WD

White Paper

Unlocking the Value of End-of-Life HDDs

Scalable Recapturing for Critical Materials, U.S. Supply Chain Resilience, and Environmental Impact Reduction.

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Introduction and Problem Statement

This paper presents the results of an advanced hard disk drive (HDD) recovery process, enabled by a partnership between WD (San Jose, CA), REcapture (joint venture between Critical Materials Recycling (Boone, IA) and Paladin EnviroTech (Tampa, FL)), and cloud service providers' data centers. The demonstration reveals end-of-life HDDs that represent a high-value, domestic (United States) source of critical materials with substantially lower environmental impacts compared with primary production (virgin mining and refining). This process efficiency compared with our June 2025 Advanced Recovery and Rare Earth Capture White Paper demonstrates a significant advancement of overall material capture rates from ~80% to >90%.

The process can convert 1,000 kg of HDDs into ~690 kg of aluminum; ~188 kg of recycled ferrous alloys; ~3.2 kg of rare earth oxide (REO); ~10.08 kg of critical and precious metals: ~9.92 kg copper (Cu), 0.06 kg silver (Ag), 0.02 kg gold (Au), and 0.002 kg palladium (Pd); and 15 kg of low-concentration metals. The overall material capture rate is 90.6%. Compared with primary production, the HDD recycling route cuts climate-changing gases by 94.07% overall (8.50 vs. 160.67 kg CO_2e per kg of output). The per-material reductions (kg CO_2e per kg of output) include: aluminum (Al): 0.645 vs 18.6; critical and precious metals: 1.189 vs 108.026; REO: 6.33 vs 32; and ferrous alloys: 0.205 vs 2.04. Substantial reductions were also observed in 11 additional environmental impact categories.

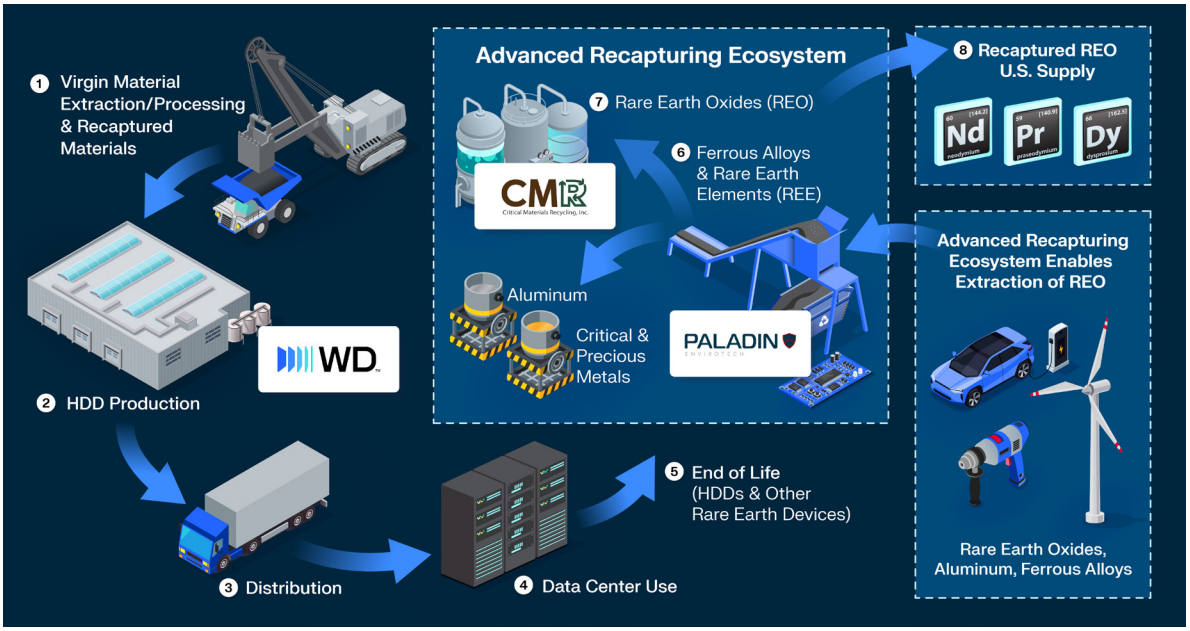


Figure 1: HDDs produced by WD and in use at data centers are then shredded and sorted at Paladin EnviroTech, before undergoing benign chemistry, acid-free dissolution at CMR where rare earth oxides are extracted, then returned to the U.S. supply pool. CMR research notes that the advanced recovery process 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.

Findings from the U.S. Geological Survey's 2025 List of Critical Minerals, alongside the growth of the data center storage facilities and the quantified risk of international trade disruptions, form a coherent rationale for scaling domestic HDD recycling. HDDs contain high-value strategic metals such as rare earth elements (REE) and strategic metals like Cu, Au, Ag, and Pd. Recapturing them at scale not only reduces environmental burdens but also functions as a strategic resilience mechanism, lowering U.S. vulnerability to geopolitical shocks, supply shortages, and concentrated foreign production. [1] This recovery approach strengthens national security, supports key clean energy manufacturing sectors with rare earth recovery, and enables the exponential growth of data storage to become an asset for the future U.S. materials economy.

The 2024 U.S. Data Center Energy Usage Report highlights a decade of rapid expansion in digital

infrastructure and associated storage requirements. [2] HDDs remain the primary medium for bulk data storage, and overall HDD installed base and capacity per drive continue to increase [3]. The enormous scale of HDD deployments ensures a large and steady stream of end-of-life drives entering the waste stream each year, making recovery and recapturing strategically important for material security.

This is fortuitous, because the United States Geological Survey (USGS) published a trade disruption analysis that provides clear evidence for why recovering each of these metals strengthens U.S. economic resilience. [4] REEs (like Nd, Pr, Dy) carry among the highest disruption risks, with China as the dominant supplier. Probability-weighted gross domestic product (GDP) losses under disruption scenarios reach $154M for neodymium, $66M for praseodymium, and $1,624M for dysprosium, placing all three in elevated- to high-risk categories. Advanced recycling can directly offset some of this risk by supplying domestically recovered REE from magnet materials. Copper shows an elevated risk as well: $56M probability-weighted GDP impact, largely tied to refined copper imports from Chile. Aluminum faces an even greater $201M expected GDP impact linked to dependence on Canadian supply. Silver, another recaptured metal, carries elevated risk with a $36M GDP impact, mainly due to reliance on Mexico supply. [4]

Study Scope

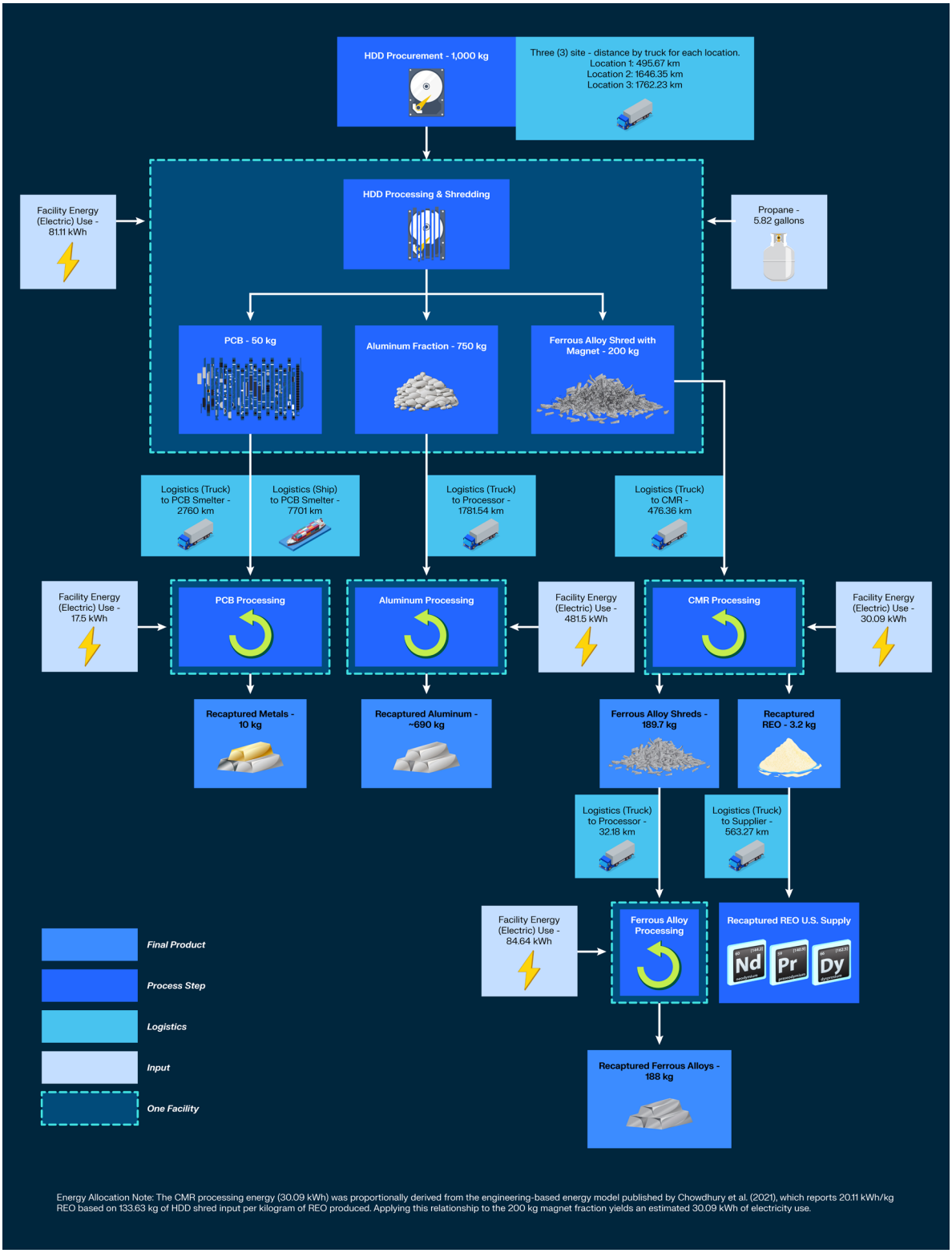


Figure 2: Schematic of the overall process, facility-level energy consumption, processing, and transportation distances. The LCA study prioritized the major metal final products (by mass) recovered from HDDs (Final Product boxes).

This demonstration was completed in 2026. For this study, a representative sample of 1,865 whole HDDs was selected from multiple cloud service providers' data centers and consolidated for further processing. This represents a small fraction of the cloud service providers' total data center HDD volume (exceeding 2 million units globally). The HDDs were transported to a Paladin EnviroTech processing facility in Minnesota for consolidation, where they were processed into three fractions: printed circuit board (PCB), aluminum, and ferrous alloys/magnets via specialized shredding and mechanical separation systems, including magnetic (ferrous alloys) separation, eddy current systems for non-ferrous alloy recovery, and density-based sorting. These closed-loop, purpose-built systems produce clean, high-purity material streams that are designed to maximize material capture rates while minimizing cross-contamination between fractions. See schematic Figure 2 for overall process and material flow.

The PCB fractions were shipped to a smelter in South Korea for recovery of precious metals such as gold, copper, silver, and palladium. Although some processes were outside of the U.S., all metals, including gold, copper, silver, and palladium, remained within a proprietary Paladin refining network.

The ferrous alloys and magnet material are shipped to CMR for processing of the REEs, and then the remaining ferrous alloys fractions are shipped to a domestic smelter for ferrous alloys material to be returned to the U.S. market. Non-ferrous alloys material is shipped to a U.S. smelter in North Carolina for Al recovery and re-introduction to the U.S. market.

As shown in Figure 3, the chemical basis of the acid-free dissolution recovery (ADR) of REEs has been previously described in detail. [5] 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% of REEs in HDD total weight.

ADR recovers >90% of the REEs from an HDD shredded feedstock to produce a >99.5% pure REO. 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. These impacts are driven by the selective leaching and avoidance of harsh chemicals, such as a high concentration of strong acids and high-temperature/pressure techniques. [5]

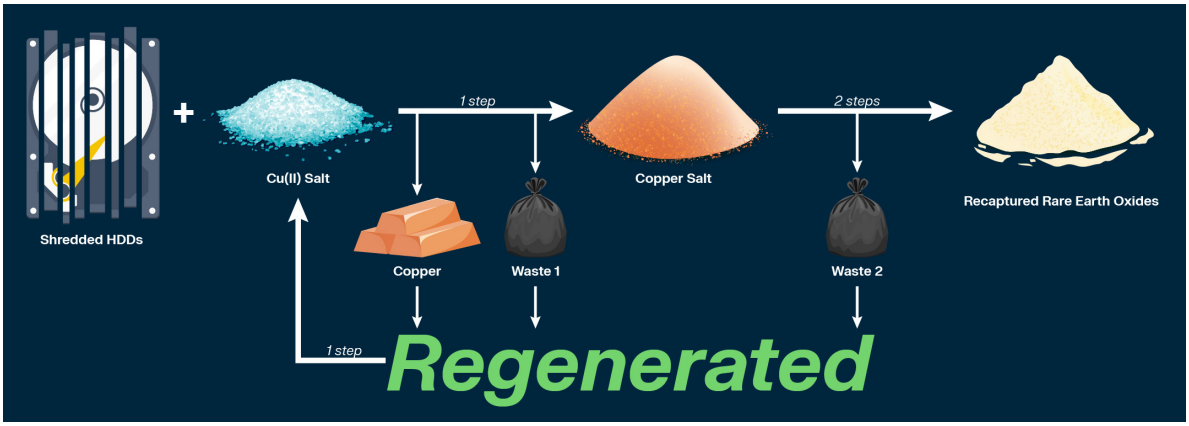


Figure 3: CMR's patented ADR process utilizes a copper salt for the selective leaching of REEs from dilute feedstocks such as shredded HDDs. The process produces a >99.5% pure REO with a recovery efficiency of >90%.

Life Cycle Assessment Methodology

A process-based life cycle assessment (LCA) was applied to evaluate the difference in environmental impact between the demonstrated recovery system (Figure 2) and conventional primary production of each metal outside of the U.S. The LCA was conducted with a functional unit of 1,000 kg of shredded material. Throughout the study, all organizations collaborated closely to collect high-quality primary data, 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 included secondary data sources such as LCA databases and published values. The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.2 impact assessment method was applied. [6], [7], [10]

Results

The entire recovery process demonstrates a 94% reduction in climate impacts, as shown in Figures 4.1 and 4.2. In addition, the reductions for specific metal fractions are also detailed.

Fig 4.1	TRACI DATA Results Summary — 1 kg Output/Process		
HDD Recapturing Total Impact (for producing 1 kg each of aluminum, recaptured metals, & REO) 9.53 kg CO_2e vs 160.67 kg CO_2e (virgin)			
HDD Recapturing (Individual Process)	**kg CO_2e**	**Virgin Material Production**	**kg CO_2e Impact**
1 kg of aluminum production	0.645	1 kg of aluminum production	18.6
1 kg of combined recaptured PCB metals production	2.346	1 kg of combined PCB recaptured metal	108.026
1 kg of REO production	6.331	1 kg of praseodymium-neodymium oxide	32
1 kg of ferrous alloy production	0.205	1 kg of ferrous alloy production	2.04
Net impact per 1 kg of recaptured material produced	9.53	Net impact per 1 kg of virgin material produced	160.67
Climate Impact Reduction (total % CO_2e impact reduction recycled vs virigin)			**94.07%**

Figure 4.1: Results demonstrate that HDD recapturing can cut CO_2 emissions by ~94% compared to virgin material production. [6]

Fig 4.2	HDD Recapturing Total Impact		
Starting Input for 1,000 kg of Material			
Weight	**Propane Used in Forklifts**	**Energy Used (sorting process + general facility)**	
1,000 kg	5.82 gallons	81.11 kWh	
Output for 1,000 kg of Material			
Output Distribution	**Weight (kg)**	**% Distribution**	**Emission Distribution (kg CO_2e/ kg)**
Aluminum fractions	750	75%	0.1335
Ferrous fractions for CMR	200	20%	0.0356
PCB fractions	50	5%	0.0089
Total	1,000	100%	0.178
Transportation for 1,000 kg of Material			
Data Center Location	**Destination**	**Transportation Method**	**Distance Traveled (km)**
Des Moines, IA	Paladin (St. Cloud, MN)	Truck	496
Boydton, VA	Paladin (St. Cloud, MN)	Truck	1,646
San Antonio, TX	Paladin (St. Cloud, MN)	Truck	1,762

Figure 4.2: Recapturing also reduces dependency on environmentally damaging mining processes, which involve high energy use, acid leaching, and other waste. [8]

These results demonstrate that the WD-Paladin-CMR collaboration delivers a scalable, lower-carbon, strategically important recycling pathway that accelerates U.S. supply chain resilience, reduces environmental burdens, and transforms HDD end-of-life management into a significant materials recovery opportunity. With global HDD inventories projected to remain substantial for decades, this partnership provides a model for circularity and critical minerals security in the data center ecosystem. [9]

Environmental sustainability is multi-dimensional, and in addition to details about climate impact reduction, the next few sections describe changes in 11 additional environmental impact categories for each metal fraction.

Aluminum

From the 750 kg of aluminum fraction produced at Paladin's facility, downstream processing yields ~690 kg of new aluminum, with a recycling-based carbon intensity of 0.645 kg CO_2e per kilogram, compared with 18.6 kg CO_2e for primary aluminum production. [8] This represents more than a 97% reduction in climate impact. In addition, compared to primary production of aluminum (from mining), aluminum recovery from HDD substantially reduces impacts on human health (particulate matter, photochemical smog, cancer, and non-cancer impacts), biodiversity (acidification, eutrophication), and ozone depletion. [7] Water consumption is also reduced, which is important in the context of water scarcity. [7] The remaining ~8–9% of material loss is consistent with smelting of clean aluminum scrap streams and is primarily attributable to non-recoverable fractions such as coatings (e.g., paint and anodization, ~3–4%) and typical process-related losses including oxidation and dross formation during melting.

The exception (one out of 11) is in the category of ecotoxicity. The outcome is primarily attributable to the modelling of the recycling process, which is dominated by electricity consumption based on the U.S. grid mix. Within the TRACI 2.2 methodology, ecotoxicity characterization is particularly sensitive to emissions of trace substances such as heavy metals to air, water, and soil, which are associated with upstream energy generation processes. As a result, the use of region-specific electricity datasets can disproportionately influence ecotoxicity results, even when greenhouse gas emissions are comparatively low. [10]

In contrast, the primary virgin material production for aluminum dataset represents a globally averaged supply chain encompassing multiple stages such as bauxite mining, alumina refining, etc. The environmental burdens in this system are distributed across a broader set of processes, regions, and co-products, which may result in a relative dilution of ecotoxicity contributions within the aggregated dataset.

The results reflect the influence of methodological choices, including system boundaries and the selection of background datasets. Therefore, we conclude that aluminum recycling is not environmentally inferior with respect to ecotoxicity.

Fig 5.1	TRACI DATA Results Summary — 1 kg Output for Aluminum		
Recapturing vs Virgin Impact / 1 kg of Aluminum Production			
Aluminum Processing Impact Categories	**Recapturing Process Impact / 1 kg**	**Virgin Material Impact / 1 kg**	**Climate Impact Reduction**
TRACI 2.2, Acidification Air [kg SO2 eq.]	7.30E-04	1.10E-01	99%
TRACI 2.2, Ecotoxicity (recommended) [CTUe]	2.07E-02	1.10E-02	-88%
TRACI 2.2, Eutrophication - Freshwater [kg P eq.]	2.87E-07	2.53E-03	100%
TRACI 2.2, Eutrophication - Marine [kg N eq.]	4.08E-04	3.29E-02	99%
TRACI 2.2, Human Health Particulate Air [kg pm2.5 eq.]	4.39E-05	3.26E-02	100%
TRACI 2.2, Human Toxicity, Cancer (recommended) [CTUh]	3.66E-11	3.45E-09	99%
TRACI 2.2, Human Toxicity, Non-Canc. (recommended) [CTUh]	4.89E-12	9.33E-10	99%
TRACI 2.2, Ozone Depletion Air [kg CFC 11 eq.]	3.26E-12	1.10E-07	100%
TRACI 2.2, Photochemical Oxidation Formation [kg O3 eq.]	1.25E-02	1.28E+00	99%
AWARE 1.2C, Global Average for Unspecified Water [m^3 world equiv.]	7.79E-02	4.52E+00	98%
Blue Water Consumption [kg]	2.45E+00	1.05E+02	98%

Figure 5.1: Results indicate recapturing has significantly lower impacts across all water and TRACI midpoint indicators except ecotoxicity. The higher ecotoxicity impact is likely the result of U.S. electricity use with higher TRACI 2.2 factors, whereas emissions from virgin material production are typically distributed over a larger system. [6], [7], [8], [10]

Fig 5.2	Aluminum Recapturing Total Impact			
Aluminum Input-Output for 1,000 kg of HDD Shreds to Aluminum Processor				
Aluminum Fractions Input		**Recaptured Aluminum Output**		
Weight (kg)	**Energy Utilized (kWh)**	**Process Capture Rate***	**Weight of Recaptured Aluminum Produced (kg)**	**Material Wastage (kg)**
750	481.5	92%	690	60
***Process captures >99% of aluminum; other non-aluminum materals attribute to wastage**				
Transportation				
Start Location		**Destination**	**Transportation Method**	**Distance Traveled (km)**
Paladin (St. Cloud, MN)		Farmville, NC	Truck	1,781.54
Emission Results for Aluminum Input-Output for 1,000 kg of HDD Shreds to Aluminum Processor				
Source of Emission				**kg CO_2e**
Emission for producing 1 kg of virgin aluminum ingot (primary to aluminum, cast alloy market, GLO)				18.6
Emission for producing 1 kg of recaptured aluminum				0.512
Total emission for recaptured aluminum (Paladin processing % + aluminum processing) / 1 kg				**0.645**

Figure 5.2: As noted above, the process capture rate is 92% of overall with 99% aluminum being captured and ~8% containing mixed non-aluminum materials attributed to wastage. [8]

Printed Circuit Board

Similarly, 50 kg of PCB material routed to the smelter produces 10.08 kg of high-value metals, primarily copper, silver, gold, and palladium, at an emissions intensity of 1.19 kg CO_2e per kilogram of mixed metals. Primary production of the same materials would require 108.03 kg CO_2e per kilogram, demonstrating a ~98% reduction in carbon impact and providing domestic access to metals identified by USGS as carrying significant geopolitical and supply chain risks. [7]

Fig 6.1	TRACI DATA Results Summary — 1 kg Output for Recaptured Metals		
Recapturing vs Virgin Impact / 1 kg of Recaptured Metals Production			
PCB Processing Impact Categories	**Recapturing Process Impact / 1 kg**	**Virgin Material Impact / 1 kg**	**Climate Impact Reduction**
TRACI 2.2, Acidification Air [kg SO2 eq.]	9.53E-03	2.28E+00	99.58%
TRACI 2.2, Ecotoxicity (recommended) [CTUe]	7.54E-02	5.34E-01	85.89%
TRACI 2.2, Eutrophication - Freshwater [kg P eq.]	1.26E-06	1.91E-01	100.00%
TRACI 2.2, Eutrophication - Marine [kg N eq.]	7.14E-03	4.82E-01	98.52%
TRACI 2.2, Human Health Particulate Air [kg pm2.5 eq.]	1.01E-03	3.58E-01	99.72%
TRACI 2.2, Human Toxicity, Cancer (recommended) [CTUh]	5.77E-11	1.08E-08	99.47%
TRACI 2.2, Human Toxicity, Non-Canc. (recommended) [CTUh]	2.12E-11	5.24E-07	100.00%
TRACI 2.2, Ozone Depletion Air [kg CFC 11 eq.]	4.46E-11	1.45E-06	100.00%
TRACI 2.2, Photochemical Oxidation Formation [kg O3 eq.]	2.48E-01	1.70E+01	98.54%
AWARE 1.2C, Global Average for Unspecified Water [m^3 world equiv.]	3.58E-02	4.05E+01	99.91%
Blue Water Consumption [kg]	7.25E+00	9.44E+02	99.23%

Figure 6.1: Results indicate recapturing has significantly lower impacts across all water and TRACI midpoint indicators. [6], [7], [8], [10]

Fig 6.2	PCB Recapturing Total Impact				
PCB Input-Output for 1,000 kg of HDD Shreds to PCB Processor					
PCB Fractions Input		Recaptured Metals Output			
Weight* (kg)	Energy Utilized (kWh)	Process Capture Rate*	Weight of Recaptured Precious Metals Produced (kg)	Weight of Recaptured Other Metals Produced (kg)	Material Wastage (kg)
50	17.5	20.164% (Cu: 20%, Ag: 0.12%, Au: 0.04%, Pd: 0.004%)	10.08	14.02	25
*Process captures >99% metals from PCB; ~50% OF PCB weight is organic material (epoxy resin blend)					
Transportation					
Start Location		Destination	Transportation Method	Distance Traveled (km)	
Paladin (St. Cloud, MN)		Smelter (South Korea)	Truck	2,760	
			Ship	7,701	
Emission Results for PCB Input-Output for 1,000 kg of HDD Shreds to PCB Processor					
Weighted Virgin Production Baseline Impact / 1 kg Metal Output					kg CO_2e
Impact for producing 1 kg of virgin copper (GLO, market for copper)					4.66
Impact for producing 1 kg of virgin silver (GLO, market for silver)					448.00
Impact for producing 1 kg of virgin gold (GLO, market for gold)					47,674.46
Impact for producing 1 kg of virgin palladium (GLO, market for palladium)					31,074.47
Weighted impact from 99.19% copper in 1 kg virgin metal output					4.62
Weighted impact from 0.60% silver in 1 kg virgin metal output					2.67
Weighted impact from 0.20% gold in 1 kg virgin metal output					94.57
Weighted impact from 0.02% palladium in 1 kg virgin metal output					18.6.16
Total weighted virgin production impact / 1 kg virgin metal output					**108.03**
Output Distribution					kg CO_2e
Impact to produce 1 kg of recaptured metals					2.337
Total impact to produce 1 kg of recaptured metals (including Process 1 allocation)					**2.346**

Figure 6.2: Summary of PCB recapturing total impact [8]

Based on scientific literature, averaged across many types of PCBs, the metals and inorganic elements compose about 50% of the total weight (25 kg of the total 50 kg fraction). The 10.08 kg are quantified in this study from smelter recovery, and an estimated 14.02 kg are metals recovered by the smelter that are “unpaid” (not reported back to the smelter’s customer). Recent literature indicates these elements might include aluminum, antimony (Sb), barium (Ba), calcium (Ca), Iron (Fe), potassium (K), sodium (Na), nickel (Ni), lead (Pb), tin (Sn), zinc (Zn), manganese (Mn), molybdenum (Mo), and titanium (Ti). [11], [12], [13], [14] The reduction in environmental impacts does not include these trace metals. They are listed here to explain the mass recovery rate.

Ferrous Alloys

The ferrous alloys stream from CMR is transported to Des Moines, Iowa and transformed into 188 kg of recaptured ferrous alloys with a reclamation rate of 98% at 0.21 kg CO_2e per kilogram, and a 92% CO_2e reduction relative to virgin steel production.

Fig 7.1	TRACI DATA Results Summary — 1 kg Output for Ferrous Alloys		
Recapturing vs Virgin Impact / 1 kg of Ferrous Alloys Production			
Ferrous Alloys Processing Impact Categories	**Recapturing Process Impact / 1 kg**	**Virgin Material Impact / 1 kg**	**Climate Impact Reduction**
TRACI 2.2, Acidification Air [kg SO2 eq.]	2.13E-04	7.53E-03	97%
TRACI 2.2, Ecotoxicity (recommended) [CTUe]	1.88E-03	6.84E-03	73%
TRACI 2.2, Eutrophication - Freshwater [kg P eq.]	1.61E-08	5.34E-04	100%
TRACI 2.2, Eutrophication - Marine [kg N eq.]	9.57E-05	3.11E-03	97%
TRACI 2.2, Human Health Particulate Air [kg pm2.5 eq.]	1.54E-05	6.02E-03	100%
TRACI 2.2, Human Toxicity, Cancer (recommended) [CTUh]	1.78E-11	1.36E-10	87%
TRACI 2.2, Human Toxicity, Non-Canc. (recommended) [CTUh]	3.99E-13	9.05E-10	100%
TRACI 2.2, Ozone Depletion Air [kg CFC 11 eq.]	2.12E-12	1.10E-08	100%
TRACI 2.2, Photochemical Oxidation Formation [kg O3 eq.]	3.36E-03	1.16E-01	97%
AWARE 1.2C, Global Average for Unspecified Water [m^3 world equiv.]	4.30E-02	6.92E-01	94%
Blue Water Consumption [kg]	1.32E+00	1.61E+01	92%

Figure 7.1: Results indicate recapturing has significantly lower impacts across all water and TRACI midpoint indicators. [6], [7], [8], [10]

Fig 7.2	Ferrous Alloys Recapturing Total Impact			
Ferrous Alloys Input-Output for 1,000 kg of HDD Shreds to Ferrous Alloys Processor				
Ferrous Alloys Shred Input		**Recaptured Ferrous Alloys Output**		
Weight (kg)	**Energy Utilized (kWh)**	**Process Capture Rate**	**Weight of Recaptured Ferrous Alloys Produced (kg)**	**Material Wastage (kg)**
189.7	84.6	99%	188	1.7
Transportation				
Start Location		**Destination**	**Transportation Method**	**Distance Traveled (km)**
CMR (Boone, IA)		Processor (Des Moines, IA)	Truck	32.18
Emission Results for Ferrous Alloys Input-Output for 1,000kg of HDD Shreds to Ferrous Alloys Processor				
Source of Emission				**kg CO_2e**
Emission for producing 1 kg of virgin ferrous alloys (market for low-alloyed ferrous alloys, GLO)				2.04
Total emission for recaptured ferrous alloys (ferrous alloys processing + transport) / 1 kg				0.205
Climate impact reduction in 1 kg of recaptured ferrous alloys production (virgin vs recycled)				**1.835**

Figure 7.2: Summary of ferrous alloys recapturing total impact [8]

Rare Earth Oxides

The inclusion of CMR significantly enhances the system's strategic value by enabling recovery of REE from HDD ferrous alloy and magnet shreds. CMR processes 200 kg of ferrous alloys shreds to recover 3.2 kg of REO, primarily neodymium-praseodymium oxide, using a low-impact refining pathway that emits 6.33 kg CO_2e per kilogram of REO, compared with 32 kg CO_2e for conventional REO production. This provides an 80% reduction in emissions, while supplying rare earth materials essential for HDDs, EV motors, wind turbines, and other data center equipment.

The present study incorporates previously published LCA results for ADR, which applied a different version of TRACI. [6], [15] Therefore, the comparison between primary production and our recapturing process is qualitative, except for climate change impact. For climate change specifically, we utilized a Monte Carlo simulation (95th percentile) from the recycling study plus transport emissions and compared with virgin production using TRACI 2.2. [10] This is acceptable because Global Warming Potential (GWP) factors are consistent across TRACI versions, while using Monte Carlo (95th percentile) ensures a conservative estimate of recycling impacts for robust comparison.

In other environmental impact categories, the numbers for each scenario cannot be directly compared, and we do not calculate an impact reduction.

The REO primary production datasets may also underestimate impacts associated with mining activities, tailings management (including radioactive residues), land use, and high energy intensity, which are not always fully captured in midpoint-level LCA indicators.

Higher impacts are observed for the CMR process in categories such as acidification and ecotoxicity. Based on the literature data, these seem to be primarily driven by process-specific factors, including the electricity mix and chemical inputs. These impacts, however, should be optimizable for hotspots rather than inherent limitations of REO recapturing pathways. Toxicity results are not directly comparable due to different TRACI Life Cycle Impact Assessment (LCIA) methodologies.

Fig 8.1	TRACI DATA Results Summary — 1 kg Output for REO (CMR)
Recapturing Process Transport + CMR: Impact / 1 kg of REO Production	
Impact Categories - Transport of Materials for REO Extraction	**Material Impact / 1 kg**
TRACI 2.2, Acidification Air [kg SO2 eq.]	9.93E-05
TRACI 2.2, Ecotoxicity (recommended) [CTUe]	2.24E-03
TRACI 2.2, Eutrophication - Freshwater [kg P eq.]	6.45E-08
TRACI 2.2, Eutrophication - Marine [kg N eq.]	7.76E-05
TRACI 2.2, Human Health Particulate Air [kg pm2.5 eq.]	4.40E-06
TRACI 2.2, Human Toxicity, Cancer (recommended) [CTUh]	9.73E-13
TRACI 2.2, Human Toxicity, Non-Canc. (recommended) [CTUh]	1.30E-12
TRACI 2.2, Ozone Depletion Air [kg CFC 11 eq.]	2.92E-14
TRACI 2.2, Photochemical Oxidation Formation [kg O3 eq.]	2.04E-03
AWARE 1.2C, Global Average for Unspecified Water [m^3 world equiv.]	1.00E-03
Blue Water Consumption [kg]	3.69E-02
Impact Categories - REO Extraction (CMR)	**Material Impact / 1 kg**
TRACI 2.1 or lower, Acidification [kg SO2 Eq]	1.76E+00
TRACI 2.1 or lower, Ecotoxicity [CTUh]	1.26E+01
TRACI 2.1 or lower, Eutrophication [kg N]	1.67E-03
TRACI 2.1 or lower, Ozone Depletion[kg CFC-11-Eq]	3.50E-07
TRACI 2.1 or lower, Human Health- Carcinogenics [CTUh]	1.24E-01
TRACI 2.1 or lower, Human Health- Non-Carcinogenics [CTUh]	2.57E+02
TRACI 2.1 or lower, Human Health- Respiratory Effects, Average [kg PM2.5-Eq]	1.57E-02
TRACI 2.1 or lower, Global Warming [kg CO_2-Eq]	6.69E+00

Figure 8.1: The estimated impacts of transportation and ADR. Note that this key combination of processes enabled domestic recovery of REO. Numerical values of impact cannot be directly compared between recovery and primary production (shown in Figure 8.3). However, there is a decrease in impact in many categories. [6], [7], [8], [10]

Fig 8.2	TRACI DATA Results Summary — 1 kg Output for REO Virgin Material
Virgin Material Production: Impact / 1 kg of REO Production	
Impact Categories	**Material Impact / 1 kg**
TRACI 2.2, Acidification Air [kg SO2 eq.]	1.28E-01
TRACI 2.2, Ecotoxicity (recommended) [CTUe]	5.29E+00
TRACI 2.2, Eutrophication - Freshwater [kg P eq.]	3.67E-03
TRACI 2.2, Eutrophication - Marine [kg N eq.]	6.44E-02
TRACI 2.2, Human Health Particulate Air [kg pm2.5 eq.]	8.09E-02
TRACI 2.2, Human Toxicity, Cancer (recommended) [CTUh]	1.30E-09
TRACI 2.2, Human Toxicity, Non-Canc. (recommended) [CTUh]	1.05E-08
TRACI 2.2, Ozone Depletion Air [kg CFC 11 eq.]	2.16E-06
TRACI 2.2, Photochemical Oxidation Formation [kg O3 eq.]	2.44E+00
AWARE 1.2C, Global Average for Unspecified Water [m^3 world equiv.]	9.89E+00
Blue Water Consumption [kg]	2.30E+02
TRACI 2.2, Global Warming Air [kg CO_2e]	3.20E+01

- Recapturing process shows reduced climate impact by ~80% vs virgin production and reduced air-related impacts due to avoidance of mining and primary refining
- Higher impacts observed for the recapturing process in categories such as acidification and ecotoxicity are primarily driven by process-specific factors, including the electricity mix & chemical reagent inputs. These impacts represent optimizable hotspots rather than inherent limitations of REO recycling pathways
- Toxicity results are not directly comparable due to different TRACI LCIA methodologies
- Virgin REO production datasets may underestimate impacts associated with mining activities, tailings management (including radioactive residues), land use, and high energy intensity, which are not always fully captured in midpint-level LCA indicators

Figure 8.2 TRACI Data Results Summary - 1 kg Output for REO Virgin Material [6], [7], [8], [10]

Fig 8.3	REO Virgin vs Recapturing Total Impact			
REO Input-Output for 1,000 kg of HDD Shreds				
Ferrous Alloys Shred Input		**Recaptured Ferrous Alloys Output**		
Weight (Magnet)	**Weight (Magnet + Ferrous Alloy Fractions for CMR Processing) [kg]**	**Process Capture Rate of REE**	**Weight of Recaptured REO Produced [kg]**	**Ferrous Alloy Biproduct (ferrous alloy/non-REE fraction of magnet) [kg]**
1.03% of total 1,000 kg shreds	10.03	91.3%	3.2	7.1
Transportation				
Start Location		**Destination**	**Transportation Method**	**Distance Traveled (km)**
Paladin (St. Cloud, MN)		CMR (Boone, IA)	Truck	476.36
Ferrous alloy shred goes back to further downstream processor				
Emission Results for REO Input-Output for 1,000 kg of HDD Shreds				
Rare-Earth Elements Recapture from Electronic Waste: Techno-Economic & Life Cycle Analysis				
• Assessment conducted in Open LCA by using the ecoinvent database with the TRACI impact assessment method and various impact allocation methods [6] • Acid-free Dissolution Recovery (ADR) process used to produce 3.2 kg of REO from 200 kg of HDD shreds • Emission to produce 1 kg of REO: 6.3 kg CO_2e (95% percentile)				
Source of Emission				**kg CO_2e**
Emission for producing 1 kg of virgin praseodymium neodymium oxide				32
Emission for producing 1 kg of recaptured REO				6.2
Total emission for recaptured REO (Paladin processing % + CMR + transport) / 1 kg				6.33

Figure 8.3: Comparative life-cycle impacts of recaptured and virgin rare earth oxide (REO) production. Recapturing reduces climate and air-emission burdens, although there are trade-offs in certain impact categories due to process-dependent energy and chemical inputs. Results should be interpreted with methodological differences in toxicity assessment in mind, and primary production datasets may lead to underestimating mining-related impacts. [8]

Conclusion

Fig 9	Conclusion — Data Summary					
Output Material	Input Material Qty / Process / 1,000 kg Input (kg)	Output Material Qty / 1,000 kg Input (kg)	Adv. Recovery Impact / kg of Output Material (kg CO_2e)	Virgin Material Production Impact / kg (kg CO_2e)	Adv. Recovery Impact / Total Output for 1,000 kg Input (kg CO_2e)	Virgin Production Impact / Total Output for 1,000 kg Input (kg CO_2e)
Aluminum	750	690.00	0.65	18.60	445.12	12,834.00
Rare Earth Oxides	10.3	3.20	6.33	32.00	20.26	102.40
Ferrous Alloys	189.7	188.00	0.20	2.04	38.50	383.52
PCB (Cu, Ag, Au, Pd)	50	25.00	2.35	108.03	58.66	2,700.65
All Output	**1,000**	**906.2**	**Total Material Capture: 90.6%**			
Process		**Net CO_2e Impacts / 1 kg of Input Material**			**CO_2e Impact Reduction**	
HDD Recapturing		9.53			**94.07%**	
Virgin Material Production		160.67				

Figure 9: Shows the conclusion of the impact of virgin and recaptured materials

This white paper presents a scalable, collaborative HDD recycling solution developed by WD and REcapture that demonstrates how end-of-life hard disk drives can be transformed into a high-value domestic resource stream. The process recovers significant quantities of aluminum, ferrous alloys, rare earth oxides (REO), and precious metals from end-of-life shredded drives. A key enabler of this performance is the use of specialized shredding and mechanical separation systems at Paladin and CMR's selective leaching technology ideal for low-concentrated rare earth feedstocks producing high rare earth recovery rates (high purity (99.5%)) with lower environmental impacts.

An LCA comparing this recycling pathway to conventional virgin material production shows substantial environmental benefits. The process reduces total greenhouse gas emissions by approximately 94.07%. Across individual material streams, emissions reductions exceed 90% in most cases, including aluminum, ferrous alloys, and mixed precious metals, while rare earth oxide recovery achieves roughly an 80% reduction. In addition to climate, the recycling approach lowers impacts across most environmental categories, including air quality, water use, and human health indicators.

Beyond environmental performance, the study highlights the strategic importance of HDD recycling for supply chain resilience. Many recaptured materials, particularly rare earth elements, copper, and aluminum, are currently subject to high import dependency and geopolitical risk. By recovering these materials domestically, the process reduces exposure to trade disruptions and strengthens U.S. manufacturing security. The demonstrated workflow, combining mechanical separation, advanced acid-free dissolution (ADR) for rare earth recovery, and established refining networks, provides a replicable model for data center operators seeking to integrate circular economy practices into asset disposition strategies.

Hard disk drive recycling is no longer a niche sustainability initiative, but a scalable and economically and strategically relevant solution. The WD-REcapture collaboration demonstrates that end-of-life drives can be efficiently processed into high-purity materials suitable for reintegration into domestic supply chains, while achieving significant environmental impact reductions.

The model is particularly attractive because it leverages existing infrastructure: secure data destruction, materials sorting, and downstream refining, while integrating innovative technologies such as ADR to unlock rare earth recovery.

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Literature Cited

[1] United States Geological Survey. "About the 2025 List of Critical Minerals." Mineral Resources Program, U.S. Department of the Interior, www.usgs.gov/programs/mineral-resources-program/science/about-2025-list-critical-minerals. Accessed 26 June 2026.

[2] A. Shehabi et al., "2024 United States Data Center Energy Usage Report Energy Analysis & Environmental Impacts Division Citation," 2024.

[3] Coughlin, Tom. "How Has AI Changed Hard Disk Drive Storage Demand?" Forbes, 30 May 2026, https://www.forbes.com/sites/tomcoughlin/2026/05/30/how-has-ai-changed-hard-disk-drive-storage-demand/.

[4] N. T. Nassar et al., "Methodology and technical input for the 2025 U.S. List of Critical Minerals—Assessing the potential effects of mineral commodity supply chain disruptions on the U.S. economy," Open-File Report, vol. 2025, 2025, doi: 10.3133/OFR20251047.

[5] E. Sanchez Moran, D. Prodius, I. C. Nlebedim, and M. Mba Wright, "Rare-Earth Elements Recovery from Electronic Waste: Techno-Economic and Life Cycle Analysis," ACS Sustain. Chem. Eng., Sep. 2024, doi: 10.1021/ACSSUSCHEMENG.4C04100/SUPPL_FILE/SC4C04100_SI_001.PDF.

[6] J. C. Bare, G. A. Norris, D. W. Pennington, and T. McKone, "TRACI: The tool for the reduction and assessment of chemical and other environmental impacts," J. Ind. Ecol., vol. 6, no. 3–4, pp. 49–78, 2003, doi: 10.1162/108819802766269539/ABSTRACT.

[7] J. Bare, "TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0," Clean Technol. Environ. Policy, vol. 13, no. 5, pp. 687–696, 2011, doi: 10.1007/S10098-010-0338-9.

[8] ecoinvent Association. ecoinvent Database. ecoinvent, 2024, ecoinvent.org/database/. Accessed February-May, 2026

[9] Burns, Edward. Worldwide Hard Disk Drive Forecast Update, 2024–2028. IDC, Dec. 2024, doc. no. US52746924. (idc.com)

[10] TRACI 2.2 Citation: U.S. Environmental Protection Agency, Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) Version 2.2. Washington, DC, USA: U.S. EPA. [Online]. Available: https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci. [Accessed: Jul. 22, 2026]

[11]. M. Arshadi, S. Yaghmaei, and S. M. Mousavi, "Content evaluation of different waste PCBs to enhance basic metals recycling," Resour. Conserv. Recycl., vol. 139, pp. 298–306, Dec. 2018, doi: 10.1016/j.resconrec.2018.08.013.

[12] P. P. M. Ribeiro, I. D. Dos Santos, and A. J. B. Dutra, "Copper and metals concentration from printed circuit boards using a zig-zag classifier," Journal of Materials Research and Technology, vol. 8, no. 1, pp. 513–520, Jan. 2019, doi: 10.1016/j.jmrt.2018.05.003.

[13] F. P. C. Silvas, M. M. Jiménez Correa, M. P. K. Caldas, V. T. de Moraes, D. C. R. Espinosa, and J. A. S. Tenório, "Printed circuit board recycling: Physical processing and copper extraction by selective leaching," Waste Management, vol. 46, pp. 503–510, Dec. 2015, doi: 10.1016/j.wasman.2015.08.030.

[14] L. H. Yamane, V. T. de Moraes, D. C. R. Espinosa, and J. A. S. Tenório, "Recycling of WEEE: Characterization of spent printed circuit boards from mobile phones and computers," Waste Management, vol. 31, no. 12, pp. 2553–2558, Dec. 2011, doi: 10.1016/j.wasman.2011.07.006.

[15] N. A. Chowdhury, S. Deng, H. Jin, D. Prodius, J. W. Sutherland, and I. C. Nlebedim, "Sustainable Recycling of Rare-Earth Elements from NdFeB Magnet Swarf: Techno-Economic and Environmental Perspectives," ACS Sustain. Chem. Eng., vol. 9, no. 47, pp. 15915–15924, Nov. 2021, doi: 10.1021/acssuschemeng.1c05965.

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