scenario 2:

Ecoinvent is the data source for all materials, except Stainless Steel cold rolled coil (304), for which Eurofer is the data source.

Table 3: Material

Material	Region of Unit Process	Dataset Name or flow	Source
Aluminum ingot	Global	primary, to aluminum, cast alloy market	
Copper	Global	market for copper	
Gold	Global	market for gold	
Palladium	Global	Palladium primary route	IPA
Silver	Global	market for silver	ecoinvent
Steel, low-alloyed	Global	market for Steel, low-alloyed	
Stainless Steel cold rolled coil (304)	Rest of European Region	Stainless Steel cold rolled coil (304)	

Results

The advanced recycling process results in a 95% reduction in climate changing gases when aggregated over all elements recovered. The performance of the five processes contributed to this overall reduction, and are described in detail, along with key environmental performance metrics. Note that the Intergovernmental Panel on Climate Change Global Warming Potential (IPCC GWP) reflects the amount of energy absorbed by a gas emission over a defined period of time, compared to carbon dioxide (CO_2). In this study, the GWP time period is 100 years. Numbers are reported in terms of kg of carbon dioxide equivalents (kg CO_{2e}).

- Process 1: Advanced Sorting and Transport (*0.193 kg CO_{2e}/kg shredded material*)

Advanced sorting segregates REO material from other metals with little carbon impact. Resources include propane for forklifts, and electricity to power the sorting and other general activities at the facility. These resources were allocated to the processed material based on direct processes and a portion of the building baseload (lights, heating, cooling and ventilation (HVAC), etc.). The baseload applied was 33% of the total facility because PP operates three primary workstreams in the facility. Starting with 1,000 kg of shredded material, the output from advanced sorting produced 985 kg, comprised of 318.6 kg of Ferrous material (to CMR), 641.7 kg of Al (to processor), and 24.7 kg of PCB (to smelter). Material wastage was 15 kg.

Input - Output for 1,000kg of Material

Input

- Weight input 1,000kg
- Propane used in Forklifts: 5.9 gallons
- Energy used (Sorting process): 145.4kwh
- Energy used (General facility): 7.29kwh

Output

- Total output: 985 kg
- Weight of Ferrous fractions going to CMR: 318.6 kg
- Weight of Al fractions going to AL processor: 641.7 kg
- Weight of PCB fractions going to Smelter: 24.7 kg
- Material wastage: 15 kg

Transport

MSFT(Des Moines, IA) to PP(Elgin, IL): 482.80 km by road by Truck
MSFT(Boydton, VA) to PP(Elgin, IL): 1335.75 km by road by Truck
MSFT(San Antonio, TX) to PP(Elgin, IL): 1971.44 km by road by Truck

Results (IPCC GWP 100, AR6)

- Emission from processing 1000 kg of materials at PP: **193.82 $kgCO_{2e}$**
- Emission from processing 1kg of material at PP: **0.193 $kgCO_{2e}$**

Output Distribution	Weight kg	% Distribution	emission distribution kgco2e/kg
Al fractions	641.7	65%	**0.126**
Ferrous fractions for CMR	318.6	32%	**0.062**
Circuit Board Fractions	24.7	3%	**0.006**
Total	**985.0**		

Figure 6: Mass balance and carbon intensity for advanced sorting and transport.

- Process 2: Aluminium smelter (*0.778 kg CO_{2e}/kg Al*)

The Aluminum smelter captures 75% of Aluminum and generates 96% less CO_{2e} than primary production.

Input - Output for 1,000kg of Shreds

Input

- Weight of Al and non-Al fractions (e.g., plastics) going to Al processor: 641.7 kg
- Energy utilized: 481.5 kwh

Output

- Process capture rate: 75%
  - Captures >99% of Al, other non-Al materials attribute to wastage
- Recycled Aluminum produced: 481.5 kg
- Material wastage: 160.5 kg

Transport

PP(Elgin, IL) to Farmville, NC: 1609.34 km by road by Truck

Results (IPCC GWP 100, AR6)

Advanced Recycling

- Emission for producing 1kg of recycled Aluminum: **0.652 $kgCO_{2e}$**
- Total emission (PP processing % + Al processing)/1kg: **0.778 $kgCO_{2e}$**

ecoinvent dataset

- Emission for producing 1kg of virgin aluminum ingot (primary, to aluminum, cast alloy market, GLO): **19.1 $kgCO_{2e}$**

Figure 7: Mass balance and carbon intensity for producing recycled Al at a smelter, and transport between sorting location and smelter.

- Process 3: Printed Circuit Board Smelter *(1.14 $kgCO_{2e}$/kg combined new metals)*

Cu is the major metal in PCB (15-30%). It should also be noted that the process efficiency is stated to be 20%, however most of the weight of the PCB is fiberglass, epoxy/organic compounds that are incinerated during the smelting process. Even with this uncertainty, the primary production of metals is so carbon intensive that advanced recycling compares favorably, even with a long transport distance to South Korea.

Input - Output for 1,000kg of Shreds

Input

- Weight of PCB fractions going to PCB processor: 25.0 kg
- Energy utilized: 8.7 kwh

Output

- Process capture rate: 20.164% (Cu: 20%, Ag: 0.12%, Au: 0.04% & Pd: 0.004%)
  - Process captures >99% metals from PCB
  - ~80% of PCB weight is organic material (epoxy resin blend of non
- Recycled Metals produced: 5.041 kg
- Material wastage: 19.96 kg

Transport

- PP(Elgin, IL) to Smelter, SK: 10460.71 km by Sea

Results (IPCC GWP 100, AR6)

Advanced Recycling process Impact	$kgCO_{2e}$
Impact to produce 1kg of Recycled Combined Material	1.14
Total impact to produce 5.041kg of Recycled Combined Material: Copper: 5kg; Silver: 0.03kg; Gold: 0.01kg (1000kg input equivalent)	**5.77**

Virgin Material production Impact (ecoinvent/IPA)	$kgCO_{2e}$
Impact for producing 1kg of virgin Copper (market for copper, GLO)	4.66
Impact for producing 1kg of virgin Silver (market for silver, GLO)	448
Impact for producing 1kg of virgin Gold (market for gold, GLO)	48729.28
Impact for producing 1kg of virgin Palladium (Primary route IPA, GLO)	23427.38
Impact to produce 5kg of virgin Copper	**23.30**
Impact to produce 0.03kg of virgin Silver	**13.44**
Impact to produce 0.01kg of virgin Gold	**487.29**
Impact to produce 0.001kg of virgin Palladium	**23.43**
Total impact to produce 5.041kg of Virgin Combined material (1000kg input equivalent)	**547.46**

Figure 8: Mass balance and carbon intensity for secondary production of Cu and Au at a smelter, and transport between sorting location and smelter.

- o Process 4: REO Capture (CMR) and transport (*6.26 kg CO_{2e}/kg REO*)
- o The CMR process captures up to 90% REO and generates 80% less CO_{2e} than primary production. After transport of the Ferrous fraction (318.6 kg) from PP to CMR, the ADR process produced 2.4 kg of REO and 305.9 kg Steel shreds (transported back to PP recycler). Per kg of REO, the CMR process is substantially less carbon intensive (6.33 kg CO_{2e}) than primary production. The environmental sustainability benefits of the CMR process, applied specifically to HDD, has been recently published[13].

Input - Output for 1,000kg of Shreds

Input

- Weight of Fe fractions going to CMR process: 318.9 kg

Output (Allocated based on CMR LCA and actual data)

- Recycled REO capture rate: 2.4 kg (~90% capture rate)
- Steel Shreds: 305.9kg (including Heavies)

Transport

- PP(Elgin, IL) to CMR (Boone, IA) : 563 km by road
- Steel Shred goes back to PP recycler from CMR

Rare-Earth Elements Recovery from Electronic Waste: Techno-Economic and Life Cycle Analysis

(Refer: ACS Sustainable Chem. Eng. 2024, 12, 14164–14172)

- Assessment conducted in OpenLCA by using the ecoinvent database with the TRACI impact assessment method and various impact allocation methods
- Acid-free dissolution recovery process (ADR) used to produce 1kg of REO from 134kg of HDD shreds
- Emission to produce 1 kg of REO : 6.2kgCO_{2e} (95% percentile)

Results

Advanced Recycling

- Emission for producing 1kg of recycled REO: **6.2kgCO_{2e}**
- Total emission (PP processing % + CMR+ Transport)/1kg: **6.26 kgCO_{2e}**

ecoinvent dataset

- Emission for producing 1kg of virgin praseodymium - neodymium oxide: **32 kgCO_{2e}**

Figure 9: Mass balance and carbon intensity for acid-free dissolution recovery (ADR) and transport.

- o Process 5: Ferrous (Steel) (*0.449 kg CO_{2e}/kg Steel*)

Steel recycle captures 98% of Steel and generates 89% less CO_{2e} than primary production. Note differences in emissions intensity for primary production of different types of Steel. Production of recycled Steel compares well to both the upper and lower carbon intensities. In this case, energy was not reported as primary data. Carbon emissions data were reported from the Steel recycler.

Steel processing (1000 drive equivalent)

Input

- Weight of Steel Shred to Steel processing: 305.9 kg

Output

- Recycled Steel: 299.8 kg
- Process capture rate: 98%

Transport

- PP (Elgin, IL) to Steel Recycler (Farmville, NC): 1609.34 km by road

Results

- The emission data for Steel processing was provided by supplier

Advanced Recycling

- Emission for producing 1kg of recycled Steel: **0.306 $kgCO_{2e}$**
- Total emission (Steel processing+Transport)/1kg: **0.449$kgCO_{2e}$**

ecoinvent/Eurofer dataset

- Emission for producing 1kg of virgin steel (market for steel, low-alloyed, GLO): **1.29 $kgCO_{2e}$**
- Emission for producing 1kg of virgin steel (Stainless steel cold rolled coil (304), RER): **4.09 $kgCO_{2e}$**

Figure 10: Mass balance and carbon intensity for producing recycled Steel, and transport between sorting location and smelter.

The aggregated results from all processes are very promising, and demonstrate that advanced recycling can cut CO_2 emissions by 95% compared to virgin material production. Recycling also reduces dependency on environmentally damaging mining processes, which involve high energy use, acid leaching, and radioactive waste. Figures 11 and 12 illustrate the positive impact. Figures 11 and 12 illustrate the positive impact.

Output Material	Output Material Qty/1000kg input (kg)	Adv. Recycling impact/kg of output material ($kgCO_{2e}$)	Virgin Material Production impact/kg ($kgCO_{2e}$)	Adv. Recycling impact/ total output for 1000kg input ($kgCO_{2e}$)	Virgin Material production impact/total output for 1000kg input ($kgCO_{2e}$)
Recycled Aluminum	481.5	0.778	19.1	374.61	9,196.65
Rare Earth Oxides	2.4	6.26	32	15.02	76.8
Recycled Steel	299.8	0.449	4.09	134.61	1,226.182
Recycled Metals (Cu, Ag, Au & Pd)	5.04	1.14	Cu: 4.66; Ag: 448; Au: 48729.3; Pd: 23427.4	5.77	547.46

	Adv. Recycling	Virgin Material production
Net Impacts / 1000 kg of input material	**530.01**	**11047.09**
CO_2 impact reduction	**95.20%**	

Figure 11: Detailed results, presented on the basis of 1000 kg of input material. Advanced recycling compares favorably for all metals, compared to virginal material production.

Advanced Recycling Total impact
(for producing 1kg each of Al, New Metals, REO and Steel)

8.63 $kgCO_{2e}$ vs. 163.8 $kgCO_{2e}$ virgin

Advanced recycling (Individual process impact)	Virgin Material production impact	CO2 Impact reduction
1kg Aluminum production: **0.778 $kgCO_{2e}$**	1kg of Aluminum ingot production: **19.1 $kgCO_{2e}$**	**96%**
1kg Combined New Metal production: **1.144 $kgCO_{2e}$**	1 kg of Combined New Material: **108.6 $kgCO_{2e}$**	**99%**
1kg of REO Production: **6.26 $kgCO_{2e}$**	1kg of praseodymium-neodymium oxide: **32 $kgCO_{2e}$**	**80%**
1 kg of Steel production: **0.449 $kgCO_{2e}$**	1kg of Stainless-Steel production: **4.09 $kgCO_{2e}$**	**89%**

Figure 12: The overall process results in a range of climate change impact reductions. New metals refers to Ag, Au, and Pd.

Conclusion

The circular economy relies on strong technological systems and robust business processes. The results from this study establish a breakthrough advance towards the long-term, high priority goal of closed-loop circularity. The study has demonstrated the reduced climate change impact, relative to primary production (mining). The reduced carbon intensity materials, in the U.S. supply chain, will have a significant, positive impact on related industries, such as electric vehicle (EV), wind turbine, other electronic products that utilize these materials. Thus, this partnership has helped reduce the environmental "footprint" (impacts) of other companies.

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