

Value Recovery Project, Phase 2



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CONTENTS

PROJECT BACKGROUND AND PURPOSE

FOREWARD	2
Buzzards, Bugs and Bytes.....	2
EXECUTIVE SUMMARY	3
1. Background	4
Why hard disk drives?	4
HDDs as a source of scarce rare earth elements.....	4
Barriers to maximizing recovery.....	5
2. Scope of Project	7
Assembling the expertise	7
Project approach	8
Decision trees	8
iNEMI demonstration projects	14
References	15

DEMONSTRATION PROJECT 1: DIRECTLY REUSING HDD VOICE COIL MAGNET ASSEMBLIES IN NEW HDDS

EXECUTIVE SUMMARY	17
1. Scope of Demonstration	18
2. Background	18
3. Results	19
4. Conclusions	20
5. Recommendations/Next Steps	20
Acknowledgement	21
References	21

DEMONSTRATION PROJECT 2: REUSING HDD MAGNETS IN AXIAL FLUX GAP MOTORS FOR NON-HDD APPLICATIONS

EXECUTIVE SUMMARY	23
1. Scope of Demonstration	24
2. Background	24
Alternative supply of REEs	24
HDD motor design	25
3. Results	26
4. Conclusions	28
5. Recommendations/Next Steps	28
Acknowledgement	28
References	28

DEMONSTRATION PROJECT 3: MAKING MAGNETS FROM MAGNETS AND SHRED

EXECUTIVE SUMMARY	30
1. Scope of Demonstration	31
2. Background	31
The m2m [®] process	31
3. Results	32
4. Conclusions	34
5. Recommendations/Next Steps	34
References.....	35

DEMONSTRATION PROJECT 4: MAKING RARE EARTH OXIDES FROM HDD MAGNETS

EXECUTIVE SUMMARY	37
1. Scope of Demonstration	38
2. Background	38
3. Sources of Feedstock Materials	39
4. Results	41
Momentum MSX demonstration	41
Acid-free dissolution recycling technology	41
5. Conclusions	43
6. Next Steps	43

Acknowledgement	44
References	45

DEMONSTRATION PROJECT 5: CREATING A BUSINESS MODEL TO SUPPORT REUSE & RECOVERY

1. Scope of Demonstration	47
2. Background	47
3. Discussion.....	47
Data security	47
Accountability.....	47
Corporate social responsibility	49
Internal reuse	49
Remanufacturing companies.....	49
Cash recovery	49
Policies and processes	50
Pathways for value recovery from HDDs.....	52
Economic analysis of recovery options	54
Recovery steps and value streams	56
4. Conclusions	59
5. Recommendations/Next Steps	59
Acknowledgement	59
References	59

ENVIRONMENTAL IMPACTS OF HDD VALUE RECOVERY

EXECUTIVE SUMMARY	60
1. Scope of Demonstration	62
2. Background	62
3. Results	63
4. Conclusions	64
5. Recommendations/Next Steps	65
Acknowledgement	65
References	65

ROLE OF LEVERAGE IN ACHIEVING A CIRCULAR ECONOMY

EXECUTIVE SUMMARY	68
1. The Role of Leverage in Achieving a Circular Economy	69
2. Background and Strategic Assumptions	69
3. Five Chief Barriers to a Circular Economy of HDDs.....	70
Data security.....	70
Aggregation of quantities	70
Technical solutions	71
System-wide guidelines	71
Transboundary movement	71
3. Available Tools of Leverage	71
Technical documentation	72
Industry norms and voluntary agreements.....	72
Structured discourse and action.....	72
Purchasing specifications.....	73
Industry voluntary consensus standards.....	73
Who would develop and operate each of the leverage tools for HDD recovery?	74
An implementing organization	74
4. Conclusions and Recommendations – A Pathway to Success	75

PROJECT CONCLUSIONS

1. HDD Magnet Assemblies Can Be Effectively Harvested and Used to Build New Hard Drives .	77
2. HDD Magnets Can Be Directly Reused in New Motor Designs.....	77
3. New HDD Magnets Can Be Produced from Magnets and Coarse Shred.....	78
4. Rare Earth Oxides Can be Made from EoL HDD Magnets	78
5. Created Processes and Partnerships for Securely Wiping and Selling Functional HDDs to New Users.....	78
Conclusions & Next Steps	79

PROJECT BACKGROUND AND PURPOSE

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FOREWARD

Buzzards, Bugs and Bytes...

Nature thrives when a “circular economy” is stable. The stability of living things - homeostasis - is defined as when creation, life, death and back to creation again is supported by the external environment (water, weather, and human intervention such as pollution, over-consumption, climate change, etc.). It is the state to which the system naturally tends – a state of equilibrium and optimal use of resources. Not just existing but thriving. Electronics need to be created and used in this spirit. Know what is being made, nurture it through use but when it is no longer meeting our needs, implement a plan for taking it to the next stage of use and creation– the product, the components, the materials. Nature has agents to do this – buzzards and bugs that live in harmony in the ecosystem; electronic manufacturers need to do the same with their bits and bytes in the human-HDD ecosystem.

This work looks at the central aspects of creating a circular economy (CE) for hard disk drives (HDDs). The HDD is a common electronic component, integral to consumer and infrastructure data storage. HDDs are an essential part of the electronics eco-system and can be designed, built, used and reused in ways that support and extend the health of that eco-system.

Current typical practice of HDD product life cycle management is that a particular 2.5" or 3.5" HDD has one owner and then the data storage component (most often the complete drive) is shredded for material recovery (mostly aluminum). This is incredibly inefficient in terms of material recovery, with so many materials “e-wasted,” and is the worst-case scenario for recovering economic value of this resource.

This report illustrates how the many hundreds of millions of HDDs in the global economy can be used as “technical nutrients” in the reuse of HDDs and the creation of new HDDs or other products, thus maximizing value recovery over the working life of the HDD.

EXECUTIVE SUMMARY

The expanding demand for electronic products is good for the electronics industry worldwide but is also increasing resource consumption by products with intrinsically short lifetimes. Many leading electronics companies have started to modify their business practices to transform from a linear economy – based on the traditional linear “take-make-waste” model – to a circular economy that will return resources into the supply chain.

The International Electronics Manufacturing Initiative (iNEMI) has been bringing together stakeholders who acknowledge the components of sustainability – economic, environmental, societal – required to realize a circular economy for hard disk drives (HDDs). Using HDDs as a model, the members of iNEMI’s Value Recovery from Used Electronics project have been working to improve the economics of value recovery across electronic life cycles that can lead to conservation of resources while increasing profitability. The initial groundwork was laid in Phase 1, which identified the Ostrom Framework as a viable means of creating a circular economy for HDDs.

Key deliverables of the Phase 2 project were:

1. Demonstrate value recovery pathways necessary for an HDD circular economy
2. Develop decision-making tools for data wiping, life cycle analysis and logistics assessments, economic return on HDD resale, systems dynamics models for HDD stocks and flows for large-volume users of HDDs necessary to assess the sustainability of specific pathways
3. Identify barriers to reuse and develop a strategy to remove them

This report describes in detail how these deliverables have been met through five demonstration projects implemented by project stakeholders. Project conclusions and recommended next steps are discussed. Based on the results of this project, the iNEMI team members have been discussing the formation of a third phase of the project to broaden the implementation of these pathways and to build more robust supply chains for value recovery.

1. Background

Phase 1 of this iNEMI project identified an opportunity for systematically increasing the value of HDDs, a common electronic component, via application of the Ostrom Framework [1]. This framework seeks to optimize the economic outcome for common pool resources that many people rely on for their livelihoods but that are often ignored, mismanaged or exploited to the great detriment of the “commons” (which is all of us). The Phase 1 report [2] focused on optimizing value recovery because it was inherently understood that a financial outcome must be favorable to ensure sufficient incentive for management of the resource in a self-sustaining manner. To accomplish this goal, Phase 2 participants created a multi-stakeholder project comprised of university, OEMs, national labs, end-of-life providers, enterprise data managers, start-up entities and NGOs. This team worked together to maximize value recovery of HDDs as common pool resources via the Ostrom Framework.

Why hard disk drives?

HDDs are good candidates for a circular economy because they have a standard form factor (2.5" or 3.5"), consistent manufactured design, and the market demand for data storage is outpacing the ability of HDD and SSD manufacturers to keep up with demand. There are a number of ways to fill this gap: continued investment in fabs and technologies, increased HDD reliability, and increased reuse of used HDDs and their subsystems so that they are available to meet some of our global data storage needs.

The secondary market for HDDs is flourishing by data wiping and reselling millions of functioning HDDs per year. However, there are severe barriers that keep reuse and recovery far lower than what could potentially be returned to the market. The most significant barriers are perceived data security risks, technological challenges in HDD separation, and the lack of coordination of stakeholders in the supply chain. Most notably, users frequently demand physical destruction even when complete, verifiable data wiping is possible economically and logistically. This leads to widespread HDD shredding, which precludes reuse of the HDDs, harvesting of components for reuse, and recovery of trace — but critical and strategic — materials.

HDDs as a source of scarce rare earth elements

Another advantage of developing a circular economy around HDDs is that they contain rare earth elements (REEs), which are critical for development of many high-tech products. REEs are buried as magnets within electronic products and are used not only in computers, cell phones and HDDs, but are also needed to manufacture electric motors, wind turbines, electric vehicles, aircraft, etc. Permanent magnet manufacturing consumes large quantities of REEs and demand is increasing with the proliferation of electric vehicles and other “green” technologies.

Although REEs are not rare per se, sources for minable concentrations are limited. As a result, there are very limited REE mining operations [3]. REEs are being consumed at a rate that simply cannot be maintained over the long term. Reserves of both the light and heavy rare earths will eventually be exhausted if global markets continue to deliver more and more high-tech products like permanent magnets, based on newly mined and refined rare earths, to the world’s expanding consumer base.

A critical review by Binnemans et al. [4] confirms that REE recycling can both mitigate the supply chain risk and reduce the environmental challenges associated with REE mining and processing. Even though recycling presents a viable opportunity for recovering REEs from waste and can be a source of secondary feedstock for REEs, the current level of REE recycling is still insignificant (<1%), which is likely due to

the difficulties associated with recycling REEs [5]. Both the cyclical nature of the instability in the prices of REEs and the typical low concentrations in end-of-life materials make recycling of REEs less appealing, particularly when prices are low.

The creation of new processes and business models to enable new material flows that work in a closed loop, reclaiming used parts is a challenge for the REE recovery path. In the case of HDDs, the supply chain relationships are unusually mature and highly developed (20-30 years) meaning, in part, that component and subassembly costs have been pared continuously, making it extremely challenging to become cost-neutral when new processes are developed. In addition, there are only three HDD OEMs globally, so the supply chain relationships needed for HDDs are limited.

Permanent magnet materials represent readily available and accessible feedstock materials for recycling REEs because they consume significant amounts of REEs, compared with many other applications [5]. For example, most of the global production of praseodymium, neodymium, samarium and dysprosium are used for magnets. Permanent magnets are used in large quantities for HDD production and can easily be harvested and recycled for the REE content. Nguyen et al. reported that recycling permanent magnets used in the United States alone could meet >5% of the REE demand for neodymium-iron-boron (Nd-Fe-B) magnet production for the rest of the world (excluding China) [6].

In this Phase 2 project, the team was able to successfully demonstrate five different options to reclaim and reuse REEs from HDDs:

- Logistics, economics, and business models for HDD wiping and reuse
- HDD magnet assembly removal and reuse
- Intact magnet recovery for non-HDD use
- Making magnets from recovered magnets and shred
- Making rare earth oxides from HDD magnets and shred

These demonstration projects are discussed in detail in later sections of this report.

Barriers to maximizing recovery

Reuse and recycling systems are built to extract valuable resources through product reuse and recovery and, as private businesses, they exist to generate revenue. Societal and/or environmental value and resource recovery cannot be improved in the absence of financial gain.

One of the weaknesses of the current recycling system for HDDs is that recovery is stove-piped and generally limited to only a few options. Individual recovery operators focus on a subset of opportunities, based on their core expertise, experience, and economics. However, for HDDs there are multiple, quite different value generating pathways, and it is likely that few recycling facilities are currently equipped to use all of them. That means that value recovery, i.e., potential financial revenue, is being left on the table, with negative environmental and societal effects.

Figure 1 shows the combination of diverse subsystems and materials that are contained in an HDD and are available for reuse, first, as an intact functioning HDD, and later, if non-functioning, for component and materials recovery downstream. In Phase I of the project, a small survey was conducted to better understand

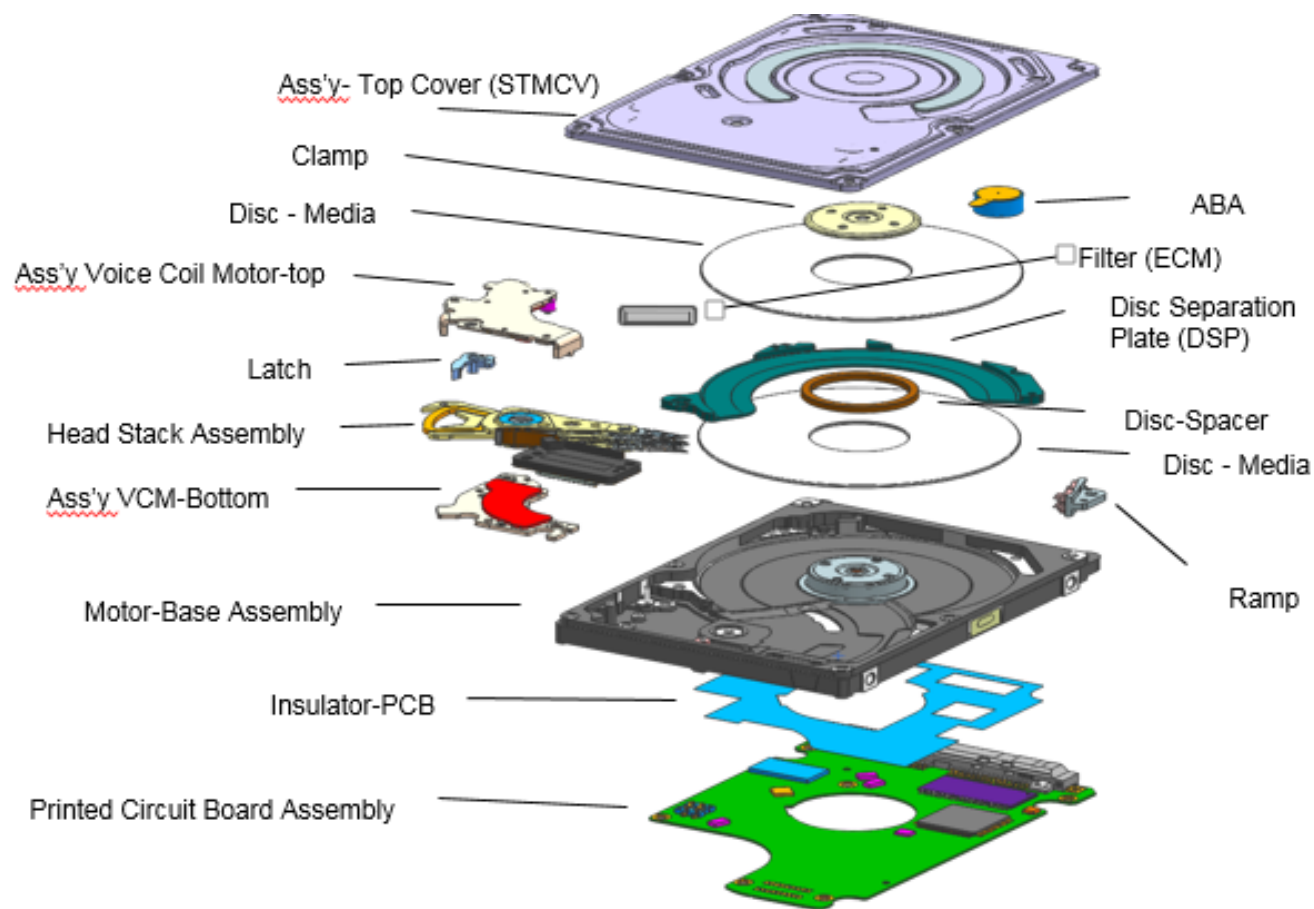


Figure 1. The hard disk drive.

current practices, barriers to greater recovery and economic viability, and the willingness of community stakeholders to change to other options if they became available. The survey included an HDD manufacturer, HDD users (3), used HDD processors (9), recyclers (7) and researchers and others (11). One key line of questioning explored what they saw as barriers to increasing recovery of resources from HDDs. Table 1 summarizes the barriers identified.

Table 1. Barriers to Maximizing Recovery Value

- Demand by last user for physical destruction, eliminating disassembly and reuse options
- Lack of reliability assurances of data wiping
- Economically viable collection
- Expense of dismantling
- Lack of standardization of parts or quality standards for reuse

Two barriers that are interconnected stood out in the survey. First is that the requirement of shredding for data destruction for some drives can affect the processing for all drives. Many drives that do not require a high level of security are sent to the shredder, which eliminates any opportunity for higher level value recovery from reuse, component reuse, or trace metal recovery other than of gold, aluminum and iron. The second is verification that data wiping has been performed. Data wiping of functioning used HDDs works, but there must be processes and infrastructure in place to verify that the wiping has been performed correctly given the absolute need to assure data privacy. The last three barriers identified in the survey were all related to having economically viable options and the knowledge to identify and apply them. A final result of the survey was that recyclers and other members of the HDD supply chain were open to implementing new options if they were economically viable. These results were important inputs into Phase 2 of the iNEMI project.

2. Scope of Project

Assembling the expertise

iNEMI brought together a team of individuals and organizations who not only represent the full supply chain for value recovery for HDDs, but also the wide range of expertise and creative thinking needed to address this multi-dimensional challenge of value recovery from HDDs. The specific stakeholders who participated in the Phase 2 project include:

- HDD original equipment manufacturer (OEM) (Seagate Technology, and through them, magnet manufacturers)
- OEM of electronic products containing HDDs (Cisco)
- Large cloud service providers (Google, Microsoft)
- IT asset management companies (Teleplan, Geodis, Cascade Asset Management, Echo Environmental and, through them, smelters)
- Metals and magnet value recovery (Urban Mining, Momentum Technologies)

- Major research institutions (the DOE Critical Materials Institute, Ames Laboratory, Idaho National Laboratory, Oak Ridge National Laboratories, Purdue University)
- Electronics ecolabeling organization (Green Electronics Council)

Project approach

A goal of Phase 2 of the iNEMI Value Recovery project was to create opportunities to cooperate by providing the information needed for businesses to make the most value-generating decisions for used HDDs. These products embody a variety of characteristics including manufacturer, age, condition, wishes of last user, etc. A series of decision points, based on individual unit characteristics, with appropriate parameters and tests, can direct units down the optimal pathway for value recovery.

The project focused on three key activities:

1. Constructing a set of decision trees to identify the options (pathways) for value recovery in the context of a circular economy and what information each of the stakeholders needs to pursue higher value recovery along a given pathway.
2. Developing the economic models, life cycle assessments and logistics models to determine which value recovery options generated the highest value/profit by type and size of drive. These models then become the basis for business decision-making by the stakeholders, both individually and collectively, as part of supply chains.
3. Conducting demonstration projects for critical-to-market circular economy pathways.

Decision trees

Value recovery is based on people and companies making decisions about what options to choose. The project team used decision trees to explicitly define the choices that are being made, who makes them, and what additional options are available for value recovery. Understanding and quantifying the analyses going into the decisions being made are key to unlocking opportunities. The decision tree shown in Figure 2 shows the most widespread value recovery pathways for HDDs, as identified in Phase 1.

Each decision point in the processing chain (shown in red) represents an opportunity to maximize value recovery. The first decision point frequently begins with negotiating with the HDD owner on disposition, where the decision “to shred, or not to shred” is frequently determined before the drives are even received based on either security concerns or economics.

For example, if shredding is determined to be the only allowable option, even if the economics of wiping and reuse are favorable, this is identified as decision point (1). Sometimes, circuit boards are removed before shredding for more effective recovery of precious metals, such as Au (2); however, many drives are shredded directly. After shredding, the only remaining value recovery option is to send the shred for mixed aluminum recycling and, where possible, Au recovery (3).

If wiping and reuse are allowed, then orders of magnitude higher revenue may be possible from selling the drives. An outline of the information required to make an informed decision about what options can be followed, based on economics, is shown in Figure 3. If the economics of recovery are not favorable even if reuse is allowed, the drives will be shredded, as will drives that do not pass the SMART test, a functionality test showing working HDD capacity and performance (4). For the HDDs that pass the SMART test and for

which resale is economically favorable (5), the final two value recovery options are wiping the drive and reselling it with the capacity of the drive being the original capacity or at a different capacity as a “white label” drive (6).

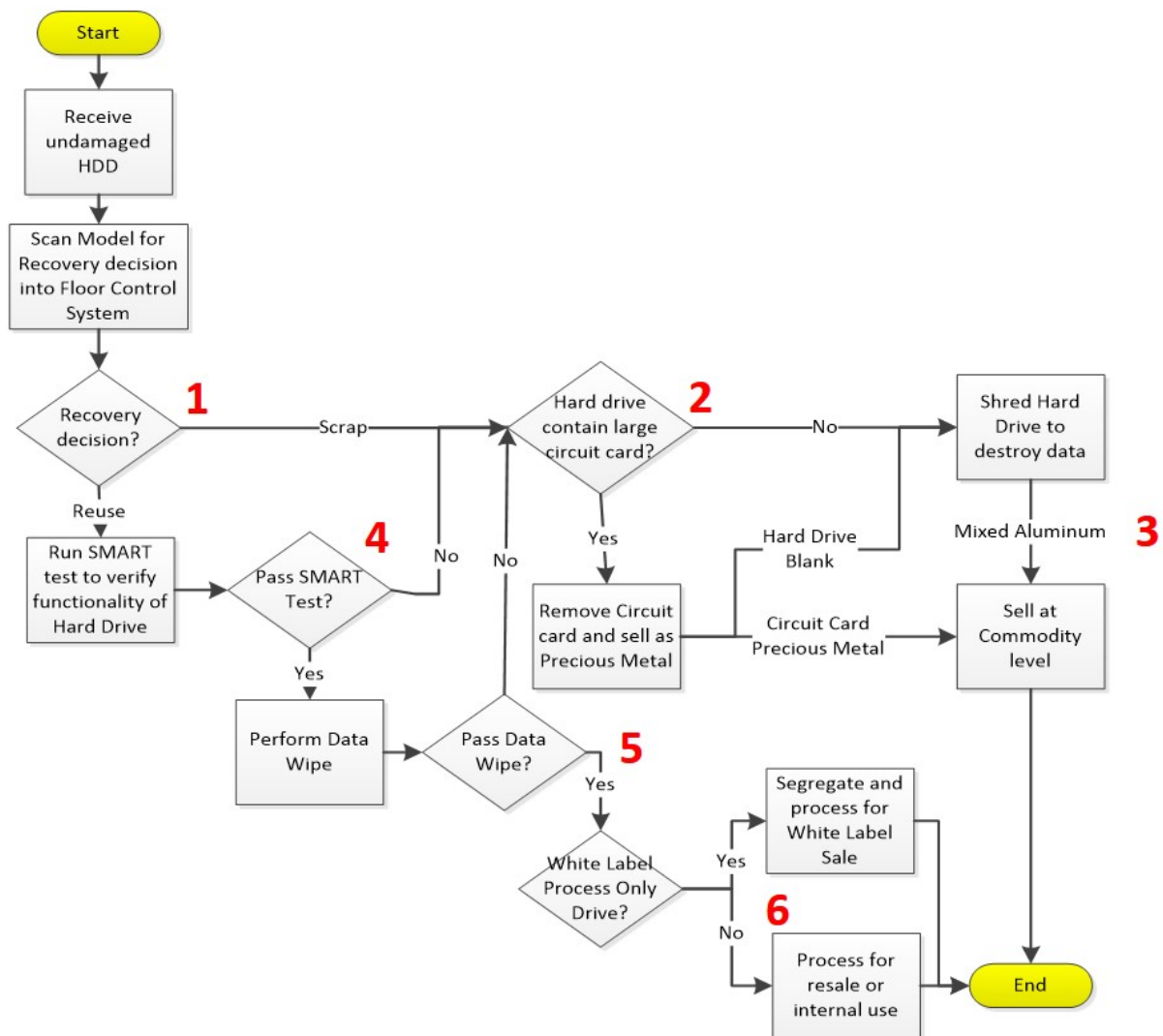


Figure 2. Decision tree for common practices in HDD value recovery.

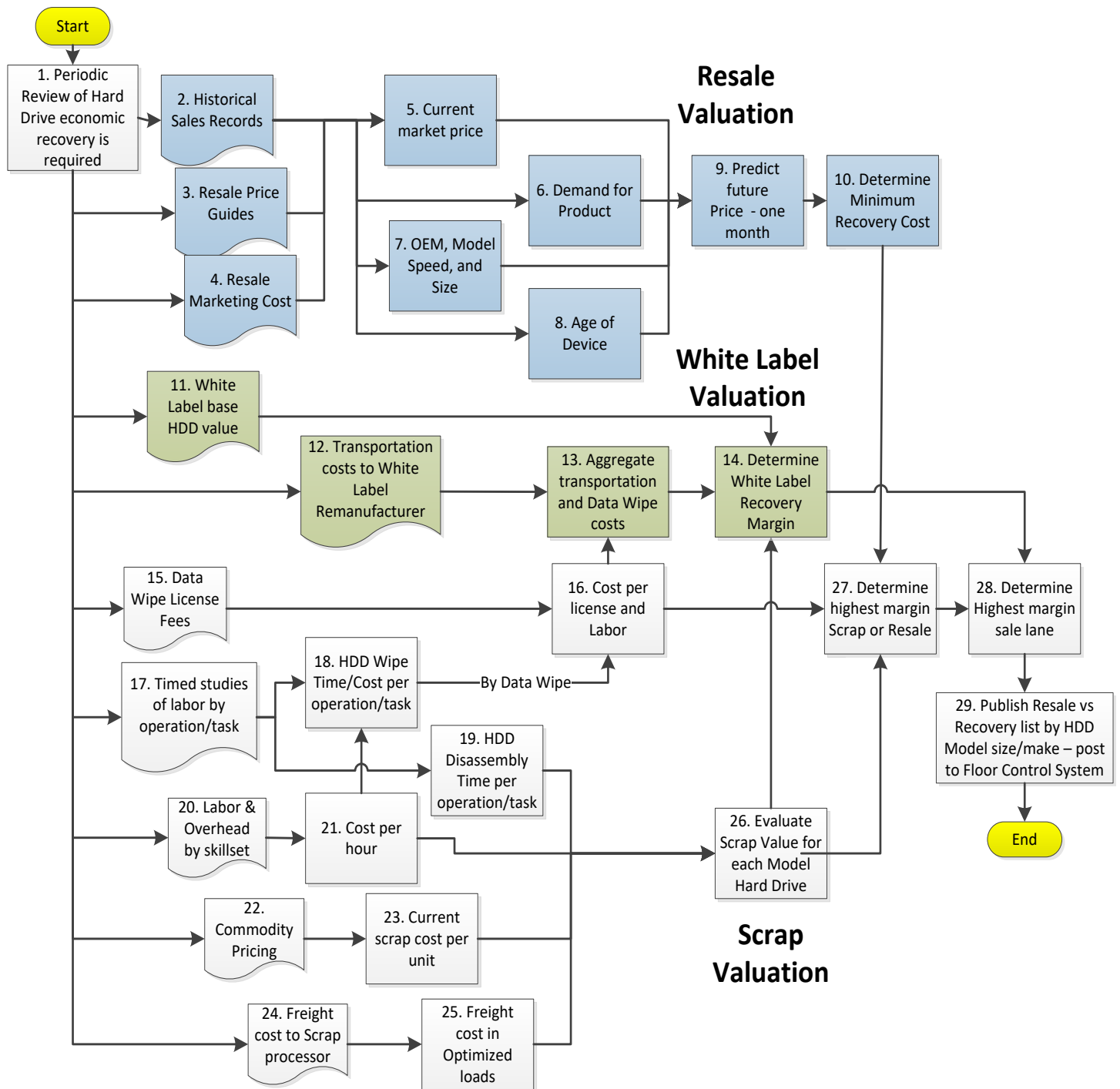


Figure 3. Economic model for value recovery decision-making in Phase 1 corresponding to the options shown in Figure 2. (Blue boxes indicate the pathway for OEM-labelled HDDs that can be performed in-house; green is for white label HDDs that are outsourced to the authorized aftermarket service provider.)

In Phase 2, the project team created an expanded decision tree for the pathways needed for a circular economy (CE) for HDDs (Figure 4). The original decision tree in Figure 2 and the expanded decision tree from Phase 2 shown in Figure 5 can be directly mapped into the CE pathways. The viability of these pathways is quantified by economic modeling, life cycle analysis, and logistics analyses as presented below. The CE system for hard disk drives in Figure 4 focuses at a high level on value recovery after the first use of an HDD.

Pathway (1) in Figure 4 is focused on maintaining and prolonging the use of an HDD for the first user or the first user's organization. This is common corporate practice and, as such, does not require any further development or outside support to increase value recovery over common practice. For this reason, the path was not investigated in this project.

Pathway (2) – to wipe and reuse/redistribute/resell functioning, data-wiped HDDs – has been an important part of the iNEMI project in removing the barriers to wiping and reuse/resale. Millions of full functioning state-of-the-art drives that could be wiped and sold to the secondary market are not because HDD owners decide to shred them for a variety of reasons. Those reasons range from the mistaken belief that all HDDs must be shredded, crushed, or otherwise physically made unreadable to ensure data security due to an uncertainty that available wiping systems and the people operating them are not controlled enough to ensure that all data have been removed from all drives.

Reuse provides the highest value recovery for functioning drives and is used when the logistics and supply chains for wiping are controlled. Many large data centers, cloud and Internet service providers replace their HDDs while still under warranty to increase data center capacity without increasing facility size. This means that millions of high-capacity, state-of-the-art, under-warranty drives could be available for wiping and resale every year if proper controls were in place to verify that the data wiping had been performed properly. This pathway corresponds to decision points (4), (5), and (6) in Figure 2.

Circular economy pathways (3) and (4) in Figure 4 are embodied in all the pathways and decision points in Figure 5 which support value recovery from non-functioning drives and drives that cannot be wiped and reused.

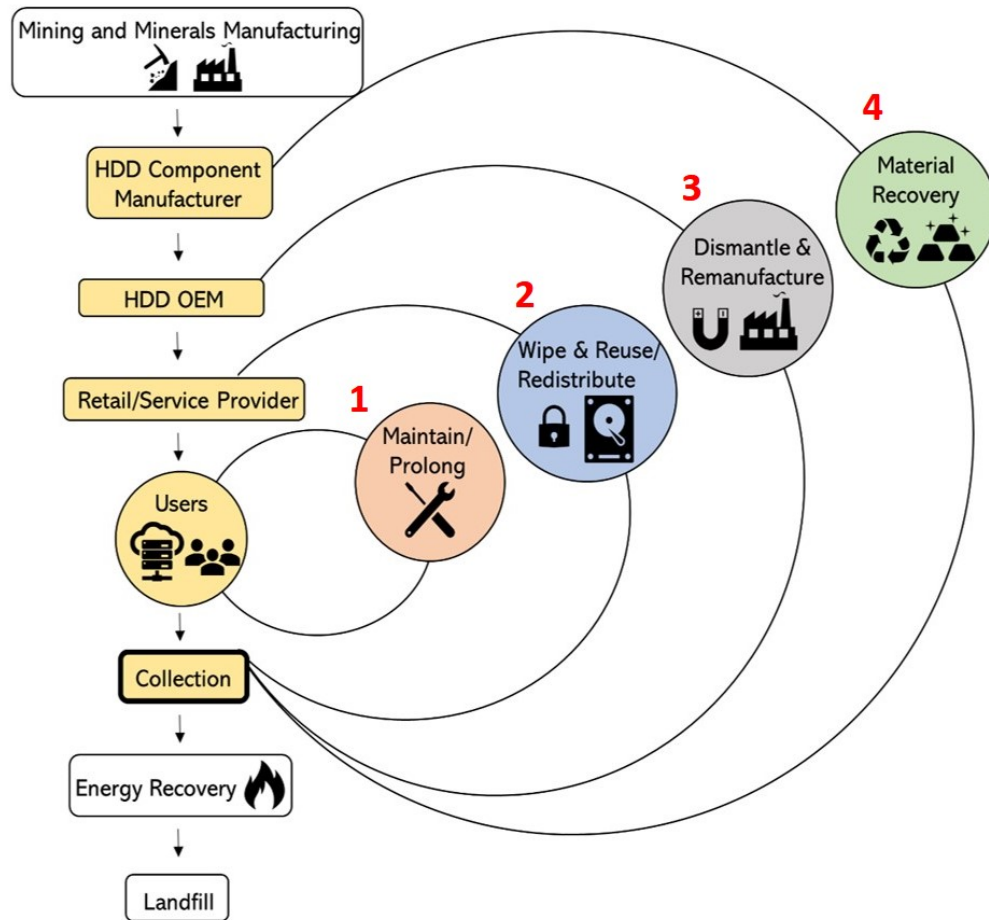


Figure 4. Circular economy schematic for hard disk drives, derived from general schematic from the Ellen MacArthur Foundation.

The decision tree in Figure 5 covers value recovery from rare earth-containing magnets, circuit board recovery, Au recovery, and Al recovery from non-functioning HDDs or drives that are not wiped and resold. In Figure 2, the only non-reuse pathway available was shredding followed by mixed Al recycling, with some pre-shredding removal of circuit boards. Now there are four uses for recovery of REE-containing material, with multiple technologies available for each pathway. In this project all four uses were demonstrated with multiple technologies and functioning prototype supply chains. The first pathway (1) enables recovery of magnet assemblies through dismantling or punching for use in new or remanufactured HDDs. Pathway (2) allows for the magnets to be used in non-HDD applications, not a “circular” pathway for HDDs, but allows the magnets to be used as high-value-added products. Pathway (3) allows for magnets to be processed into magnet powder and remanufactured into magnets for HDDs and other uses. Pathway (4) produces rare earth oxides and metal that can be used to manufacture new magnets without mining.

Decision Matrix – Magnet Focused recovery V11

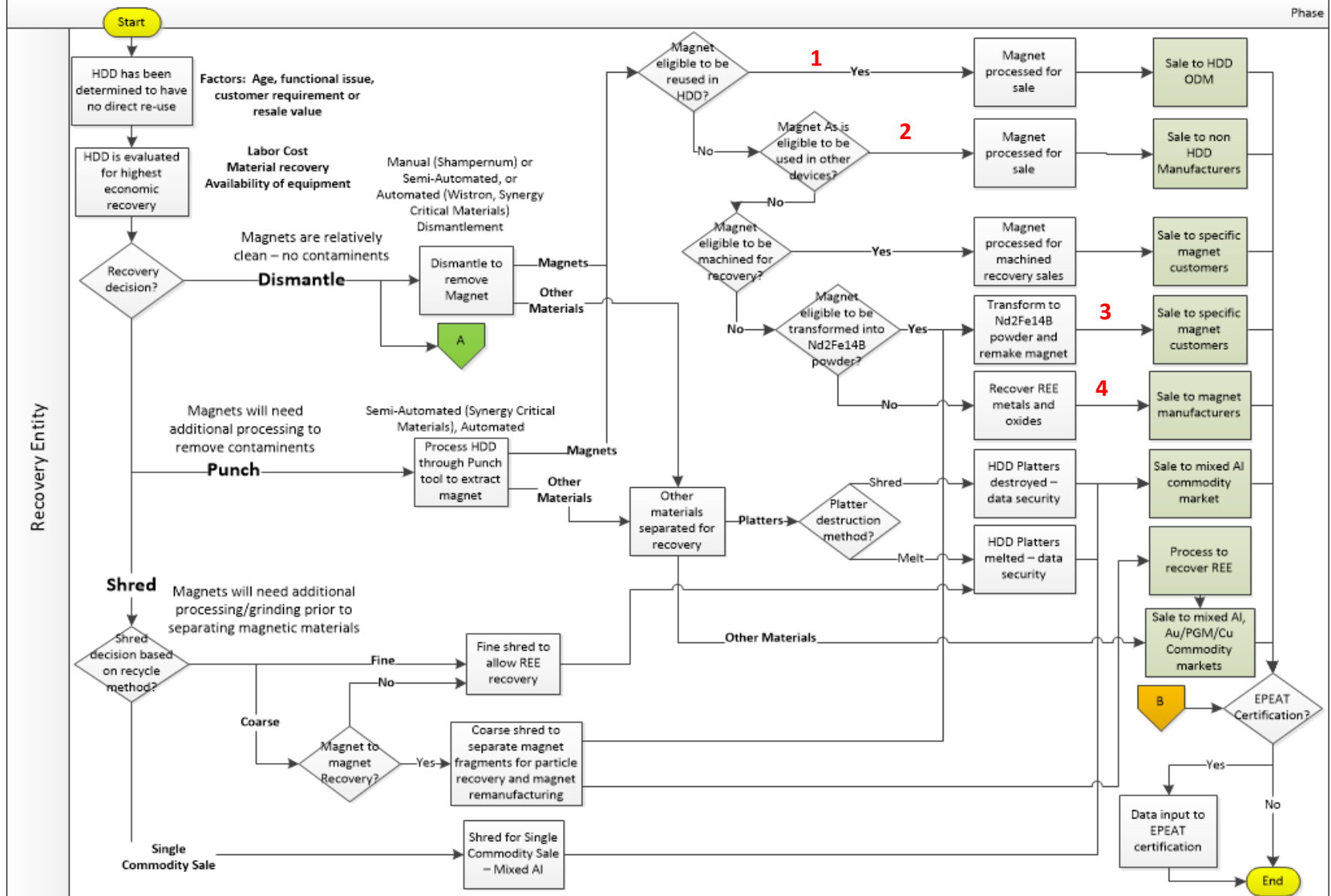


Figure 5. Decision tree for value recovery from non-functioning hard disk drives or drives that will not be wiped and resold. This decision tree replaces the single pathway seen in Figure 2. (A and B are the start and end Points for other material recovery, as shown in Figure 5 of the Demonstration Project 5 section.)

iNEMI demonstration projects

Through five demonstration projects, the iNEMI Value Recovery team delved deeply into some of the toughest challenges in creating new pathways for value recovery. For these demonstrations, team members formed prototype supply chains with authentic product and materials hand-offs to demonstrate these CE technologies. The goals and outcomes of each demonstration project are presented in Table 2.

Table 2. iNEMI Demonstration Projects: Pathways to a Circular Economy for Hard Disk Drives

Focus	Goals	Outcome/Lessons Learned
DEMONSTRATION 1 <i>HDD magnet assembly reuse</i>	Implement a process for harvesting a voice coil magnet assembly (VCMA) that contain rare earth magnets from a used enterprise hard drive at an electronics recycler and place back into a new hard drive on the OEM production assembly line	<ul style="list-style-type: none"> Conduct a trial build of HDDs containing used magnet assemblies Although technology already exists to reuse magnet assemblies <i>within</i> an HDD OEM, engaged supply chain partners and process innovations are required to make the reuse of externally sourced VCMA's viable at a large scale
DEMONSTRATION 2 <i>Intact magnet recovery for non-HDD use</i>	Determine if magnets recovered from a punching process can be reused as a magnet powder or as an intact magnet	<ul style="list-style-type: none"> Develop new designs for motors, actuators, etc. for the direct reuse of HDD magnets in non-HDD high value-added applications
DEMONSTRATION 3 <i>Making magnets from magnets and shred</i>	Demonstrate technology and supply chain for recovering magnets from end-of-life HDDs for reprocessing into new magnets using the Urban Mining Company's m2m® (Magnet-to-Magnet®) recycling process	<ul style="list-style-type: none"> A mix of used HDDs was collected from project members and processed into new sintered magnets with magnetic properties similar to those used in HDDs
DEMONSTRATION 4 <i>Making rare earth oxides from HDD magnets</i>	Prove technology for recovering magnets from end-of-life HDDs for processing into rare earth oxides using a membrane solvent extraction process	<ul style="list-style-type: none"> A mix of end-of-life HDDs was collected from various contributing partners and processed into high purity rare earth oxides (e.g., neodymium, dysprosium) for reuse in REE magnets
DEMONSTRATION 5 <i>Changing the paradigm from "limited reuse and widespread shred" to "widespread reuse and widespread recovery"</i>	Identify and remove barriers to switching from reuse or shred to reuse and recover	<ul style="list-style-type: none"> Data wiping (cryptoerase/NIST wipe) works. Verification processes are required to minimize risk to an acceptable level Map the roles of business models and relationships within the HDD recovery economy Life cycle assessment and techno-economic analysis are useful tools for assessing and justifying a particular value recovery pathway

Subsequent sections in this report describe the underlying framework for how the project was organized to enable the CE goals to be achieved and the structure and results of the five demonstration projects which were identified as integral to realizing a CE supply chain for managing this valuable resource in an economically sustainable way. Each pathway has its own set of unique drivers and boundary conditions that must be satisfied to construct a working, high-value outcome. To the project team's knowledge, this project is the first of its kind to prototype supply chains with authentic product and materials hand-offs to demonstrate the reuse of HDD magnet assemblies from post-consumer HDDs to build new HDDs and to build motors or other articles from recovered (whole) HDD magnets. Today's common practice for HDD recycling results in millions of drives being unnecessarily shredded and thus unavailable for resale and reuse and a complete loss of the rare earth oxide metals during mixed Al recycling. The project team sought to change that by systemically mining the "waste" HDDs for recovery of the rare earth magnetic materials – either as intact assemblies, magnets, rough shredded magnets, punched magnets or shredded HDDs. Again, these demonstration projects are highly significant as none of these processes, with the exception of magnet-to-magnet (Demo 3), are currently commercially available. The hope is that the approaches demonstrated will be implemented at scale by global supply chains and used to maximize the material and economic value recovery of the millions of HDDs that are "e-wasted" every year.

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DEMONSTRATION PROJECT 1: DIRECTLY REUSING HDD VOICE COIL MAGNET ASSEMBLIES IN NEW HDDS

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EXECUTIVE SUMMARY

This proof-of-concept demonstration harvested rare earth voice coil magnet assemblies (VCMAAs) from used hard disk drives (HDDs) at an electronics after-market services provider and built them into new HDDs on the HDD OEM production assembly line. HDD VCMAAs were effectively harvested and used to build new drives of a model utilizing the same magnet assembly part number. This new circular path for HDD components required process innovation in the supply chain beyond today's existing material flows to make this reuse of VCMAAs (sourced from partners outside the HDD OEM) viable for this demonstration and at a large scale. A preliminary analysis also quantified expected environmental impact reduction and a viable cost range for production. Next steps would include scaling builds to demonstrate yields, reliability and commercial viability to make direct reuse of rare earth magnets in new drives a value recovery path in the global supply chain.

1. Scope of Demonstration

This first proof-of-concept demonstration recovered voice coil magnet assemblies (VCMA) containing rare earth elements (REEs) from post-consumer drives and used them to assemble new drives. This new, circular path for HDD components consisted of removing VCMA from used Seagate Enterprise Makara drives from a large enterprise user (Google) at an electronics after-market services provider (Teleplan) and assembling them into new drives back on the HDD OEM (Seagate Technology) production line. Doing so required creating a new process beyond existing material flows to enable reclaiming used parts outside Seagate. It also required an inventory mechanism for the reused parts to be placed in new drives on Seagate's production assembly line. In this demonstration, expected environmental impact reduction relative to business-as-usual and a viable cost range of production were also quantified based on preliminary environmental and cost analyses.

2. Background

A critical review by Binnemans et al. [1] confirms that REE recycling can both mitigate the supply chain risk and reduce the environmental challenges associated with REE mining and processing. A potentially higher level of circularity with environmental and economic benefits could be realized by reclaiming REE VCMA from post-consumer HDDs for direct reuse into new drives. This reuse path is feasible as the VCMA does not require further processing, other than harvesting from drives at the end of their lives and cleaning before use in new drive assembly.

Figure 1 shows a schematic representation of the comparison between business-as-usual and the VCMA reuse path conducted in a preliminary environmental analysis of this project.

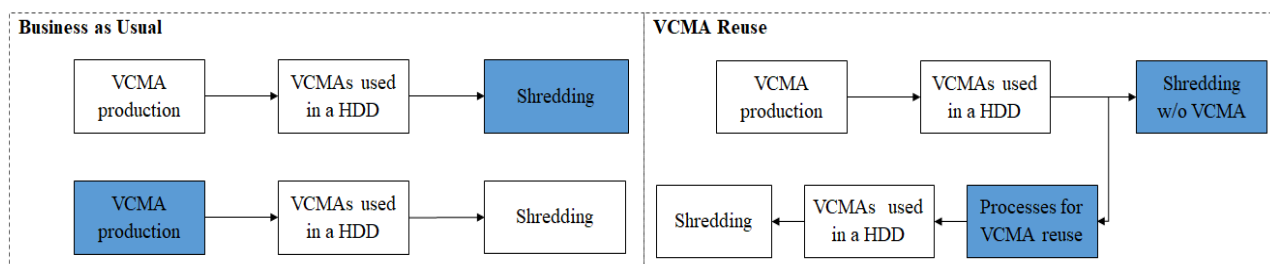


Figure 1. Comparison between business-as-usual and VCMA reuse in preliminary environmental analysis.

The business-as-usual case was modeled as two identical open-loop material flows, consisting of VCMA production, and VCMA use and shredding of post-consumer HDD containing the VCMA. The two VCMA life cycles were considered because VCMA must first be produced in order to be reused. The VCMA reuse scenario was modeled as a partially closed-loop material flow, assuming one additional life cycle of VCMA by reusing them. The blue boxes highlight major differences in key processes between the two cases. Some common processes, such as transportation and HDD data wipe, are aggregated and not explicit in this process diagram. Processes unique to the VCMA reuse case include: transportation of HDDs from a data center in the United States to Teleplan in Malaysia, sorting and retrieval of VCMA, placement of VCMA into special trays, shipment of trays to Thailand, and CO₂ cleaning of VCMA prior to assembly into a new HDD.

From an engineering perspective, the VCMA is a good candidate for reuse because the technological feasibility of VCMA reclamation and reuse is well established within the HDD industry. Furthermore, modification or change of part numbers is not required in order to reuse the VCMA within a drive model family. This is also key for lowering the economic and logistical barriers for reuse at the OEM, because preparing the VCMA for reuse does not require modification of engineering processes.

The creation of new processes and business models to enable new material flows that work in a loop reclaiming used parts is, however, a challenge for this REE recovery path. The HDD supply chain relationships are unusually mature and highly developed (20-30 years), meaning in part that component and subassembly costs have been pared continuously making it extremely challenging to become cost-neutral when new processes are developed. This demonstration is a first trial by key stakeholders in the HDD value chain — Seagate, Teleplan and Google — that embraced the challenge and learned from testing new processes for reclaiming and reusing VCMA's from post-consumer drives in new drives. This demonstration also provided multi-stakeholder engagement, internal and external to the organizations, which can be leveraged for future pilots.

3. Results

This proof-of-concept demonstration project successfully created and tested a recovery path for reclaiming REE magnet assemblies from used HDDs via a new trial process in the value chain between the HDD enterprise user, the OEM's after-sales services provider and the OEM's new production. Key results from this practical demonstration include:

- Assessed HDD magnet assembly removal processes in a clean room (CR) environment
 - Factors considered included CR rating (Class 100 was used), cost, and number of manual vs. semi-automatic steps.
- Conducted magnet assembly removal trials at Teleplan
 - Tested “candidate” processes, with specific attention to potential for part damage and contamination in staging.
 - Class 100 benchtop process was developed for magnet removal. This process would likely further evolve for large-scale demonstration or production.
- Confirmed engineering and manufacturing processes are ready for production
 - No further engineering process development is necessary in order to move forward into yield and reliability builds.
- Developed a trial part number reclaim process at Seagate for reclaiming used VCMA's and other parts in post-consumer HDDs from external partners outside Seagate and using them in new drives. This required unique business processes:
 - Transport and intake of reclaimed post-consumer parts. A crucial factor hampering reclaim process development is legislation restricting transboundary movement of e-waste/scrap and associated tax penalties. The restrictions on movement and the tax burdens result in narrower (and less cost-effective) options for material transport.
 - An inventory mechanism to allow placing reclaimed post-consumer parts into new drives.
 - These processes must be further developed in order to plan a large-scale demonstration or production.

- Process, energy and materials data collection and scenario modeling for quantifying environmental gains from direct reuse of magnet assembly relative to business-as-usual
 - Life cycle analysis (LCA) was conducted to compare the environmental performance of reusing VCMA sets with business-as-usual. System boundaries are as shown in Figure 1 and primary data was collected from Seagate, Teleplan, Geodis, Cascade Asset Management and literature [2, 3].
 - Preliminary LCA results showed that direct reuse of magnet assembly saves 6 kg of CO₂ eq. emissions, measured by the difference between business-as-usual and VCMA reuse highlighted in blue in Figure 1. The saved emissions represent 96% of the global warming impact of one virgin VCMA set (one top and one bottom). However, if post-consumer HDDs are to be transported by air for a long distance (e.g., U.S. to Malaysia) with the sole purpose of reusing VCMA sets, it would actually increase the global warming impact of VCMA by emitting 4.8 kg more CO₂ eq. emissions than the virgin production route. These preliminary results should be interpreted with the awareness that they are subject to the system boundaries defined in Figure 1, assumptions made, and data used. More detailed information will be available in Jin et al. (in preparation) [4].
- Preliminary cost modeling with hourly wage and throughput assumptions
 - Estimated \$1.50 per VCMA set for manual disassembly, which is within a viable cost range for production.

4. Conclusions

This project demonstrated for the first time that HDD magnet assemblies can be effectively harvested at the end of an HDD's working life and used in building new hard drives of a model utilizing the same magnet assembly part number. A preliminary analysis quantified expected environmental impact reduction and a viable cost range for production. There were also key business and value chain process learnings in this demonstration, which included the need to address tax and material transport restrictions associated with transboundary shipments of recovered components to achieve and maintain required cost and quality targets. Close partnering between the HDD manufacturer and scrap HDD reclaim provider is required to ensure successful disassembly and magnet assembly reuse in a production setting by the HDD manufacturer, in this case Seagate and Teleplan.

5. Recommendations/Next Steps

The recommendation to move forward with a large-scale demonstration and production process is made with confidence. Steps that will be necessary to do this include:

- Refine HDD sorting criteria to identify candidates for VCMA reclamation
- Continue development of business processes and create controlled process documents
- Scale builds sufficiently to demonstrate yields and reliability, and ultimately, economic and commercial viability

Acknowledgement

We appreciate the contributions and significant efforts of the demonstration project members through all phases. Special thanks go to Wade Fott of Seagate, without whose crucial communications and business process knowledge the demonstration would not have become a reality. K.M. Lee of Teleplan also provided outstanding support and communication as we navigated process decisions. His deep experience and knowledge of HDD technology were also critical to the success of this demonstration. This work was supported, in part, by the Critical Materials Institute, an Energy Innovation Hub funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, and the NSF Purdue-Tuskegee IGERT Program: Global Traineeship in Sustainable Electronics (DGE Grant #1144843).

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DEMONSTRATION PROJECT 2: REUSING HDD MAGNETS IN AXIAL FLUX GAP MOTORS FOR NON-HDD APPLICATIONS

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EXECUTIVE SUMMARY

Permanent magnets containing rare earth elements (REEs) are in high demand due to expanding electric vehicle and green energy technology markets. The United States currently relies almost exclusively on foreign REE suppliers to obtain these essential permanent magnets and other REEs. REE magnets are needed to manufacture electric motors, computers hard disk drives, wind turbines, electric vehicles, aircraft, etc. Production of each of these items is at risk due to supply disruption or price spike. Additionally, green energy technology expansion may be limited because of foreign supply disruption. For this reason, Critical Materials Institute (CMI) researchers at Oak Ridge National Laboratory (ORNL) and Ames Laboratory (Ames Lab) are developing electric motors by directly reusing REE permanent magnets harvested from computer hard disk drives (HDDs). High-throughput, cost-effective, recycling technologies have been developed by ORNL to economically recover intact HDD magnets for direct reuse in motor designs. ORNL and Ames Lab have designed and built functional permanent magnet motors that directly reuse recovered HDD magnets from the recycling technologies developed by CMI. This demonstration project showed for the first time that HDD magnets can be directly reused in new motor designs.

1. Scope of Demonstration

This demonstration project developed conceptual motor designs utilizing magnets recovered from HDDs. One of these designs, an axial flux gap motor, was constructed by directly reusing HDD magnets and characterized in the laboratory. Several conceptual motor designs were studied including axial flux gap, radial flux gap and linear motors. Direct magnet reuse takes advantage of alternate and economic supplies of highly desirable REE magnets, having potentially significant environmental impact by avoiding thermo-chemical processing required to make original magnets.

2. Background

Electric motors are produced by the millions, in many forms, with an array of specifications. One important motor specification is efficiency. Motor efficiency is determined by the ratio of the mechanical output power to the electrical input power denoted as a percent. Low operating cost and high output power is desirable for electric motor consumers and may be achieved by the introduction of permanent magnets. Although permanent magnets improve a motor's efficiency and performance, they may increase manufacturing cost. This project shows a pathway to direct HDD magnet reuse (e.g., using the magnet in its existing geometry). This approach eliminates costly and environmentally impactful manufacturing from virgin material sources.

REE prices and availability also present challenges. In a single supplier system, commodity material prices can vary wildly over short time periods. REE prices of neodymium, dysprosium, and praseodymium (REEs contained in permanent magnets) may range from \$ 30/kg to \$ 300/kg. The high cost of magnets for a motor design may discourage manufacturers from using REE magnets. An alternative — more economical — supply chain must be developed. Toward this end, the U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program were tasked with developing a non-rare earth electric motor with similar efficiency to a permanent magnet-bearing motor [2]. Concurrently, the Critical Materials Institute (CMI) was designing and developing new strategies to overcome the challenges presented by uncertain availability of REE magnets and magnet materials. One such strategy was explored in Demonstration Project 2 where CMI teams at ORNL and Ames Lab created conceptual designs for motors, and other electric machines, that rely on direct reuse of existing magnets from HDDs.

Alternative supply of REEs

Many devices and machines that people encounter on a daily basis contain REE magnets. These magnets are buried within electronic components that enable the device or system to have superior functionality. Permanent magnet manufacturing consumes large quantities of REEs and demand is increasing due to proliferation of electric vehicles and other “green” technologies.

CMI has targeted HDDs for magnet recovery due to their availability, standard size and shape, and material composition. From 2010 to 2018, approximately 4 billion HDDs were shipped globally [2]. The majority of HDDs are used by data centers for reliable and cost-effective storage. Even with typical HDD warranties of five years, HDDs are often replaced every three to five years to ensure data reliability and continued operational efficiency, at both the HDD and data center levels. That is, as demand for storage increases, it becomes more economical to replace HDDs with higher capacity drives rather than to continue using the lower capacity HDDs. In addition, based on the remaining useful life of the HDDs, it is sometimes more economical to retire HDDs and sell them while they retain retail value. This model of decision-making is based on an analysis of “the total cost of ownership.” This rapid and large-scale turnover of HDDs creates a rich source of REE magnets for potential applications for magnet reuse.

HDD motor design

A commercially available 130-Watt, single phase, non-REE industrial fan motor was purchased to perform a motor swap with the axial flux gap motor designed by ORNL that contained recovered HDD magnets. The HDD magnet motor was designed to fit within the commercial motor footprint to contrast the new direct reuse motor with an existing commercial motor. An axial gap motor design was chosen because the harvested HDD magnets have a crescent shape that could easily be integrated into a common motor design (Figure 1). The HDD magnets were not physically altered in any way. They were demagnetized as part of the recovery process and then repolled to suit the axial flux gap design.



Figure 1. Half magnet assembly revealing crescent shaped Nd-Fe-B permanent magnet.

The axial gap design uses a dual-sided rotor that faces two stators. This configuration balances the strong magnetic attraction between each rotor face (Figure 2). Shaft collars were specifically made to lock the rotor to the shaft to prevent slipping. The shaft collars also provided mechanical separation between the magnets and the stator (Figure 4) which prevents collision of rotor magnets and stator coils. Electromagnetic field (flux) increases as a function of distance and therefore, a smaller gap increases attraction between the permanent magnet rotor and the stator coils. The flux generated by an inductor may be calculated using the equation

$$H = \frac{Z * i}{3 * P * (m + g)}$$

where “Z” is the total number of conductors, “i” is winding current, “m” is magnet thickness parallel to the direction of flux, and “g” is the air gap parallel to the direction of flux [3]. Permeance of the magnetic circuit must also be calculated with this equation

$$P = \frac{F * m}{K * g}$$

where “F” is flux leakage, and “K” (kappa), is a magnetic reluctance factor-typically 1.1-1.5. Higher torque and efficiency are a result of decreasing the air gap which is shown mathematically from the equation

$$T_{torque} = B_{magnetic\ flux} * r_{winding\ radius} * l_{stack\ length\ of\ conductor} * Z_{\#\ of\ conductors} * i_{current}.$$

Currently this prototype motor is gapped to 1.5mm, which is not optimal and could be improved (Figure 3).

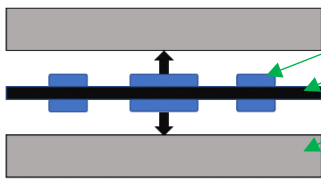


Figure 2. Balanced magnetic attraction between rotor faces and stators.

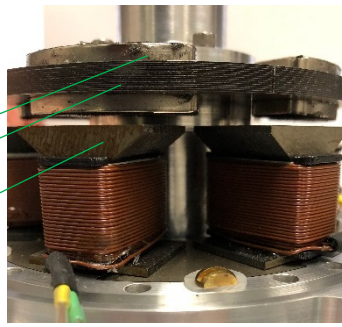


Figure 3. Assembled stator and rotor demonstrating 1.5mm gap between HDD magnets and stator coils.



Figure 4. HDD magnets radially distributed around the rotor. Also showing shaft collars that prevent the rotor from slipping axially on the shaft.

Stator coils were hand-wound around high-silicon steel lamination stacks (shown in Figure 5). The stators are stationary electrical inductors set into back-irons that provide the flow of energy into the rotor, producing flux. Six stator coils interact with each side of the rotor and collectively total 12 coils (points of induction).

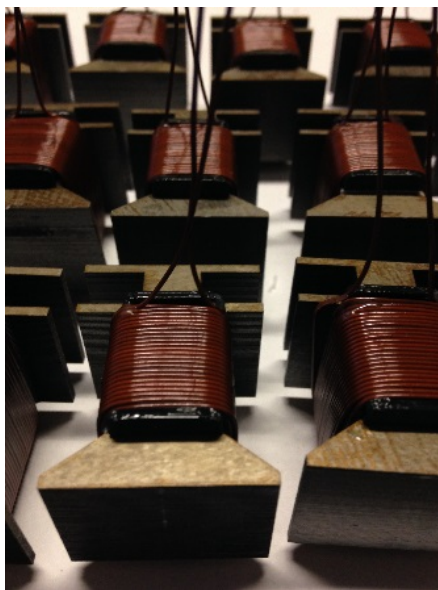


Figure 5. Hand-wound coils.

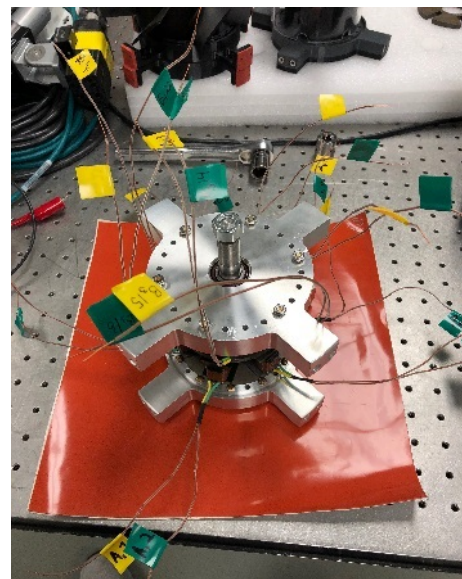


Figure 6. Assembled HDD magnet motor being wired in a 3-phase "Y" configuration.

3. Results

Properties of magnets recovered from HDDs have been modelled for direct reuse applications. Figure 7 depicts a 3D finite element model (FEM) showing a) the magnetic flux patterns, and b) flux density anticipated from an HDD magnet rotor.

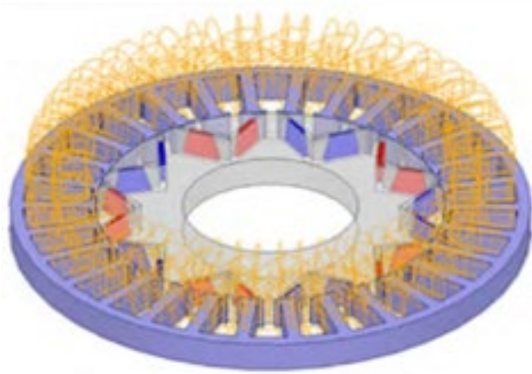


Figure 7(a) Magnet flux patterns from an HDD magnet rotor.

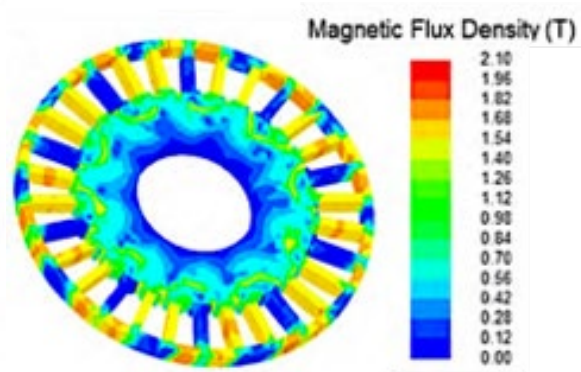


Figure 7(b) Magnet flux density anticipated from the motor design.

Figure 8 shows the performance characteristics predicted by the modelling efforts compared to characterization data. These data come from Ames Lab efforts to directly substitute recovered HDD magnets with ferrite magnets removed from a commercial clothes dryer. In this case, the magnets were modestly reshaped to form a more rectangular magnet without the tapered corners typically found on HDD magnets. Greater than 85% of the magnet's volume was preserved after reshaping. Motor designs were finalized in MotorSolve and the performance metrics were determined by FEA in ANSYS Maxwell 3D.

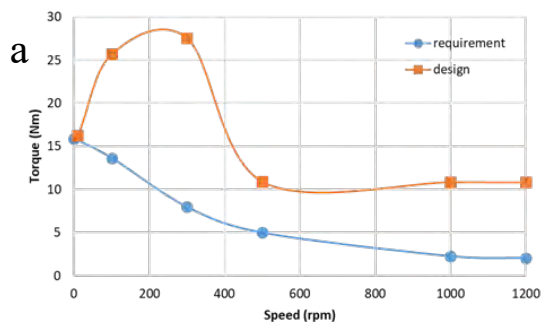


Figure 8(a). Torque-speed relationship for HDD direct reuse motor.

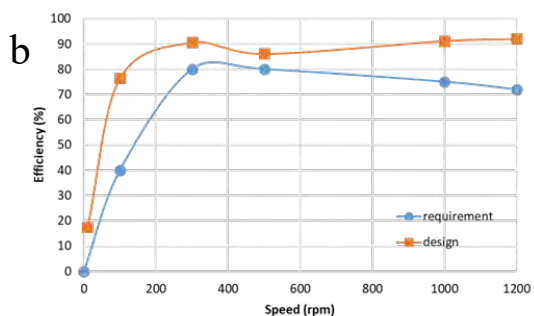


Figure 8(b). Efficiency-speed relationship for the same motor.

These data show direct reuse motors can be developed with impressive performance characteristics. Harvesting intact magnets is key, and CMI has invested in the development of technologies that can harvest large quantities of magnets from HDDs economically.

4. Conclusions

This project demonstrated for the first time that HDD magnets can be directly reused in new motor designs. Modeling of conceptual designs demonstrated that impressive performance is possible, and construction of the motor mock-ups provided data that verifies and exceeds anticipated performance targets. Intact magnets can be harvested in a manner that provides ample supply of magnets for motor designers at a price point that indicates direct reuse magnet motors could become a viable enterprise.

5. Recommendations/Next Steps

The future direction of this work includes refining motor designs and establishing contacts and partnerships with suppliers of HDD magnets, motors designers and end users. The benefits that may be derived from continuing this effort include:

- Reduce carbon footprint of motor manufacturing by utilizing harvested magnets versus creating magnets from mining ore
- Create very high-performance motors (or other reuse opportunities) derived from the high magnetic performance provided by Nd-Fe-B magnets
- Establish a supply chain to source Nd-Fe-B magnet for direct reuse applications

Acknowledgement

We appreciate the opportunity for collaboration between researchers at Ames Lab and ORNL and the interactions among the iNEMI team members that shaped our thought processes. A special thanks to CMI for allowing us to leverage process knowledge and related experience regarding HDD magnet harvesting and reuse. This research was supported by the Critical Materials Institute, an Energy Innovation Hub funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office.

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DEMONSTRATION PROJECT 3: MAKING MAGNETS FROM MAGNETS AND SHRED

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EXECUTIVE SUMMARY

This demonstration project focused on Urban Mining Company's (UMC's) patented process called Magnet-to-Magnet® (m2m®). This commercialized process recycles end-of-life (EoL) magnets directly into new magnets from a wide variety of magnet-containing EoL devices. The iNEMI team demonstrated the m2m process, using it to recycle magnets from hard disk drives (HDDs) for potential reuse within a circular economy model based on processing a mixed batch of computer HDDs, covering different manufacturers and years of production, and fabricating new magnets for new HDDs. The demonstration project collected 3,000 HDDs to extract the sintered Nd-Fe-B magnets using a semi-automated harvesting tool (also developed by UMC). The extracted magnets were then recycled using the m2m process and compared in terms of their magnetic properties with conventionally produced magnets manufactured for new HDDs. The results provide very strong evidence that the m2m recycling process can be employed to create a circular economy for HDD magnets.

1. Scope of Demonstration

This demonstration project team wanted to recover and recycle end-of-life (EoL) sintered Nd-Fe-B magnets from HDDs for use in a circular economy for HDD magnets using the Urban Mining Company's Magnet-to-Magnet® (m2m®) recycling process. EoL HDDs typically contain 4–20 grams of sintered Nd-Fe-B magnets. The project team evaluated the m2m process as a means to produce new magnets with suitable magnetic properties and new geometrical shapes and to meet new critical-to-quality (CTQ) requirements. The evaluation involved a real-life batch of EoL HDDs that were collected from collaborating partners. The HDDs came from different manufacturers and had various dates of manufacture. They were then reprocessed to evaluate m2m recycling in the context of a circular economy for HDDs.

2. Background

Urban Mining Company has developed the m2m recycling process for Nd-Fe-B rare earth magnets. This process involves harvesting EoL Nd-Fe-B magnets from devices and reprocessing the extracted magnets into new magnets with different shapes and magnetic properties. It involves a powder-metallurgy (PM) route whereby the harvested magnets are turned into a powder and pressed into new magnet blocks prior to sintering and the blocks are machined to the required dimensions and coated for corrosion protection before being magnetized. The processing stages are shown in Figure 1 and discussed below.



Figure 1. Overview of the manufacturing steps for Nd-Fe-B sintered magnets. [1]

The m2m® process

UMC's m2m process (Figure 1) begins with harvesting magnets from EoL applications (1-2b), which typically include HDDs, electric motors and generators. In the next step the extracted EoL sintered Nd-Fe-B magnets are demagnetized (2b) by heating them above their Curie temperature (for Nd-Fe-B this temperature is ~380°C, depending on the specific composition). Once heated above this temperature and allowed to cool to room temperature, the magnet is in the demagnetized state, with the magnetic domains orienting in such a way as to leave the magnet with no external flux paths. In the next step the surface is cleaned (2c) to remove any coating used to prevent corrosion, after which, the PM processing stages can begin (3-8). The harvested, cleaned EoL magnets can then be used as the raw material for the new magnets. The next stage is hydrogen mixing (3). Cleaned EoL magnets are exposed to hydrogen at room temperature, allowing the hydrogen molecules to disassociate on the surface of the materials, after which the hydrogen

diffuses rapidly into the bulk, causing a dramatic physical expansion (up to ~20%). This causes the brittle Nd-Fe-B intermetallic to become heavily cracked, and then fracture into a powder. During this stage additional material can be introduced to alter the overall chemical composition and distribute compounds that can enhance the magnetic properties.

The coarse powder produced by the hydrogen-mixing procedure is typically ~150 microns in size and contains ~0.5 wt.% hydrogen. Some of this hydrogen is removed by heating under vacuum before the powder is jet milled (4). The purpose of the jet milling is to produce a fine powder (~3–5 microns) with a controlled particle size distribution. This fine powder is required for efficient filling of the mold tools and good alignment of the powder during the alignment-and-pressing stage that takes place in a magnetic field (5). The pressed block within the alignment press is extracted carefully and further densified by cold isostatic pressing (6) before sintering (7) to full density. The sintering operation requires heating the previously pressed block under vacuum to enable diffusion to occur within the pressed particles and produce a fully dense metal block. All the remaining hydrogen is removed by this vacuum sintering stage. After sintering, the block is heat treated (8), resulting in subtle changes to the microstructure, which can improve the magnetic properties. Finally, the block is machined to the required geometry, and a corrosion-protection coating is applied, in accordance with the customer's requirements.

Results

The magnetic properties were measured for two popular, modern brands of HDD. The second-quadrant demagnetization measurements at room temperature are shown in Figure 2.

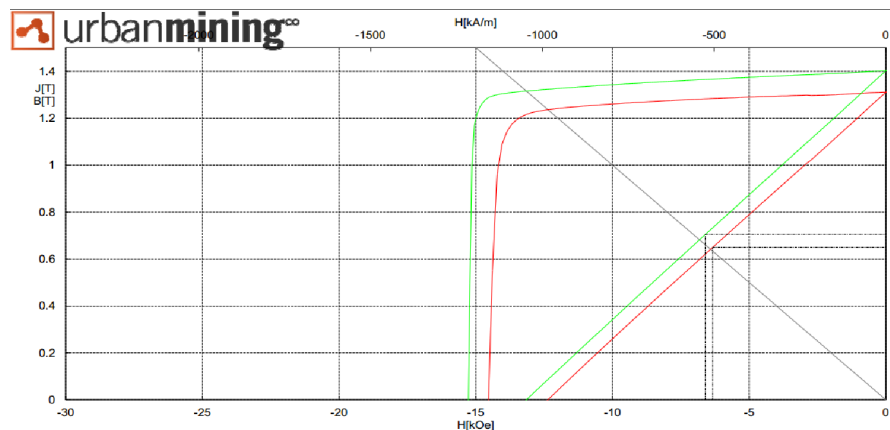


Figure 2. Room-temperature 2nd-quadrant demagnetization curves for two modern brands of HDD.

The magnetic properties of these two modern brands of HDDs are summarized in Table 1. The measured magnetic properties of the two HDD magnets act as a benchmark and the target for engineering the mixed batch of recovered HDD magnets into new HDD magnets for potential reuse within a circular economy.

Some of the stages of the m2m process are shown below in Figure 3.

Table 1. Summary of Measured Magnetic Properties for New HDDs

Magnetic Property	HDD #1	HDD #2
Remanence (T)	1.31	1.4
Intrinsic coercivity (kOe)	14.5	15.3
Energy product (MGOe)	41.2	46.5



Figure 3. Some of the stages of the m2m process for computer HDD magnets.

One of the 4-kg sintered blocks of Nd-Fe-B that was produced from the EoL HDD magnets was machined into new HDD magnets (Figure 4) and the magnetic properties tested (Figure 5) using the same method as used to generate the benchmark magnetic properties. The magnetic properties are summarized in Table 2.

Figure 4. New sintered Nd-Fe-B magnet produced using the m2m process, which was then machined to produce new HDD magnets.



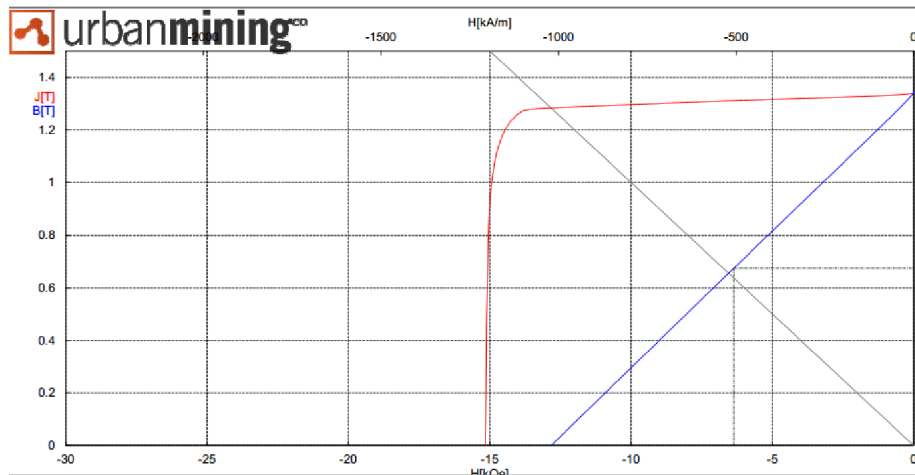


Figure 5. Room-temperature 2nd-quadrant demagnetization curve for the HDD magnet produced using the m2m process.

Table 2. Summary of the Magnetic Properties from HDD Magnets Produced Using the m2m Process

Remanence (T)	1.34
Intrinsic coercivity (kOe)	15.2
Energy product (MGOe)	42.9

4. Conclusions

This demonstration project has shown that it is possible to harvest magnets from a range of post-consumer HDDs and recycle these EoL magnets using the m2m process to produce new HDD magnets that have magnetic properties comparable to conventionally produced, modern HDD magnets. These new magnets may be suitable for reuse within a circular economy for HDD magnets. In addition, the m2m process provides a pathway to meet the new EPEAT optional criterion for servers for having at least 5% recycled REE content in the HDD magnets.

5. Recommendations/Next Steps

1. Continue to work with HDD manufacturers and users of HDDs that want to introduce ‘greener’ magnets into their supply chain and provide a closed-loop, circular-economy solution. Make improvements to the logistics of collection for a more efficient harvesting of the magnets from HDDs, which is required to reduce the energy requirements and costs involved in transportation.
2. Scale up the harvesting operations associated with HDDs and regularly use the feedstock within the UMC m2m process for the production of new HDD magnets or magnets for other applications, e.g., electric motors.

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DEMONSTRATION PROJECT 4: MAKING RARE EARTH OXIDES FROM HDD MAGNETS

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EXECUTIVE SUMMARY

This demonstration project focused on recovery of high-purity rare earth oxides from waste magnets contained in hard disk drives. Momentum Technologies and Ames Laboratory, both part of the U.S. Department of Energy Critical Materials Institute, participated in the demonstration. Momentum Technologies' Membrane Solvent Extraction (MSX) technology was applied to recover >99.5 wt.% pure rare earth oxides from waste HDDs. Ames Laboratory applied the newly developed acid-free dissolution recycling technology to recover >99.95 wt.% pure rare earth oxides. Recovered oxides were used to make metal ingots, which can be reused to make permanent magnets. The team recommended as a next step to work with a commercial partner to identify the best entry point for the recovered materials into the REE supply chain.

The products of both demonstration routes are mixed oxides of rare earth elements like Nd-oxide, Pr-oxide and Dy-oxide. While this is satisfactory for using the recovered rare earth elements (REEs) for magnet production as demonstrated in the project, there is still the need to diversify the potential applications in which the products can be used. As a result, it is necessary to develop recycling methods that recover the REEs in their individual REE phases either as oxides or, preferably, as metals. This iNEMI demonstration project proves that the value in waste magnets can be recovered via efficient recycling.

1. Scope of Demonstration

Rare earth elements (REEs) are critical for development of many high-tech products and have been termed the “vitamins” of modern industry. The increasing need to develop more efficient products and the shift toward cleaner energy technologies will accelerate the need for more REEs. This demonstration project explored opportunities for hydrometallurgical recovery of REEs from waste magnets harvested from end-of-life hard disk drives (HDDs). Although the demonstration task is limited to magnets in HDDs, the principles used can be applied to magnets in other types of e-waste.

Two approaches, pyrometallurgical and hydrometallurgical, are often proposed for REE recycling from e-waste. Unlike pyrometallurgical approaches, hydrometallurgical recycling processes consume less energy, recover REEs at higher efficiencies and purity, and can easily be scaled. However, REEs are typically recovered as oxides, rather than as metals (which have higher values), like in some pyrometallurgical processes. Pyrometallurgical methods also have the drawback of resulting in large amounts of solid waste. This task is aimed at demonstrating viable hydrometallurgical processes for recovering high-purity oxides which can be reduced to metal ingot and used as feedstock for remanufacturing of magnets. Thus, this demonstration investigates opportunities for developing a circular economy in the manufacturing of permanent magnets via REE recycling.

2. Background

Although REEs are not rare, sources for minable concentrations are limited. As a result, there are very limited REE mining operations, irrespective of many identified deposits around the world [1]. Global REE production and trade have been mostly controlled by China. For example, China produced >80% of the global REE supplies in 2016 and 2017 [2]. Recycling presents a viable opportunity for recovering REEs from waste materials and mitigating potential disruption in the supplies of REEs. Recycling can be a source for secondary feedstock for REEs, reducing the burden on mining. However, the level of REE recycling activities is still insignificant (<1%). This is likely due to the difficulties associated with recycling REEs as discussed in the literature [3]. The cyclical nature of the instability in the prices of REEs and the typical low concentrations in end-of-life materials make REE recycling less appealing, particularly when prices are low.

An inherent challenge with recycling is materials collection. In a circular economy cycle, the end-user is usually responsible for initiating the return of the material or system containing the material to restart its journey through the cycle. When the end-user is the general public, some form of incentives or types of legislation have been used to encourage collection. For example, the European Commission's 2002/96/EC and 2012/19/EU directives were meant to encourage building a circular economy [4]. However, if the material to be recycled is concentrated in manufacturing plants or in other industries that use large amounts of the material, collection may be less problematic.

Permanent Nd-Fe-B magnets represent a readily available and accessible feedstock materials for recycling REEs because they consume significant amounts of REE production, compared with many other applications [3]. For example, most of the global production of praseodymium, neodymium, samarium and dysprosium are used for magnets. In addition, global market demand for permanent magnets, currently dominated by electric motors and consumer electronics, is projected to approach 140,000 metric tons by 2020 [5]. Permanent magnets are used in large quantities for HDD production and can easily be harvested and recycled for the REE content. Nguyen et al. reported that recycling permanent magnets used in the

United States alone could meet >5% of REE demand for neodymium-iron-boron (Nd-Fe-B) magnet production for the rest of the world (excluding China) [6].

Permanent magnet manufacturing plants can be good sources of magnets for recycling. Swarfs, generated from post-manufacturing processing of permanent magnets, including grinding, polishing, dicing, etc., can readily be obtained from such plants. An estimated ~30% of original magnet materials can be lost as swarfs in magnet manufacturing plants [3,7]. Since the swarfs are fine powders of REEs which are typically oxidized, they are suitable for elemental recovery but not for direct reuse as magnet feedstock. Also, the brittle nature of REE permanent magnets means that significant amounts of damaged materials are generated during manufacturing and post-manufacturing processes such as dicing of large blocks into magnets having thickness of only a few millimeters.

When systems that use large-sized permanent magnets (e.g., wind turbines, electric vehicles, magnetic resonance imaging medical systems) reach the end of their lives, it may be argued that such large magnets are more suitable for immediate reuse, rather than being subjected to elemental separation. However, the magnets will eventually reach their own end of life and will require recycling to separate the constituent elements. When this happens, efficient recycling technologies are needed that are capable of recovering high-purity REEs from waste magnets via economically deployable and environmentally acceptable processes.

This iNEMI team demonstrated two different hydrometallurgical processes for efficient and high-purity recovery of REEs: the Critical Materials Institute's MSX Technology, developed by Momentum Technologies, Inc., and Oak Ridge National Laboratories' Acid-free Dissolution Technology, developed in conjunction with Ames Laboratory.

3. Sources of Feedstock Materials

Four types of samples were used for this demonstration: magnet "hairballs," hydrogen decrepitated powder, pre-treated powders from the multistep separation process and as-shredded HDDs. The magnet "hairballs" in Figure 1(a) were obtained from shredding HDDs and carefully separating the magnetic contents. HDD shredding is a mechanical operation in which the HDDs undergo physical destruction by being pulled through the teeth of an interlocking gear system made of hardened steel materials, i.e., by shredding. The shred sizes depend on gaps between the teeth of the gear system along with other factors such as the number of times the material passes through the shredder.

Shredding is performed to guarantee complete destruction of the data contained in the HDDs, but it leaves the shredded mix in a form that complicates reclaiming REEs from the magnet contents. It is, therefore, necessary to pre-separate the magnet contents, which adds time and cost to the process. Moreover, some of the REE-containing magnets can be lost in the process, worsening the already existing problem that HDDs contain small amounts of REEs for recycling. Depending on the type of shredder, the loss could be as high as 90% [8]. There is, therefore, a need to develop shredders designed to both physically destroy HDDs and recover critical materials.

Figure 1(b) shows a dismantled HDD magnet and its brackets. The brackets are used for shielding the sensitive electronic components of the HDD from the strong Nd-Fe-B magnetic field. Typically made of high magnetic permeability Mu-metal, the brackets contain 75% – 80% nickel (Ni). The Nd-Fe-B magnets

are also often plated with Ni to protect them from corrosion. When HDDs are shredded, especially in the case of fine shredding, the chances of Ni contamination increases. Recycling processes need to avoid Ni contamination particularly if it is intended to reuse the recovered REEs as Nd-Fe-B magnet production feedstock. This is because Ni is known to form binary precipitates in Nd-Fe-B [9] resulting in reduced magnetocrystalline anisotropy, coercivity, remanence and energy product. Moreover, most hydrometallurgical processes recover REEs as mixed oxides rather than oxides of the individual RE elements. These mixed oxides are more suitable for magnet production which typically uses mixtures of these three REEs rather than other applications such as (Nd:YAG) lasers which requires separated, pure Nd-oxide. Therefore, the economic viability of any recycling process will be limited by Ni contamination in the recovered oxides.

Figure 1(c) shows another sample used which was fine powder obtained after multistep processing to separate magnets from shredded HDDs. The processes include thermal demagnetization, eddy current separation, grinding, sieving and magnetic separation. While this multistep process helps to concentrate magnet powders for recycling, it results in additional impurities which must be separated from the REEs to obtain a technical grade of the final oxide. The particular sample contained Nd, Pr, Fe, B, Ni, Cu, Zn, Co, Mn, Si and Al.

The demonstration also used powders obtained via hydrogen decrepitation of HDD magnets, as shown in Figure 1(d). Hydrogen decrepitation is a process widely used to make Nd-Fe-B more friable prior to milling, magnetic alignment, pressing and sintering [10]. When applying hydrogen decrepitation to Ni-coated Nd-Fe-B HDDs magnets, it is necessary to fracture the magnets so they can be exposed to the hydrogen gas. When applied to HDDs magnets without shredding, hydrogen decrepitation makes it easier to separate the Ni coating as intact foils as shown in Figure 1(d).

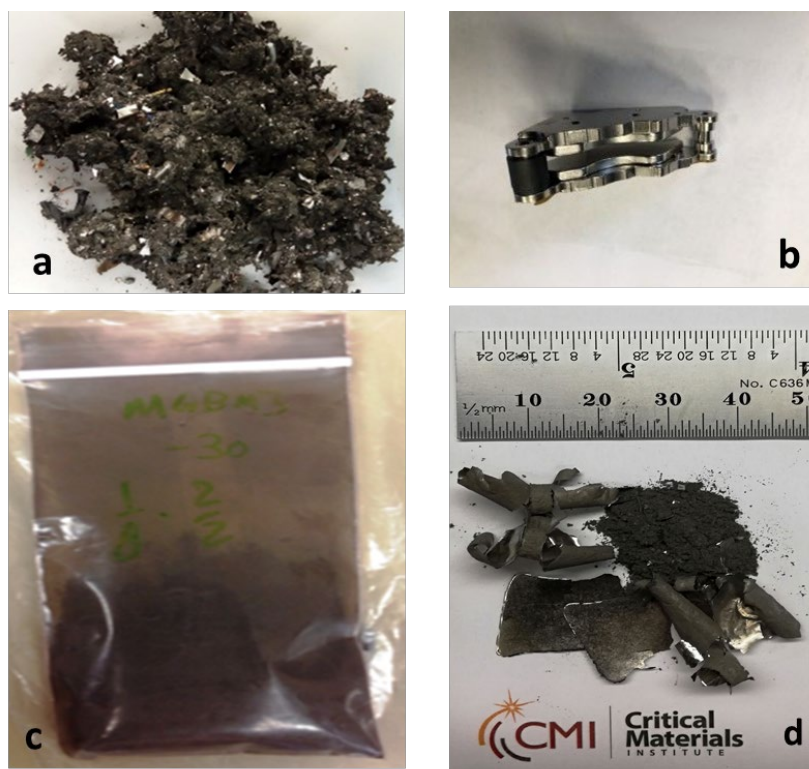


Figure 1. Four types of HDDs magnets used for the demonstration project including magnet “hairballs” (a), magnet and bracket (b), fine powders from multistep processing of shredded HDDs (c) and hydrogen decrepitated HDDs magnet powders (d) which also shows the separated Ni coatings.

4. Results

Momentum MSX demonstration

Magnet “hairballs” from shredded HDDs were dissolved in acid before being subjected to Momentum’s MSX technology process. The MSX technology was able to recover more than 99% of the rare earth content while operating at room temperature and pressure. The modular membrane design allows for substantially lower solvent waste and extractant loss, resulting in waste minimization and near-zero discharge. The compositional analysis of the demonstration study via MSX process is shown in Table 1. High-purity (>99.5 wt.%) rare earth oxides were obtained with trace amounts of aluminum (Al). If reinserting the REEs into the permanent magnets supply chain is desired, the Al impurity can be an advantage since Al is sometimes added to optimize the microstructure of Nd-Fe-B magnets in order to achieve high coercivity [11, 12]. The results of this demonstration have been analyzed by a commercial magnet manufacturer and the quality has been confirmed for reuse.



Figure 2. Rare earth oxides derived from recycling via the MSX process.

Table 1. Analysis of Composition for Rare Earth Oxides Derived from the MSX Technology Process

Feedstock type	Metal Content (wt.%)									
	Nd	Dy	Pr	Fe	Ni	B	Cu	Zn	Al	O
Magnet+ Bracket	81.3	3.2	0.98	0	0	0	0	0	0.06	14.6
Shredded Hairball	75.4	1.9	8.1	0	0	0	0	0	0.07	14.59

Acid-free dissolution recycling technology

All four types of samples were used for the Ames Laboratory acid-free dissolution recycling technology. A unique feature of this technology is the potential to treat shredded HDD samples without pre-concentration of the magnet contents. This means that the shredded material is treated in the unseparated as-shredded state, aiming at selective dissolution of only the magnet contents. This is an important feature because

eliminating the pre-processing steps while accomplishing both selective leaching and efficient recovery of REEs can help improve the economics of the recycling process.

Figure 3 illustrates the process for the as-shredded HDDs. Solid residues resulting from the dissolution process were filtered off. For the as-shredded HDDs, the unreacted parts (Figure 3) were also filtered off and washed with water. The REEs were subsequently precipitated as oxalates and calcined at 800°C to obtain the oxides shown in Figure 3. The rare earth oxides obtained from HDD recycling and magnets swarfs recycling were mixed and reduced to metal ingots at the Ames Laboratory Materials Preparation Center. Figure 4 shows the progression from shredded HDDs, extraction of REE oxalate, calcination into REE oxide and reduction into REE ingot.

Table 2 shows the compositional analysis of the rare earth oxides obtained via the acid-free dissolution Technology process, determined by X-ray fluorescence. All the samples have rare earth contents of 99.95 wt.%, or better. The purity of the recovered materials exceed typical technical grades needed for magnet production.

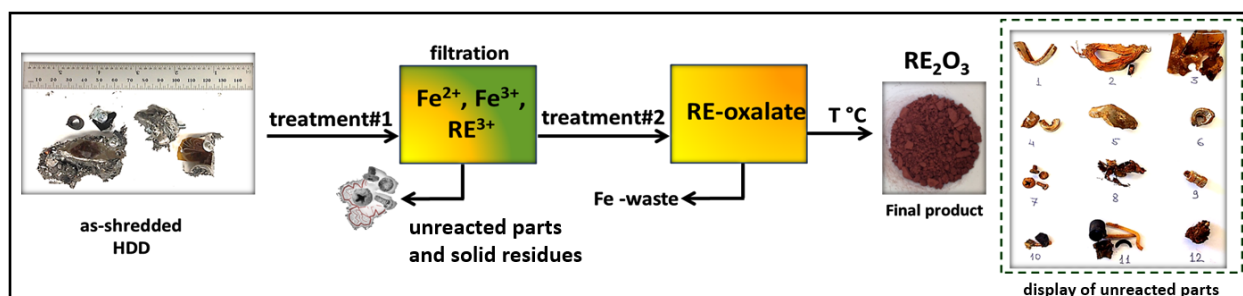


Figure 3. Schematic of the process for acid-free dissolution using shredded HDDs in as-shredded form.

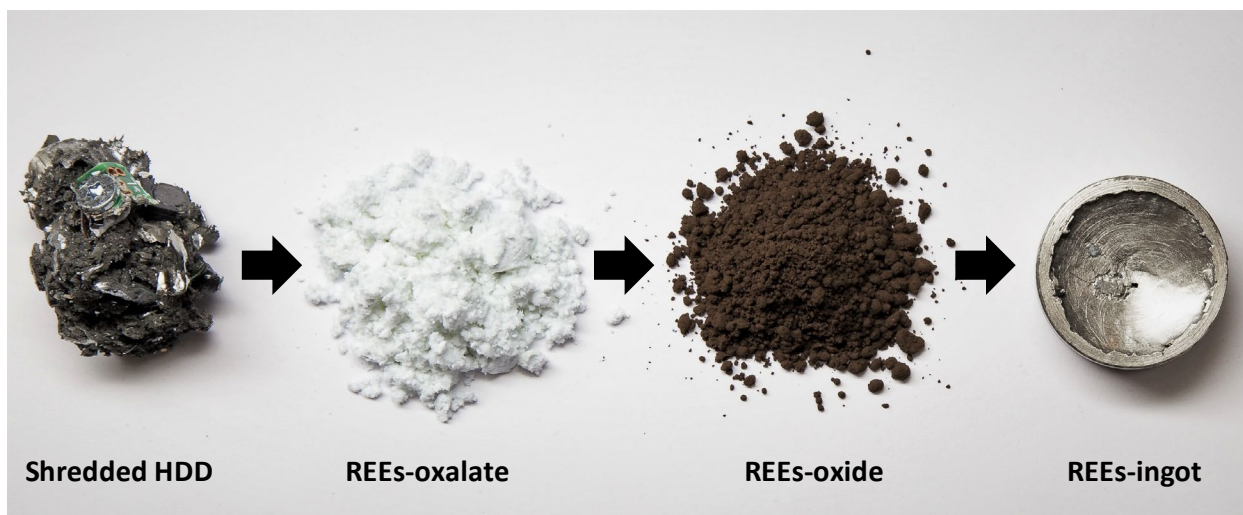


Figure 4. The progression from shredded HDDs to metal ingot via the acid-free dissolution process.

Table 2. Analysis of Composition for Rare Earth Oxides Derived from the Acid-Free Dissolution Technology Process

Feedstock type	Metal contents (wt.%)							
	Fe	Ni	Cu	Zn	La	Pr	Nd	Dy
As-shredded HDDs	0	0.01	0	0	0	10.74	87.70	1.55
Magnet “hairballs”	0	0	0.03	0	0	21.02	78.95	0
Decrepitated HDDs	0	0.05	0	0	0	20.75	79.20	0
Pre-concentrated HDDs fine powders	0	0	0	0.02	0.04	6.29	91.95	1.71

5. Conclusions

This iNEMI demonstration project successfully demonstrated the recovery of high-purity rare earth oxides from magnets contained in end-of-life HDDs. Two different technologies were applied: the Momentum Technologies MSX process and the Ames Laboratory acid-free dissolution process. Different forms of HDD feedstock materials were used in the project which demonstrates the robustness of the technologies applied. Both processes obtained high-purity rare earth oxides (99.5 – 99.95 wt.%). The recovered rare earth oxides are suitable for magnet production, proving the potential to promote a circular economy via these recycling technologies.

6. Next Steps

Despite this successful demonstration, there are other factors that need to be addressed in order to take the next step toward the desired circular economy. An important next step is to identify mechanisms for separating magnets from the rest of the e-waste. Pre-concentrating magnets will reduce the volume of chemicals used and improve recycling economics, even if the technology does not require pre-concentration. As part of the Critical Materials Institute (CMI) research, Colorado School of Mines is developing a process called “preferential degradation” technology which removes non-magnet contaminants. Oak Ridge National Laboratory, also part of CMI, developed a process for punching magnets out of HDDs and for automated disassembly. The accumulation of magnets from waste will require breakthroughs in recovery technology as well as creative partnerships across the supply chain for collection and to ensure that the material remaining after REE recovery is properly disposed of at end of life.

Another important future step is to have a partnership with a magnet manufacturer to provide an entry point for the recovered rare earth oxides into the supply chain. There is significant strategic importance for a company to have control over the critical materials in its supply chain. The increasing demand for Nd-Fe-B magnets requires a continuing, significant amount of virgin material, mined primarily from China. Unless there is a significant supply of rare earth oxides and metal available from recycling and recovery to meet the needed supply, it will be difficult to develop and maintain a long-term relationship with magnet manufacturers. Another difficulty in identifying a supply chain entry point is related to the fact that the processes described here recover mixed rare earth oxides, less useful in magnet manufacturing than the

separated REEs. Another next step is, therefore, to modify the processes to enable separation of Dy from Nd/Pr.

In addition, most of the commercial oxide-to-metal processing occurs in China, so it will be necessary to work with domestic commercial partners to convert the oxides into alloys.

Acknowledgement

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DEMONSTRATION PROJECT 5: CREATING A BUSINESS MODEL TO SUPPORT REUSE & RECOVERY

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1. Scope of Demonstration

The goal of Demonstration Project 5 was to create a business model that moves hard drive management from “reuse or shred” to “reuse and recover.” Shredding refers to the practice of using commercial shredding machines to make the data on the drives irretrievable by crushing and fracturing the platens and read/write heads. Unfortunately, shredding also makes it difficult, if not impossible, to recover components from hard drives for direct reuse. Recovery in the context of Demonstration Project 5 is the alternative to shredding and refers to the practice of dismantling the hard drives into component parts that may have higher commodity values than the metal content in a shredded hard drive.

To support the project goal of creating a business model to move toward “reuse and recover,” the following supporting processes were explored:

- Economic/practical analysis using mind maps
- Role of business models and relationships with recycling partners and others
- Implications for value recovery and scalability
- Justification for particular pathways – economic, environmental, and risk
- Build a circular economy model for HDDs to meet organizations’ needs

2. Background

Current hard drive reuse practices are dictated by: (1) commodity pricing for key components, which are set by the commodity markets responding to demand, and (2) retail pricing for used/remanufactured hard drives, which is driven by demand in the retail market. A key impediment to HDD reuse is the industry-wide premise that shredding is the only option to ensure that data security is not compromised, thus avoiding legal and business liabilities. This mindset is causing enterprises to lose significant value along with the ability to recover valuable commodities.

3. Discussion

The largest users of hard drives are large enterprises with data centers. These enterprises have the greatest influence on reuse and recycling efforts. Figure 1 is a mind map used to relate how large enterprise users can support the reuse of hard drives. This listing is not exhaustive but includes the majority of issues that should be considered as part of comprehensive policies and business processes to support hard drive reuse. Several of the concerns are highlighted below and more are included in the mind map.

Data security

The enterprise should choose a data security and sanitization standard to follow. This standard is the cornerstone of controlling risk and identifies actions needed to allow release of hard drives from an organization’s control. Most U.S.-based enterprises follow the NIST 800-88 R1 [1] standard, which defines requirements for overwrite patterns and verification requirements. The standard also includes risk analysis and decision methodology to meet the organization’s security concerns for data sanitization. The data security function must also include a complete archive of all data overwrites performed. This creates an historical record of the data sanitization results and can be used in case there are questions about the status of the drive.

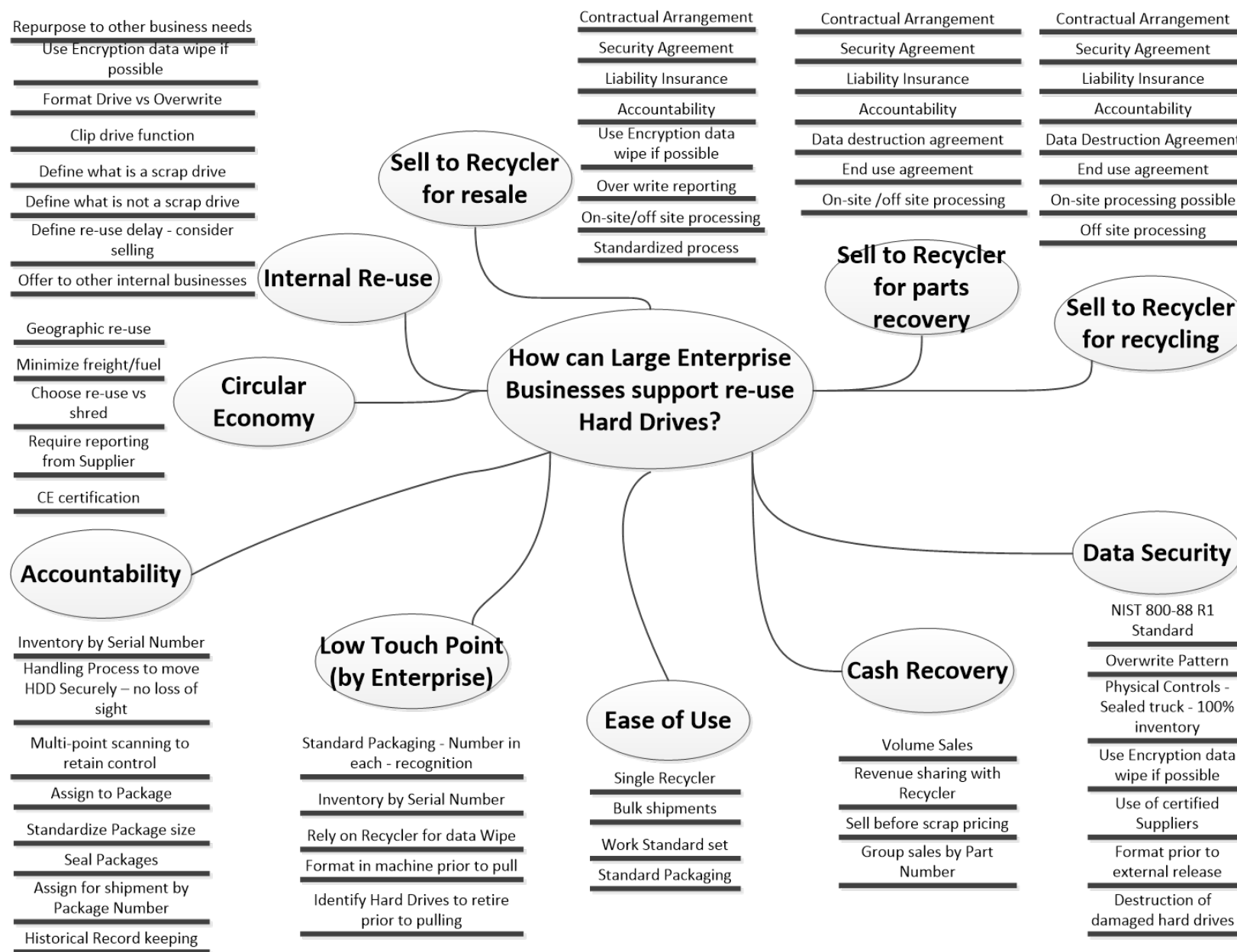


Figure 1. How can large enterprise businesses support reuse of hard drives?

Accountability

Accountability of the hard drives is required to ensure all affected drives are tracked from the operational location to the final shipment from the enterprise facility. Most hard drives have bar codes for the serial number and model for each drive, allowing rapid capture of this information. Enterprises can also use the bar code information to transfer control of the device internally as the hard drive is sanitized, assigned for shipment, then reconciled upon completion of shipment

Corporate social responsibility

Large enterprises support corporate social responsibility reporting. One of the cornerstones of this activity is creating goals to support a circular economy within their organization and their extended supply chains. Corporate responsibility programs typically include, but are not limited to, adoption of responsible business practices, compliance with environmental regulations, active engagement with local communities and commitment to reduce the corporation's energy, water and solid waste footprints. For HDD manufacturers the challenge with circularity is demonstrating material management paths that are economically sustainable and robust for all participants, are socially responsible and do not violate existing regulatory structures and laws. A punitive tax on transboundary shipments of "waste HDDs" could obviate a circular economic solution for reuse of intact magnets that require transboundary shipments. Significant shifts in commodity prices for particular materials could inhibit or increase recycling of said materials and commodities. Such shifts in the past have adversely impacted efforts to recycle materials in CRT-based televisions and displays. To effectively demonstrate a circular economy an enterprise must actively develop and incentivize supply chain solutions that are environmentally and economically sustainable for all participants in the chain. This means working collaboratively with customers and suppliers to demonstrate and implement material management and sourcing strategies that are robust and sustainable in the face of current and future market shifts.

Internal reuse

Internal reuse is often overlooked and could help an enterprise avoid purchasing new hard drives by reusing used drives. Formal policies concerning data security and reassignment need to be understood and accepted to ensure compliance. Data security standards for organizations following NIST 800-88 R1 guidance are less restrictive on internal reuse of hard drives, which is a benefit of this activity.

Remanufacturing companies

Hiring a remanufacturing company to process, account for and data wipe hard drives is a good alternative to performing this work internally. Hard drive remanufacturing companies specialize in this work and can meet any commercial standard to account for hard drive disposal. In addition, remanufacturers can operate in "purchase now" or a "revenue sharing" model. Depending on the needs of the enterprise, each option can be beneficial. The most important aspect of hiring a remanufacturer is to have a contractual agreement that meets the enterprise's needs. This limits liability and assures that requirements are clearly known by both parties.

Cash recovery

Cash recovery by selling hard drives that are no longer needed by an enterprise can yield financial windfalls. Used hard drives have been shown to have market value up to six years after initial purchase. The valuation of hard drives is discussed in the following sections.

Policies and processes

Enterprises need to establish policies and business processes for supply chain interaction to assure the numerous internal and external actors that hard drive disposition requirements are met. These should include:

- Establish data sanitization policies and processes when the hard drives are initially purchased. The fastest and safest method of data sanitizing a hard drive is to use an encryption erasure method. Removing the encryption key ensures data recovery is not possible. When the hard drives are purchased, encryption erasure should be considered part of the selection criteria, as it will make data sanitization less labor-intensive when decommissioned or reused.
- Select the standard to be followed and establish policies that ensure hard drive data sanitization standards are met.
- Include the organization's standard for data classification in the standard developed. Extremely sensitive data may lead to the destruction of the hard drives while less sensitive data may allow the reuse or sale of the hard drive.
- Understand the regulatory entities and the requirements that may be imposed on their data sanitization processes.

Figure 2 is a mind map of these interactions and aspects to be considered with the various actors.

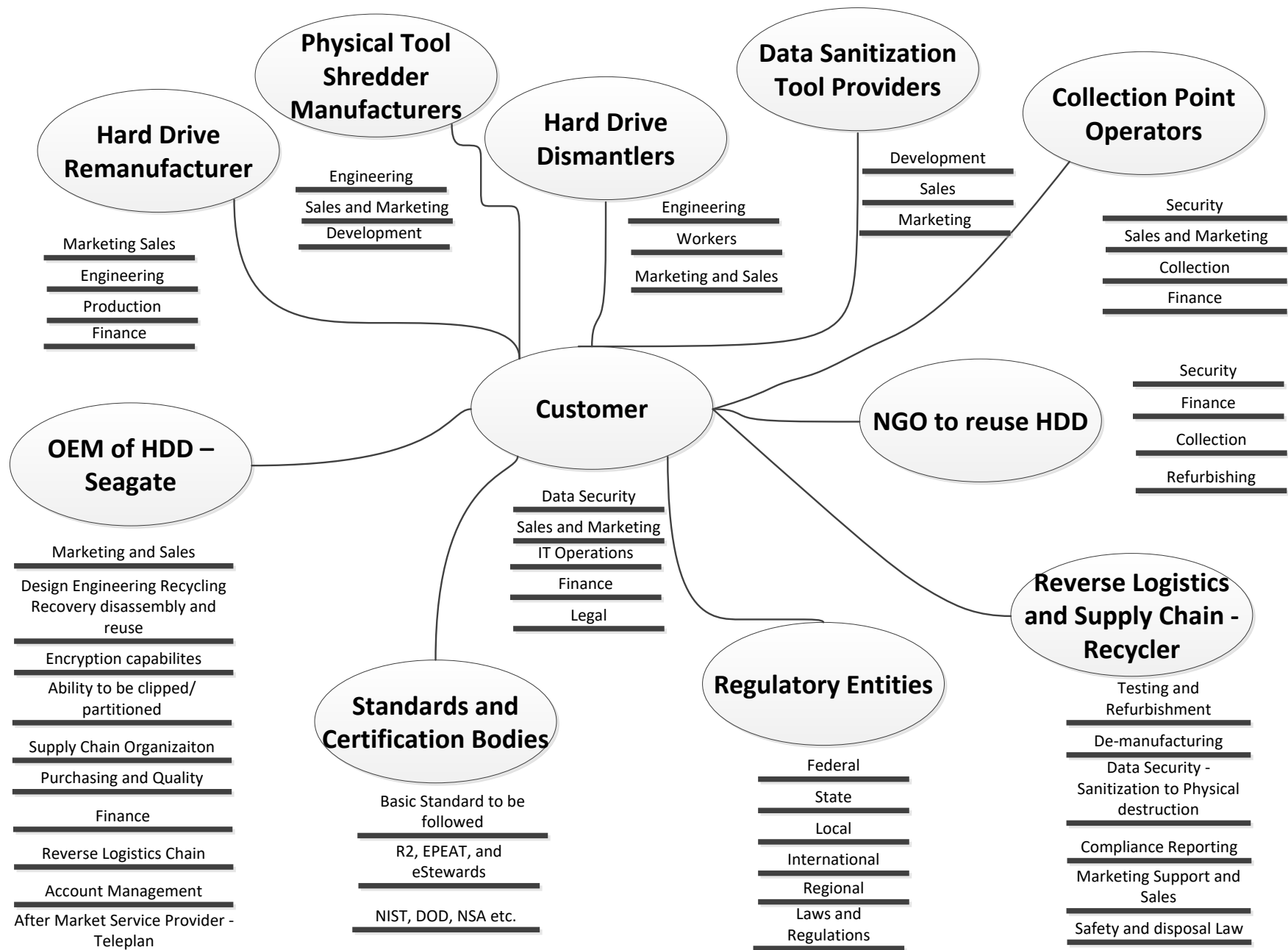


Figure 2: Who are the actors in the decision to recycle hard drives in an enterprise?

Pathways for value recovery from HDDs

Figure 3 illustrates the pathways for enterprises to consider for economic recovery of hard drives. Please note that this process is supported by the enterprise's data sanitization and reuse policy which will assist in the use of this model. The process starts with hard drives that have been identified as no longer satisfying the primary need of the enterprise due to age, technology changes, planned storage refresh time, mechanical failure or other failure of the drive. There are several factors to consider when making the decision to reuse and to determine which recovery method or methods will maximize value recovery.

Hard drive under warranty. The enterprise should review the purchase terms of the hard drives to determine if there are any warranty claims available from the manufacturer. Warranty returns are sent to hard drive remanufacturers who refurbish, data wipe and sell the drives on behalf of the manufacturer. Recent developments include the hard drive remanufacturer restoring the drive to manufacturer specifications and selling them in the market as "white label" drives. White label refers to the manufacturer's label being replaced with a label with no manufacturer listed.

Internal reuse. The enterprise should regularly validate the internal needs of the company for hard drive reuse. Back room or non-customer facing functions may be able to reuse the hard drive and defer the purchase of new drives by several years.

Enterprise direct sales. The enterprise has determined that having the capability internally or hiring an external recycler to data wipe the hard drives is allowed to support resale efforts. The benefits of supporting this activity should be considered against the recovery sales of the data-wiped hard drives. Sales can also be completed through external brokers as bulk sales or other retail sales outlets depending on the enterprise's requirements.

Revenue sharing with refurbisher/recycler. This option transfers the data sanitization activities to a refurbisher/recycler that specializes in this work. The resale activities of data-wiped hard drives is also passed to the refurbisher/recycler. The enterprise value recovery from sales is through a flat rate revenue sharing methodology with the refurbisher/recycler. This method removes much of the time and effort from the enterprise and the sales are managed by an external entity.

Value recovery from HDD magnets. The current practices for nonfunctional HDDs are to destroy or impair the drives to allow their release to the commodity market. Destruction is achieved by shredding the drive in a commercial shredder to a size that makes data recovery impossible. HDDs can be impaired through bending, crushing, punching, drilling or even degaussing to ensure data recovery is not possible. However, new technologies are emerging to enable more end-of-life options that increase the values recovered from nonfunctional HDDs. These options include (1) direct reuse of HDD voice coil magnet assemblies, as proven in Demonstration Project 1, (2) direct reuse of HDD voice coil magnets (VCMs) in products other than HDDs, as shown in Demonstration Project 2, (3) transformation of used VCMs into "new" magnets using magnet-to-magnet recycling, as validated in Demonstration Project 3, and (4) recycling of rare earth oxides from HDD magnets using membrane solvent extraction or acid-free dissolution processes as shown in Demonstration Project 4. A preliminary life cycle analysis revealed that most of these recovery options are more beneficial to the environment than the current practices of virgin production and shredding for mixed aluminum.

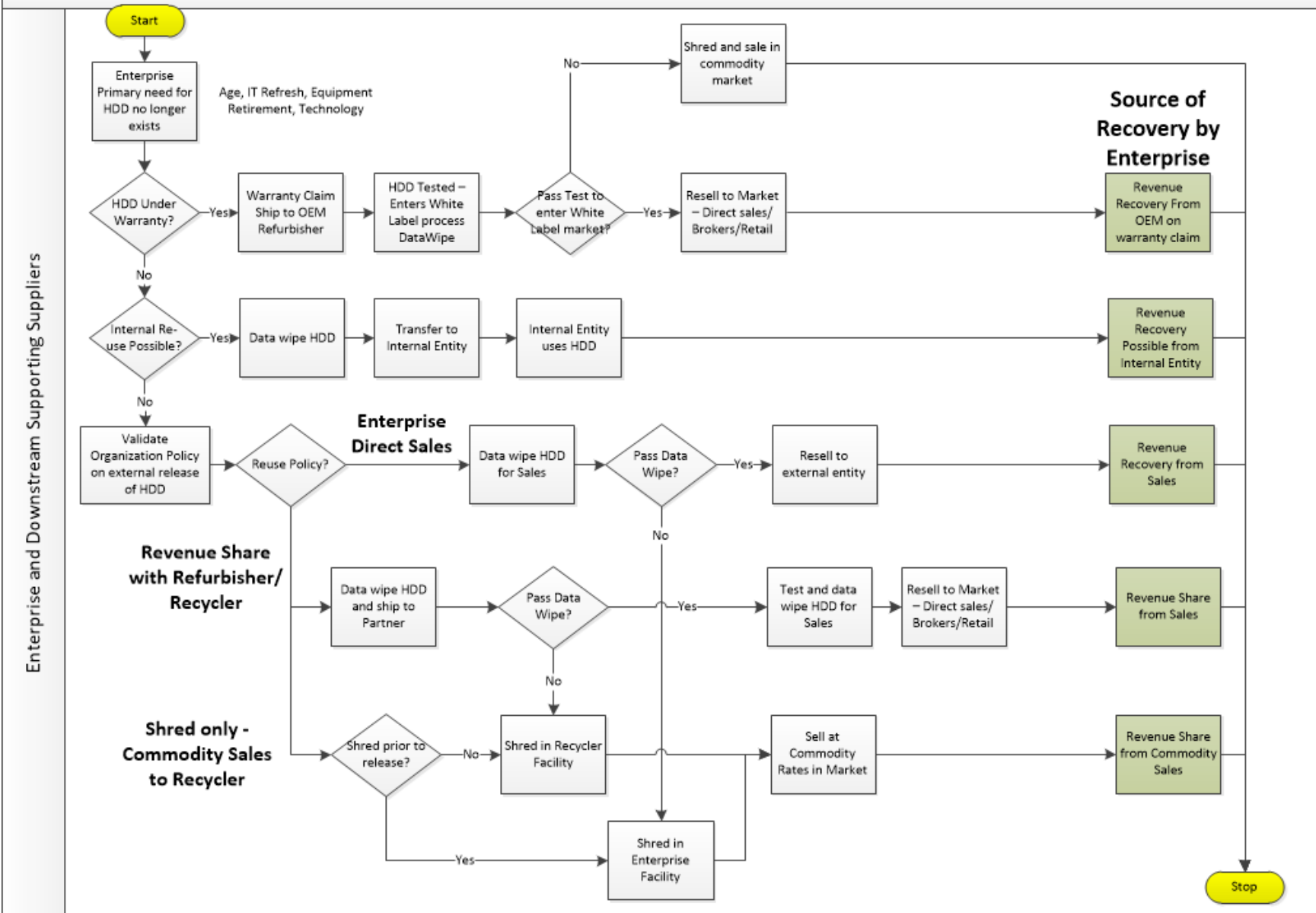


Figure 3: Economic reuse decisions for an enterprise user of hard drives.

Economic analysis of recovery options

Using enterprise economic analysis, each recovery method was evaluated and results are shown in Table 1(a) and 1(b). Please note that there are two hard drives shown: a 1 TB 3.5" enterprise hard drive, which is generally considered to have economic value supporting recovery, and a 500 GB 3.5" drive with marginal economic value that may not support recovery. Both drives are used to demonstrate the value of hard drives under both potential recovery points. Please note that labor is not considered in this evaluation since each organization's rates and production capabilities will differ.

- **Warranty claim** value shown is from submission to the manufacturer for some level of recovery. Enterprise users should consult the terms of purchase and exercise this option whenever possible. The alternative is commodity sales as mixed aluminum.
- **Internal reuse** is used when internal entities have the need for hard drives and they are able to use retired drives from first use machines. Depending on the needs of the enterprise, using this option could eliminate the expense of purchasing new hard drives. However, the recovery revenue shown is offset by the need to data wipe the hard drive internally.
- **Enterprise direct sales** is used when the organization can data wipe and manage the sales directly. It is recommended that sales be considered in bulk and not individually to avoid overhead costs of reselling in small sales.
- **Revenue sharing with recycler** pushes the handling and sales to the recycler to manage. The revenue is less than that of the enterprise direct sales method but moves any handling and data wiping costs to the recycler.
- **Value recovery from HDD magnets** is often hindered by the current practice of shredding HDDs for commodity value, which is the least preferred method simply for the small value recovered. To increase the value recovered from HDDs, iNEMI demonstration projects have focused on developing novel technologies and diversifying value recovery pathways. The potential values that can be captured from these projects are shown in Table 2. Since these technologies are still in development and demonstration phases, the reverse supply chain and demand for recovered components/materials have yet to be established or optimized to support large-scale operations. Therefore, one of the next steps from this iNEMI project is to collaborate with key stakeholders in the HDD supply chain to create business opportunities and commercialize the new technologies and recovery pathways.

Table 1(a). Example #1 of Hard Drive Values in Reuse and Sales: 1 TB 3.5" HDD

Recovery Method	Value As Is	Re-Use Method	Value when Recovered
Warranty claim	No — needs refurbished	Refurbish and resell as white label drive — prorated value	\$10 to \$35
Internal reuse	Yes	Data wipe and avoid purchase of new drive	\$42
Enterprise direct sales	Yes	Data wipe and directly manage retail sales	\$22
Revenue share with recycler	Yes	Data wipe and have recycler manage sales — 50% share back model	\$11
Shred for commodities	No — needs to be shredded	Shred drive for commodity recovery — mixed aluminum	\$0.44

Value recovered does not include bundled within a server, which could drive the individual value of the drive higher

Table 1(b). Example #2 of Hard Drive Values in Reuse and Sales: 500 GB 3.5" HDD

Recovery Method	Value As Is	Re-Use Method	Value when Recovered
Warranty claim	No — needs refurbished	Refurbish and resell as white label drive — prorated value	\$7 to \$25
Internal reuse	Yes	Data wipe and avoid purchase of new drive	\$32
Enterprise direct sales	Yes	Data wipe and directly manage retail sales	\$9.60
Sale to/with recycler	Yes	Data wipe and have recycler manage sales — 50% share back model	\$4.80
Shred for commodities	No — needs to be shredded	Shred drive for commodity recovery — mixed aluminum	\$0.44

Value recovered does not include bundled within a server, which could drive the individual value of the drive higher

Table 2. Potential Values Recoverable from Different HDD Recovery Technologies and Pathways

Recovery Method	Technology / Process	Re-Use Method	Value when Recovered
Direct reuse of voice coil magnet assemblies (VCMAs)	Disassembly, then proprietary cleaning process in class 100 clean room	Reuse magnet assemblies in new/ prime HDDs	\$3 to \$9 per HDD
Transforming used magnets into “new” magnets	Grain boundary engineering and hydrogen mixing reaction	Reuse recycled magnets into “new” HDDs or other products such as electric vehicle motors	\$30 to \$90 per kg of magnet
Recycling rare earth oxides from shredded HDDs or magnets	Shred, then apply hydrometallurgy, pyrometallurgy, electro-chemical process, or membrane-based separation	Recovered rare earth oxides for creating “new” magnets	\$51 per kg of rare earth oxide

Recovery steps and value streams

Expanding on the enterprise economic study, the project team completed a full cost recovery of a hard drive to show the potential resources that could be recovered. This section goes beyond the enterprise’s control and explores the recovery of components by the recycler that is driven by sale to commodity brokers. The original economic reuse decisions for an enterprise (as presented in Figure 3) are expanded to include the recovery steps and value streams created by available dismantle and recovery steps.

Figure 4 maps the magnet recovery methods that are supported by the other demonstration projects in this report. In Figure 5, this mapping is also expanded to include the other materials in the hard drive that can be recovered. Links between the two figures are labeled by the green A and yellow B connections.

Magnet disassembly and punching. Disassembly creates numerous issues, with the primary ones being the need for clean room-level cleanliness and the significant labor involved. Punching requires specialized machines to cleave or cut the magnet assemblies from the drive. Disassembly and punching both require disks to be shredded to ensure data sanitization.

Shredding of hard drives is also considered. The primary issue with this method is the introduction of contaminants with the magnets.

Figure 5 follows the disposal of the remainder of the hard drive:

- Hard drive circuit cards are removed and sold for precious metals recovery.
- Aluminum body or carcass, which include the platters, can be punched or disassembled.

Decision Matrix – Magnet Focused recovery V11

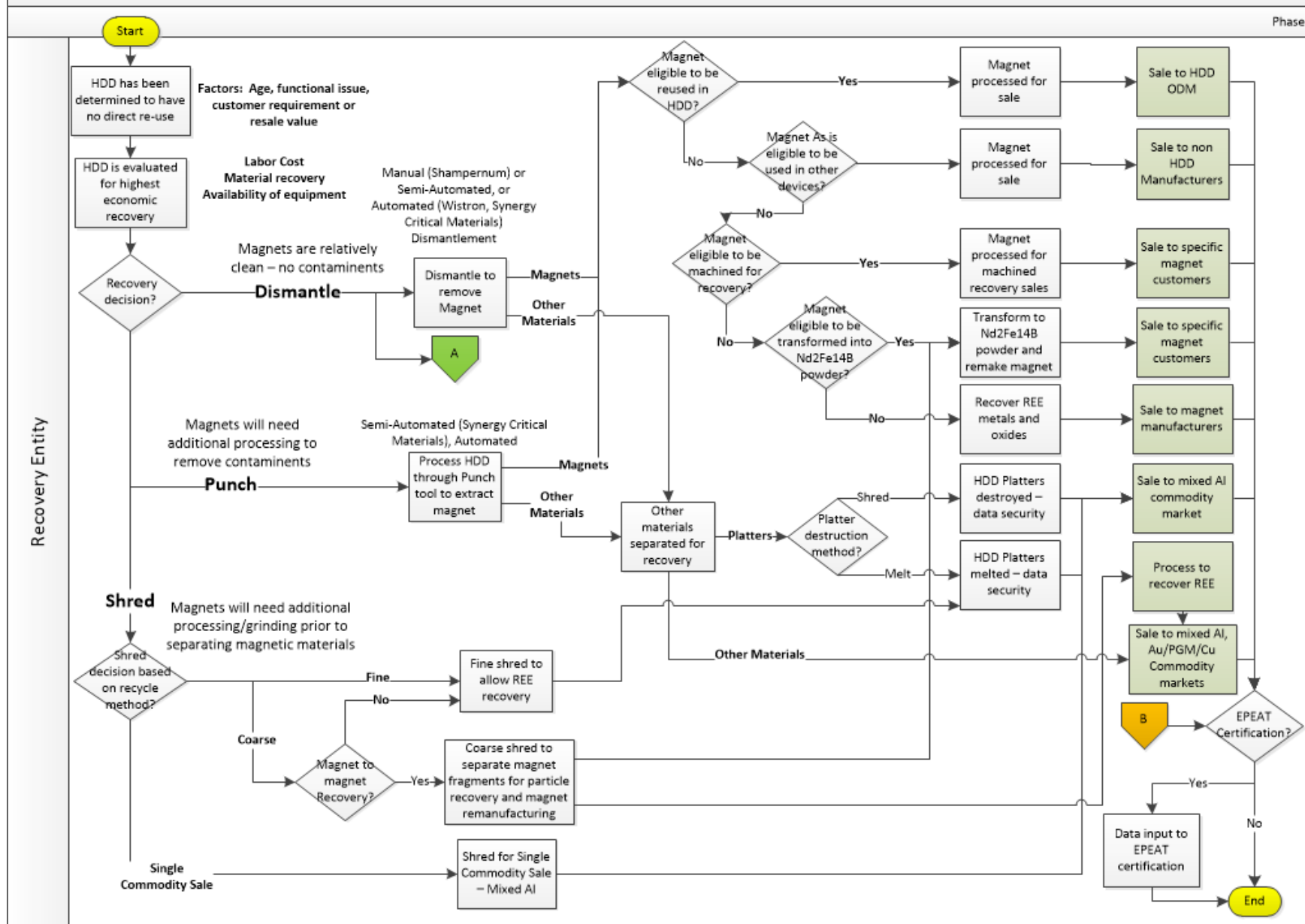


Figure 4: Magnet reuse decision chart.

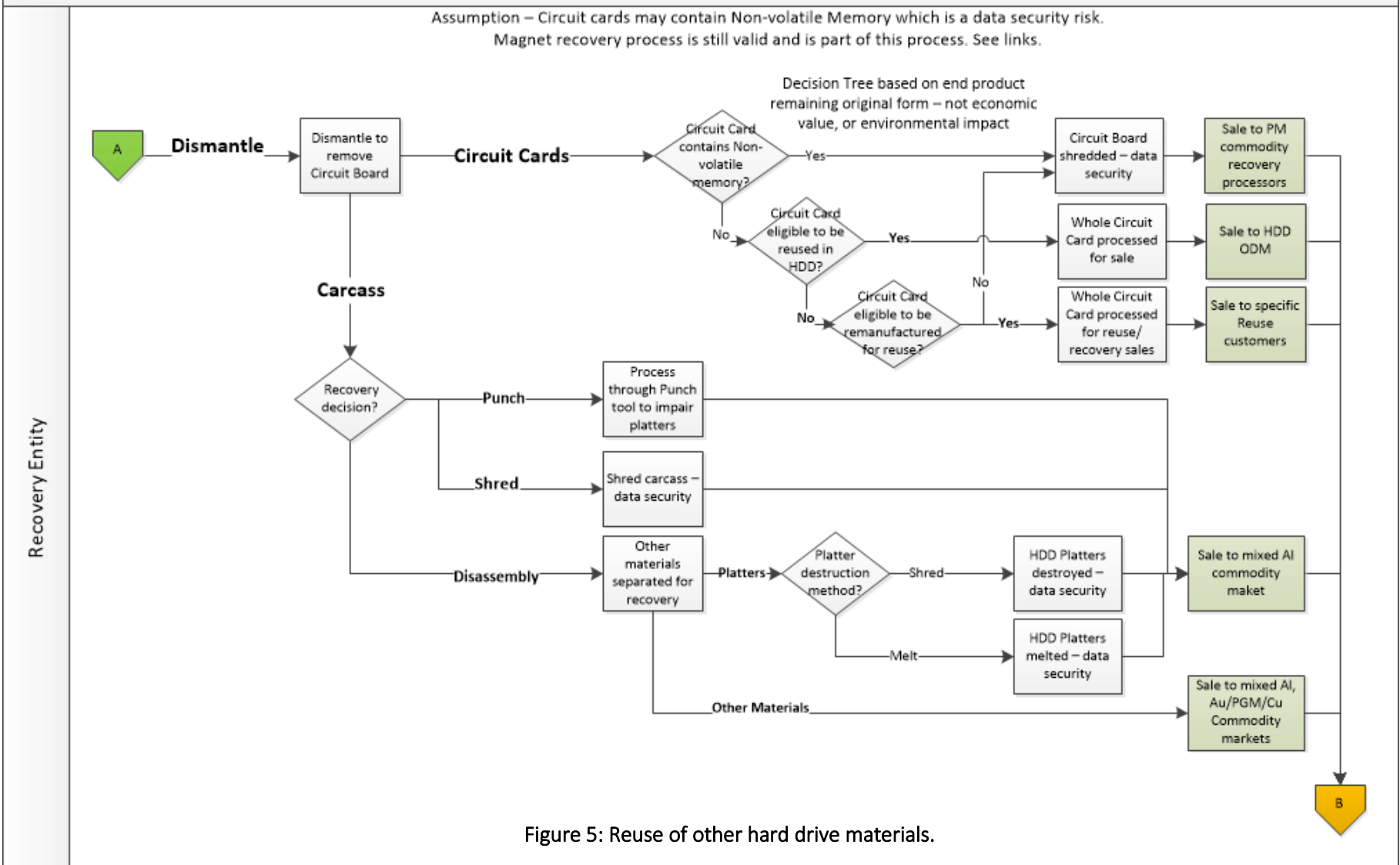


Figure 5: Reuse of other hard drive materials.

4. Conclusions

Enterprises have significant economic value present in hard drives that are ready for retirement. It is important to consider balancing data security concerns against the return on the sale of these drives. Given the maturity of the data sanitization software solutions in the market today, there are many effective ways to manage the risk of hard drive disposal.

5. Recommendations/Next Steps

This demonstration project team recommends that all organizations develop a clear data sanitization and destruction policy that reflects the standard that is to be followed, such as NIST 800-88 R1 which is the most widely used standard in the United States. This policy should define:

- How media is classified for risk of loss
- Handling/control of media
- Access and control of data
- Approved data sanitization methods
- Release of media to internal and external entities
- Communication path within the organization for issues and reporting
- Most importantly, an end-to-end history of each media device

Sufficient resources should be allocated to support this effort to ensure compliance.

Acknowledgement

This work is supported by Microsoft, Geodis, Cascade Asset Management, University of Arizona, Purdue University, and the Critical Materials Institute, an Energy Innovation Hub funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office.

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ENVIRONMENTAL IMPACTS OF HDD VALUE RECOVERY

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EXECUTIVE SUMMARY

Value recovery from electronic products, including hard disk drives (HDDs), is currently focused on high-volume metals that are easily recoverable and on low-volume, high-value precious metals. Current and future electronics will increasingly contain small quantities of materials, which are not recovered in today's recycling infrastructure. These materials include rare earth elements (REEs) that are critical to today's technology-driven society due to their importance to clean energy, as well as the risk associated with their near-monopolistic supply. This demonstration project assessed the environmental impacts of HDD value recovery pathways that include REEs and compared with those from current business practices. Four value recovery options were evaluated, specifically: (1) direct reuse of HDDs, (2) direct reuse of HDD voice coil magnet assemblies (VCMAs), (3) transformation of HDD used rare earth magnets into "new" magnets, and (4) production of rare earth oxide from shredded HDDs. The relevant primary data were collected from project participants across key stakeholders in the HDD value chain and national laboratories, and a life cycle assessment (LCA) was conducted to test expectations of environmental impact reduction from the circular strategies underlying the value recovery paths. Preliminary results strengthened the proposition of environmental benefits from circular strategies and identified impact drivers, enabling stakeholders to make more informed decisions in adopting circular strategies to improve the environmental performance of their products and businesses. Next steps were identified in order to support the implementation of HDD value recovery pathways, which require further development of the relevant technologies and the establishment of an optimal reverse supply chain.

1. Scope of Demonstration

This demonstration assesses and compares the environmental impacts from four HDD value recovery pathways focused on REE recovery with those from current business practices of shredding HDDs for mixed metal aluminum recovery. LCA was used to conduct a system-level analysis to test expectations of environmental impact reduction from the circular strategies underlying the value recovery options. Primary data collected from project participants was used to develop the LCA models and inform interpretation of results, in addition to the literature and secondary life cycle inventory data. This work was completed with the collaboration of multiple stakeholders in the HDD value chain: HDD manufacturer (Seagate), HDD user (Google), HDD after-market service provider (Teleplan), recyclers and IT asset management companies (IBM Geodis, Cascade Asset Management, Urban Mining Corporation), and research institutes (Purdue University and the University of Arizona).

2. Background

Key stakeholders in the HDD value chain have been exploring value recovery paths and developing innovative technologies that enhance materials circularity by enabling REE recovery from end-of-life HDDs. The value recovery options assessed in this project include the efforts described in demonstration projects 1 and 3, which go beyond the current practice of reusing just a limited number of HDDs or simply shredding HDDs for mixed aluminum. The options are as follows, in cascading circular economy pathways that are expected to increase value recovery from HDDs:

- 1) HDD reuse: reuse more end-of-life HDDs
- 2) Magnet assembly reuse: reuse voice coil magnet assemblies (VCMA) with NdFeB magnets
- 3) Magnet-to-magnet recycling: produce NdFeB magnets from used HDD magnets
- 4) Metal recycling: recover base metals (e.g., iron and copper), precious metals (e.g., gold and silver) and rare earth oxides (REOs) from shredded HDDs

Figure 1 shows the overall material flow associated with each recovery option.

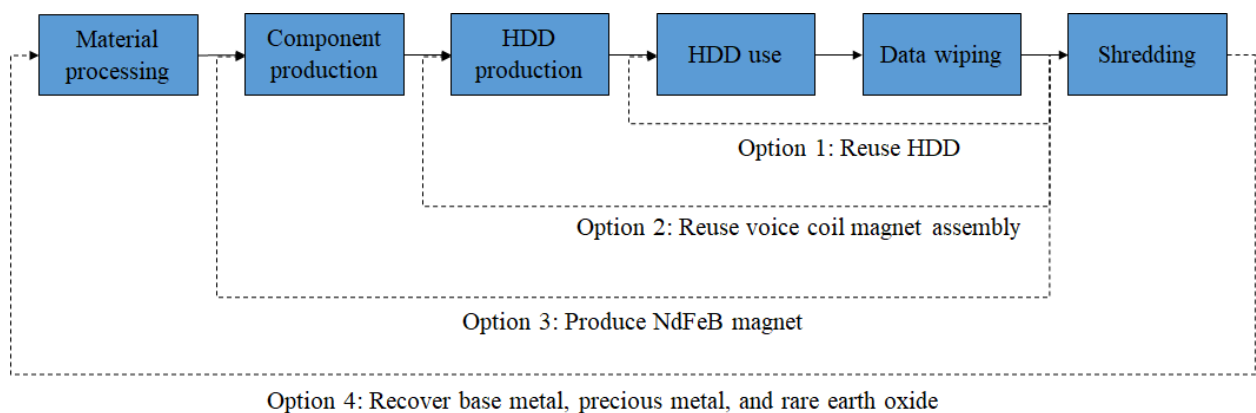


Figure 1. Value recovery options from HDDs.

These value recovery options are anticipated to be more environmentally beneficial than current business practices in the value chain, which heavily rely on virgin production of raw materials including REEs [10]. Primary production of REEs is often associated with radioactive materials, toxic chemicals and contamination of the natural environment [6-9], whereas REE value recovery options often consume less energy, chemicals, and raw materials, and thus have significantly less environmental impact than virgin production [10-11]. Circular strategies and closing material loops, however, are not always more environmentally beneficial, as they can have negative consequences. The expectation of environmental impact reduction from circular strategies underlying these value recovery options should be tested at a system level to avoid burden shifts or at least identify and acknowledge trade-offs.

For this purpose, this demonstration project focused on conducting an LCA study to compare the environmental impacts of the value recovery options represented in Figure 1 with those created by current HDD production and end-of-life (EoL) practices, namely shredding for aluminum recovery. Primary data collected from key HDD value chain stakeholders — Seagate, Teleplan, Geodis, Cascade Asset Management and Urban Mining — were used to develop the LCA models and inform interpretation of results, in addition to the literature [11-14]. The environmental impacts were assessed using the US EPA TRACI 2.1 impact assessment methodology framework (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) [15].

3. Results

Figure 2 represents net savings for each of the value recovery options compared to shredding for mixed aluminum, focusing on the global warming impact category. These benefits are calculated from avoided virgin production and EoL impacts, and the additional impacts generated from reuse and recycling activities. These are preliminary results and should be interpreted with the awareness that they are subject to the system boundaries, allocation, assumptions and data used. Detailed description of the methodology and LCA results for all impact categories will be available in Jin et al. (in preparation) [16].

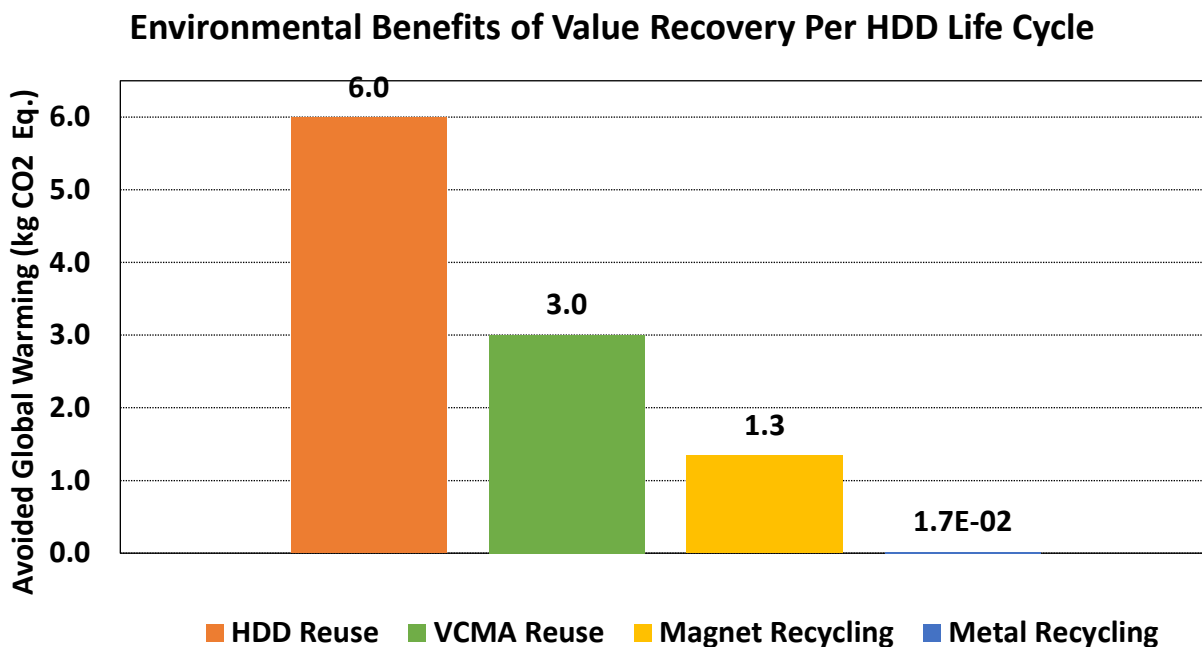


Figure 2. Greenhouse gas emissions savings from different value recovery pathways per HDD life.

Economic allocation was applied when there were co-products with different economic values. This is especially important for the metal recycling option because multiple materials, including base metals, precious metals, and rare earth oxides, are co-produced from an HDD, reducing the overall environmental impacts of REO recovery.

It is worth noting that the material loss rate of NdFeB magnet manufacturing plays a key role in determining the relative environmental benefits of magnet recycling. In this study, 40% of magnet materials are assumed to be lost during manufacturing [11], a majority of which are from magnet slicing and shaping for HDD VCM. Therefore, only 60% of NdFeB magnet demand is satisfied per HDD recycling, meaning 40% of new NdFeB magnets are required to create VCMs of one prime HDD. This is the primary reason why NdFeB magnet recycling achieves much less environmental benefit than direct reuse of VCMA.

The current study assesses each recovery pathway independently (i.e., one at a time). However, if multiple recovery pathways are applied together to recover more value from HDDs, we could achieve higher environmental benefits. For example, metal recovery is applicable to the leftover components and materials from VCMA reuse and magnet recycling (e.g., printed circuit boards) so that the combined environmental savings could be higher than the currently stated values.

Overall, the preliminary results of this LCA study align with the expectation that environmental savings tend to decrease from reusing a product or component to recycling contained materials, as embedded energy and functional value are increasingly lost. Therefore, it would be best to promote reuse rather than recycling. However, in reality, there are constraints associated with material flows, logistics, engineering, business processes, and regulations that may prevent reuse.

For example, a scenario analysis performed in this project showed that transportation mode can play a key role in driving environmental impacts of value recovery paths. With the current supply chain structure, transport of EoL HDDs to Asia was the only viable path for VCMA reuse. As a result, the global warming impacts of reusing VCMA were actually worse than those from a path with only virgin production if an entire HDD is transported by air (versus by ocean) from the U.S. to Malaysia with the sole purpose of reusing VCMA, which allocates all the HDD shipping impacts to VCMA reuse. That is, air transportation generates high environmental impacts such that reusing VCMA is not environmentally desirable, unless additional value recovery occurs in Malaysia or only VCMA are shipped to Malaysia.

Reusing HDDs or VCMA may also not be feasible if the hard drives are damaged or contaminated from EoL handling or a data wiping process, making magnet-to-magnet recycling the next best option for environmental impact reduction among those evaluated in this study. Also, when HDDs are required to be shredded by the end user, the best option is then to recycle the materials, including rare earth oxides, base metals, and precious metals.

4. Conclusions

Currently, EoL HDDs serve as a largely untapped resource of REEs. The value recovery pathways assessed in this project may help address the critical material supply issues associated with REEs and promote circular economy, while resulting in less impact on the environment when compared to virgin production. Data was collected from various stakeholders in the HDD value chain — including an HDD manufacturer, after-market service provider, recyclers and IT asset management companies — to perform a system-level environmental analysis using LCA. The environmental impacts of each of the value recovery pathways were quantified and compared with those from current HDD production and EoL practices. Preliminary

LCA results strengthened the proposition of environmental benefits from circular strategies and identified impact drivers, enabling stakeholders to make more informed decisions in adopting circular strategies to improve the environmental performance of their products and businesses.

5. Recommendations/Next Steps

In order to implement the HDD value recovery pathways, further development of the relevant technologies and establishment of an optimal reverse supply chain is crucial. The next steps to support these activities are:

- Refine LCA with more accurate and higher-quality data from primary sources
- Identify environmental hotspots
- Investigate other alternative processes and quantify the environmental impacts
- Optimize the reverse supply chain with inputs from technical, economic, and environmental analyses

Acknowledgement

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ROLE OF LEVERAGE IN ACHIEVING A CIRCULAR ECONOMY

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EXECUTIVE SUMMARY

The Value Recovery from Used Electronics project defines the pathway to a circular flow of resources from hard disk drives within a free-market economy. However, the goal of a circular economy will not achieve itself. Several barriers must be overcome, but it can be achieved through the voluntary actions of companies and organizations operating collaboratively in their own self-interests.

The creation of this system will require the application of “tools of leverage” to raise awareness and establish and enforce understandings between different participating organizations. The available tools of leverage identified here include technical documentation, industry norms and agreements, structured discourses, purchasing specifications and industry consensus standards.

1. The Role of Leverage in Achieving a Circular Economy

Humans currently extract technical resources from earth's crust far faster than those resources are replaced by geological processes. And for the most part, they dump the waste products in irretrievable forms. This is unsustainable. Unless closed resource loops can be established within a circular economy, the economic feasibility of resource supply will be degraded over time.

The iNEMI project team proposes that the way forward at this time is to create a circular flow of resources within a free-market economy through predominately voluntary actions. The framework of solutions must utilize informed and independent actors operating collaboratively in their own self-interests. This framework must be built around the consistent and reliable flow of information regarding product characteristics, optimal recovery practices and recovery technologies.

The goal is, therefore, to establish autocatalytic networks of agents that do not now exist and that will establish ways and means to effect the transformation to a circular economy. This section explores the use of leverage tools that are based predominately on information sharing, versus tools of command and control, in order to bring actors in the HDD reverse chain of commerce into mutually beneficial collaboration such that resource recovery is optimized.

2. Background and Strategic Assumptions

This section is based on three strategic assumptions regarding creation of an effective recovery system.

The first assumption is that there are barriers that must be overcome in the current EoL recovery system in order to establish a circular flow of HDD resources.

The analyses conducted by the technical and business experts on this project team demonstrate that a future state of doing business, with interlinked businesses achieving a considerably higher level of recovery, is technically and economically feasible. This implies that a more effective resource recovery system will be more economically favorable than the current situation.

However, this improved system will not arise unaided because several barriers stand in the way. Five primary barriers are described here, but it is anticipated that more in-depth economic and technical research will be necessary.

The second assumption is that the pathway to a circular economy will entail voluntary arrangements and partnerships, which do not now widely exist, involving informed and independent agents. These agents will be linked through the flow of information and resources.

When new and promising initiatives by one agent in the commerce stream are dependent on the actions of others, it is necessary for their businesses to be linked through reliable structures. Those structures are described in this section.

Of all the actors in the supply chain, from manufacturer through final recycler, an especially critical actor is the initial service provider. This company likely works directly with the final user of the old HDD and is involved in collection and consolidation, as well as in performing initial triage and processing, upon which all downstream recovery depends. This agent is directly responsible to the final users' needs, knows the options for downstream value recovery, and evaluates individual units to determine their optimal recovery pathway.

The third assumption is that tools of leverage can be applied to create the linkages along the reverse supply chain that will lower and even remove the barriers to higher value recovery.

In practice, these tools rely primarily on the generation and flow of information and on the arrangements that assure performance. Some of those means of information flow are formal institutions, such as consensus standard bodies with systems for conformance assurance. These may allow one actor – such as the last user, or an institutional purchaser of HDDs – to have confidence that their policies for internal security or product performance will be understood and respected by other actors.

The intent of this iNEMI project is to provide a systems perspective on the EoL management of HDDs in order to define a common framework within which individual actors can optimize financial and resource recovery. Their participation will be driven by an understanding of the best options that maximize their self-interest and facilitate the connection points with other actors.

The following section describes some of the chief barriers to a circular economy and then outlines a range of leverage tools that can be applied to overcome them. As with this entire project, the team does not have all the answers, but is confident that it has defined technical and business methodologies that, with further investigations and intentional actions, will move HDD management toward circularity.

3. Five Chief Barriers to a Circular Economy of HDDs

As work on creating a circular economy for HDDs moves forward based on this iNEMI project it will be essential to clearly understand the chief barriers that now impede optimal recovery, and to develop the most effective tools of leverage to overcome them. This section identifies some of those barriers.

Data security

An initial and predominant barrier is the lack of confidence by HDD users regarding data security by processing methods that do not entail total HDD destruction through shredding. Shredding closes off all reuse and many of the most profitable material recovery options. Data security is the first consideration in determining appropriate processing as, of course, is cost. However, both of these factors can be managed through new technologies of data wiping and verification that are addressed in this report.

Even with good technical solutions a key factor will still be the organizational policy of the last user regarding data security. Such policies often favor the most extreme destruction pathway since data security typically overrides any other consideration. The data wiper's ability to carry out a state-of-the-art wiping process, including chain of custody and verification, are paramount and essential to building trust between owners and recyclers. This trust opens the door to greater value recovery for both owners and recyclers.

Aggregation of quantities

A second barrier is the lack of effective aggregation of the quantities needed for cost-effective processing. It will be essential to develop a systematic means of collecting used HDDs that:

- Accumulates the quantities needed for cost-effective processing
- Provides for a comprehensive analysis of each HDD for its highest recovery potential through reuse and/or material recovery
- Assures data security

To achieve this the initial service provider must have good relationships both with last users and with downstream processors.

Technical solutions

A third barrier is the lack of wide availability of certain technical solutions for different phases of HDD processing. These are identified in this report and they will need to be developed and widely implemented. They include: disk wiping that assures data security without destruction, methods for optimal reuse of whole units and components, and separation and refining processing for valuable and critical materials. All of these technologies are under development, as outlined above, but not yet widely implemented.

System-wide guidelines

A fourth challenge is to disseminate a set of system-wide guidelines, based on a decision tree approach, that outline best practices for all downstream activity. This includes the initial steps of triage, data sanitization, reuse, processing for material recycling, and downstream resource marketing and disposal.

Transboundary movement

And fifth, there are currently barriers to the effective routing and flow of HDDs and their recovered resources across geographies from the last user to locations that have the capability and capacity to provide optimal value recovery. This will likely include transboundary movement since processing capability and markets may be lacking locally where the used HDDs are generated. Although HDDs do not, in general, contain the toxic materials that should restrict transboundary movement, they are frequently contained within larger units and are, therefore, often caught up in the overall restrictions of movement of e-waste resulting from the Basel Convention.

None of these barriers appears unsurmountable; but it may require a set of coordinated actions to bring them about. These barriers, and others that will likely be identified, should be addressed through application of some of the tools defined in the following section.

4. Available Tools of Leverage

There are several tools of leverage that can be employed to bring agents voluntarily into mutually beneficial collaboration instead of using tools for command and control such as laws and regulations. These tools will incentivize actors in the chain of commerce to collaborate through sharing information and resources because it is to their mutual benefit. Again, the purpose of leverage is to help these agents overcome the barriers that keep them in a financially and environmentally unsustainable system.

The following section identifies what kinds of levers may be appropriate and effective, who can exercise those levers, and on whom they should be applied. The desired outcome is the objectives and system described previously in this report.

Leverage tools are, in essence, ways for different agents in the chain of commerce to express their self-interest to others, and to align their activities so they are mutually supportive. Leverage begins with the customers – the users of HDDs – who specify to manufacturers the products’ desired qualities, and how they wish them to be managed at EoL. Thus, everything cascades from that collaboration between the user and the producer. Leverage then extends from the relationship between the last user and the initial service provider at product EoL. Downstream from the initial service provider may be brokers, repair/upgrade/reuse organizations, remanufacturers, material recycling processors, and specialty material refiners.

Technical documentation

The first kind of tool is technical documentation, of which there are many types. Such documentation is intended to demonstrate the feasibility of the system to recover economic and resource value. The single most valuable document will be the HDD recovery decision tree described in this report, which is relevant to each stage of the recovery process. Using a decision tree as a guide, actors at each stage of the process can assess and triage products they receive in terms of downstream recovery potential. Each node will identify how to assess the product – what tests may be needed, what data to look for, and what criteria to apply – and then indicate what kind of processing will recover the highest value resources. The indicated type of processing may be outside of one actor’s wheelhouse, but well within that of another actor, and a profitable exchange should be achieved.

One critical type of documentation is information from the manufacturer regarding the characteristics of the product and its materials. This may include notification of the location of hazards, indicators of how to disassemble the unit without destroying resources, availability of spare parts, etc.

There are several different types of guides that may be valuable, including design guides for manufacturers or best practice guides for reuse, repair and processing. For example, different HDD models have different locations for the magnets, and a guide showing a proven method to quickly remove the spindle magnet, by punching or disassembly, could facilitate magnet reuse and REE recovery. A quickly accessible website with such documentation would be an aid for processors.

One of the objectives of the Value Recovery project was to provide insight and possible guidance on choices, along with analysis of what can be done to aid in facilitating a more circular economy for HDDs.

Industry norms and voluntary agreements

Industry norms have been utilized extensively by the electronics manufacturing industry to assemble the best information from a wide segment of industry to be shared with others. A good example is the Responsible Business Alliance’s (formerly the Electronics Industry Citizenship Coalition (EICC)) work on how to achieve social responsibility. They produce codes of conduct, documents on assessment processes, and other tools. These efforts can foster voluntary initiatives or binding agreements.

Manufacturers can establish norms by which they voluntarily provide certain information about products on their websites or in product literature, which can include disassembly methods. Such requirements are included in law in the EU.

Structured discourse and action

The purposes of discourse are to increase understanding, gain consensus on outcomes and organize action. This iNEMI project is an excellent demonstration of what such an activity can produce. It brought together stakeholders who may have similar interests but very different experiences, expertise and perspectives. They shared their knowledge and engaged in technical investigations, problem solving and report production. Organizations involved in this project provided expertise from the electronics manufacturing industry, reuse and recycling businesses, academia and a standards organization. This group is dedicated to continuing the development of the ideas laid out in this report.

These kinds of activities can result in partnerships being formed to carry out agreed-upon recommendations and to implement parts of the system. These partnerships can be business-to-business, business-to-academia, or they can include standards organizations or NGOs.

Workshops and webinars, as well as conference presentations, are frequently used to educate and to engage new participants.

Purchasing specifications

Purchasing agents from government agencies, large institutions such as hospitals and universities, and large business enterprises perform their procurements by first specifying the characteristics they desire in products, and then requesting offers and prices of products that meet their requirements. Purchasers can include any characteristics and qualities they desire, per their organizational policies, in the procurement specifications. Increasingly, institutional purchasers are including environmental qualities, such as recycled content, energy efficiency, product recyclability, etc. And then manufacturers or, in some cases, third-party sellers are responsible for the products meeting the documented specifications. This system allows purchasers to be quite specific and wide ranging in their specifications, including environmental qualities, as long as manufacturers can provide products that meet them at a reasonable price.

Such specifications can apply to services as well as products, including end-of-life management services. Thus, a data center manager or government disposition specialist can specify in a bidding document that a company that collects and processes its out-of-service products manage those products in a specified manner.

However, purchasers are generally not experts in the complex, and sometimes nuanced, qualities that assure product environmental qualities, such as circularity. As a result, they often defer to standards, as described in the next section, to provide the detail needed, and to save themselves a lot of work. Institutional purchasers are, therefore, often active participants in standard setting processes because they wish to assure that those standards address their policies.

Industry voluntary consensus standards

The setting of standards is a higher level of complexity than the previous tools, but standards can establish an effective, credible and widely utilized system. Voluntary consensus standard processes that conform to the requirements of the American National Standards Institute can be lengthy and even contentious. But when completed their power in the marketplace can be substantial.

In practice, standards generally have two components — development and enforcement — that are delivered by dedicated organizations, either for-profit or not-for-profit. Standard development is generally a consensus process that involves a range of stakeholder types. Enforcement is generally conducted by an auditing organization or a certification body, either of which will audit the product or service according to the standard and issue a compliance judgment as a certificate or registration. In some cases, standard setting is conducted by the same organization that does the certification, though through a separate division and sometimes by a different organization. Standards can then be specified by institutional purchasers to fulfill their procurement policies, but without having to develop the requirements or assure conformance themselves.

There are several good examples. Product standards such as those developed by IEEE and NSF International, which are implemented on, and certified by, the EPEAT Registry (www.epeat.net), have already been used to begin to address HDD recovery. The NSF 426 environmental performance standard for computer servers includes incentives and, in some cases, requirements for some HDD environmental characteristics, such as design for disassembly, use of recovered REEs, the provision of locational information regarding REE magnets, and product take-back requirements. However, this standard was

developed in advance of, and was not fully informed by, this iNEMI project. Updated work on the server standard, and future standards, are expected to build on the findings of this project.

The field of data security is also strongly represented by standards. NIST data wiping guidelines (NIST 800-88 R1) provide the basis for the portion of this study regarding data wiping.

The world of electronic recycling includes several competing environmental, health and safety standards. Two systems dominate in the U.S. – R2 (Responsible Recycling), operated by Sustainable Electronics Recycling International (SERI), and eStewards, operated by the Basel Action Network (BAN). Both organizations manage the development of their respective standards and enforce them through certification services.

Who would develop and operate each of the leverage tools for HDD recovery?

The recovery chain involves several different actors, from the last user through to the final recycler. At each link in that chain it is possible that a leverage tool may be applied, and it may involve different tools, implemented by different actors, at each link.

For example, the link between the manufacturer and the user generally involves product purchasing specifications or standards. Purchasers may even participate in a cooperative, which would be housed within an association or not-for-profit organization, to provide support for implementation of their procurement policies. The link between the last user and the initial EoL service provider can be governed by data security and recycler standards, which are provided and governed by standards development and certification organizations. In addition, the links between actors in the reverse chain of commerce may be governed by voluntary agreements between the organizations.

An implementing organization

Since the HDD recovery system will involve so many independent actors and implementation tools working toward a common objective, it would be valuable to build a new organization to oversee its establishment. That organization would:

- Maintain the decision trees and other technical documentation
- Form partnerships with academics to perform essential research on new technologies
- Publicize the decision trees and technical documentation to data centers, manufacturers, reuse organization and recyclers
- Organize symposia and other meetings
- Coordinate with other organizations, such as industry organizations and standards bodies, to develop and implement tools that achieve the recovery objectives
- Conduct structured discourses to explore the potential for applying the tools developed for HDDs to other electronic products

This new organization would continue to improve the work performed by the iNEMI team, facilitate its implementation and explore opportunities to expand to other electronic products.

5. Conclusions and Recommendations – A Pathway to Success

This iNEMI project has developed important methodologies for addressing the currently unsustainable electronic recycling system, specifically for HDDs. The implementation of these methodologies promises to increase both economic and resource recovery, both of which are necessary for success. A diverse set of leverage tools are available to help accomplish this implementation. The tools described in this section have not been studied in depth by this project, but team members have experience with them in other contexts.

It is recommended that the iNEMI team continue this project, and possibly expand participation, to maintain the momentum to continue the explorations that have only been partially completed at this writing, and to bring in new expertise.

An immediate priority is to work toward building partnerships with companies and organizations that can help overcome the barriers identified in the report and this section. Such partnerships could help achieve the transition to the new organization and new mode of attack.



PROJECT CONCLUSIONS

The iNEMI Value Recovery from Used Electronics project went beyond the theoretical to demonstrate that an applied circular economic framework *does* work. It completed the first practical work for remanufacturing magnets from hard disk drives (HDDs), took the first step toward making new HDDs from components of old HDDs, and recovered rare earth elements (REEs) from used HDDs.

To demonstrate practical applications, there were several goals that had to be met:

- Identify and eliminate the barriers to widespread HDD reuse
- Establish the supply chains for commercializing one or more REE magnet recovery processes from HDDs
- Test whether there is value in the Ostrom Framework organizing stakeholders in the HDD value recovery chain to manage HDDs and other man-made “common pool” resources

In support of these goals, the project team successfully completed five demonstration projects for various methods of whole or partial HDD reuse, recovery/reuse of REEs, whole magnet recovery from various end-of-life streams, plus identification of the decisions required to enable organizations to derive maximum value from recovery of HDDs. Accomplishments and key findings from these five demonstrations are summarized below.

1. HDD Magnet Assemblies Can Be Effectively Harvested and Used to Build New Hard Drives

The Value Recovery project completed the first practical demonstration of magnet remanufacturing for an HDD (i.e., magnet extraction, cleaning and insertion into the manufacturing production line) which is the first step in making a new HDD from an old HDD. Specifically, the project team was able to successfully remove voice coil magnet assemblies (VCMAs) from used HDDs, and then use the recovered assemblies to build new hard drives of the same model utilizing the original magnet assembly part number. In doing so, they:

- Assessed the feasibility of HDD magnet assembly removal in a clean room environment, developed a process for magnet removal, and successfully conducted the first magnet assembly removal trials.
- Developed a trial process for reclaiming reused parts from external partners outside the HDD OEM and using them in prime drives.
- Provided process, energy and materials data for quantifying environmental gains from drive direct magnet assembly reuse. Preliminary results from life cycle analysis showed that direct reuse of magnet assembly saves 6 kg of CO₂ eq. emissions, which is 96% of the virgin magnet assembly impacts.

2. HDD Magnets Can Be Directly Reused in New Motor Designs

The iNEMI team demonstrated — for the first time — that intact magnets can be harvested in a manner that provides an ample supply of magnets for motor designers at a price point that indicates direct reuse magnet motors could become a viable enterprise.

The team was able to develop conceptual motor designs utilizing magnets recovered from HDDs and constructed an axial flux gap motor. This kind of direct magnet reuse takes advantage of alternate and economic supplies of highly desirable REE magnets and has potentially significant environmental impact

by avoiding the thermo-chemical processing required to make original magnets. The iNEMI team demonstrated that:

- HDD magnets can be recovered undamaged
- Magnets can be recovered in large numbers (>1MM/year)
- Useful products, beyond HDDs, can be manufactured with recovered magnets
- New HDDs can be manufactured by directly reusing recovered components from end-of-first-life HDDs

3. New HDD Magnets Can Be Produced from Magnets and Coarse Shred

The project team demonstrated that it is possible to harvest magnets from a mix of used HDDs (both whole HDDs and coarse shred) and produce new HDD magnets that have magnetic properties comparable to conventionally produced, modern HDD magnets. The team specifically demonstrated use of Urban Mining Company's Magnet-to-Magnet® (m2m®) process for recovering magnets from HDDs and reprocessing them into new magnets. They were able to prove that:

- It is possible to harvest magnets from a range of HDDs in a way that can be commercially viable
- The magnetic properties of produced magnets are at a level suitable for use in new HDDs (based on comparing actual magnetic performance of recycled magnets and new HDD magnets)

4. Rare Earth Oxides Can be Made from EoL HDD Magnets

The iNEMI team successfully demonstrated the recovery of high-purity rare earth oxides (REOs) from magnets contained in end-of-life HDDs. They validated the capabilities of two different technologies for REO recovery: Momentum Technologies' MSX process and the Ames Laboratory's acid-free dissolution process, both of which obtained high-purity rare earth oxides suitable for magnet production. These efforts:

- Demonstrated different recovery paths to produce REOs from HDDs
- Successfully recovered high-purity REOs (>99.5%)
- Created metal ingots from the recovered oxides, which can be used as feedstock for remanufacturing permanent magnets
- The REOs can be used to help meet the 5% EPEAT standard by reintroducing them into the supply chain to make new magnets

5. Created Processes and Partnerships for Securely Wiping and Selling Functional HDDs to New Users

Significant economic returns can be realized from hard drives that are ready for retirement, and organizations can make choices to help enable these returns while mitigating risks related to data security. The iNEMI team created a business model to move HDD end-of-use management from "reuse or shred" to "reuse and recover" to ensure the highest value recovery possible for used HDDs, i.e., direct reuse of

functioning HDDs. This model defined economic decision-making processes and developed the data required to analyze wiping and resale (as well as other recovery pathways). Key findings include:

- HDDs that can be reused internally (\$42 for a 1 TB HDD) are worth nearly 100x the value of HDDs that are shredded for commodities (\$0.44 for a 1 TB HDD). Larger capacity drives (which are newer) have an even higher value recovery ratio.
- Direct reuse of VCMAAs has a positive value recovery.
- Positive economic and environmental benefits can be realized from all the pathways; reuse of HDDs, recovery of VCMAAs, creation of new HDDs from used HDDs and recovery of REOs from HDD magnets.
- There is a market that can drive manufacturers to make different hardware decisions. *The NSF/ANSI 426-2018 Environmental Leadership and Corporate Social Responsibility Assessment of Servers* standard awards points for HDD magnets with 5% post-consumer recycled REE content. OEMs are pursuing this requirement due to the preferential purchasing status conferred by meeting this requirement in the EPEAT registry.

6. Conclusions & Next Steps

The Value Recovery from Used Electronics project was organized explicitly using the Ostrom Framework as a self-managing, sustainable system to create a circular economy (CE) for hard disk drives. The Ostrom Framework is based on establishing shared goals as well as respecting the goals of the individual organizations in the partnership. Sharing information needed to make informed project decisions and building and maintaining trust were key for keeping the project on target and for understanding what the barriers were for certain partnerships or circular economy pathways. It required that all the members of the team were able to represent the views and policies of their organizations in team discussions and showed leadership within the project in their highest priority areas. As a result of this way of collaborating, the project team went beyond the theoretical in demonstrating the major value recovery pathways for used HDDs in a circular economy. Such a systems approach taken by the team to create a circular economy for HDDs has never been done before. As far as the team knows, the Ostrom Framework has never before been used to design a multi-stakeholder system for self-managing and creating value from a man-made common pool resource, in this case HDDs.

Today, essentially all of the value of HDDs is lost by shredding them into mixed aluminum scrap sold at \$0.25/lb. This is in contrast to the significantly higher value recovery possible with HDD reuse, component reuse (VCMA), or recovery of REEs as magnet powder, oxides or metals. Establishing that all of these pathways can be realized economically, logistically and with lower environmental impact was a significant accomplishment, not just for secure data wiping/reuse but also for value recovery of REEs.

Project accomplishments include:

- People from 15+ organizations from across the electronics supply chain worked together on a practical application of circular economy concepts for electronics.
- Participating organizations developed common goals, built relationships based on trust, shared information needed to make informed decisions, and built models of what their supply chains must contain and how they must operate in order to sustain a circular economy for HDDs.

- Presented results from extensive analysis of business models, logistics, and economics necessary for secure, verifiable data wiping and identified barriers to their acceptance.
- Demonstrated cascading circular economy pathways, with the highest value recovery pathway considered first. These included reuse of HDDs, recovery of key HDD components for reuse and remanufacturing for HDD and non-HDD applications, magnet recovery for magnet remanufacturing, and REE recovery. The use of these pathways was supported by the creation of decision trees based on the information needed to select one pathway over another.
- Identified at least five pathways for high-volume REE recovery and completed demonstration projects and economic and logistics analyses to assess their overall feasibility.

The project team is discussing continuation of the project into a third phase to maintain the momentum. Future work would implement solutions identified, including validating and verifying of data wiping solutions and building broader and deeper supply chains and partnerships for realizing a circular economy for hard disk drives.