PROJECT REPORT
Value Recovery from Used Electronics

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Executive Summary

This paper details a process and methodology which holds promise to substantially improve the economic and resource value recovered by electronics reuse and recycling. Hard disk drives (HDDs) are the case example. It is built on decision pathways for HDD refurbishment, component reuse, and material recovery, which incorporate economic and resource recovery analyses. The findings are intended to remove existing barriers and establish the basis for an implementable system. Further project activity will use a collaborative, stakeholder-based approach for building a voluntary, self-governing system. The methodology could also be used as a model to address other electronic components and products.

The goal is a sustainable circular economy of HDDs, and eventually all electronics, based on efficient and full exploitation of value potentials inherent in the products. Electronics and the materials with which they are made represent common pool resources that many people rely on for their livelihoods. Dr. Elinor Ostrom (2009 Nobel Laureate in Economics) laid out a framework for how people and organizations can develop voluntary, community-based solutions involving adaptive, self-governing systems that effectively manage common pool resources.

The term “end-of-use” (EoU), rather than end-of-life (EoL), is used here because EoL is generally interpreted as materials recovery alone and is, therefore, a misnomer for both what is already being done and what we are working to maximize in this project. We can realize more value and reduce environmental and health impacts if the electronics community and its stakeholders work together to implement an integrated, circular value recovery system that includes optimized product design, life extension, reuse, refurbishment and material recovery, and the processes required to enable it.

There is increasing pressure worldwide for societal transformation from a linear economy – based on the traditional take-make-waste model – to a circular economy. The expanding worldwide demand for electronics – and specific to this study for data storage – is increasing opportunity for the electronics industry, while also increasing resource consumption, and the most successful companies will modify their business practices consistent with circular economy principals. To date, some individual companies in the electronics industry have taken this direction but, as a whole, the industry has not undertaken the business-model-level initiatives that are key for a serious transition to a circular economy. There are, nonetheless, examples that show great promise, and this report builds on those examples.

This report provides a methodological approach for the electronics industry to get ahead of the regulators, starting with HDDs, and develop new pathways for a sustainable circular economy for electronics through voluntary and coordinated stakeholder/industry action.

The analysis used in this paper produces decision trees that show the sequence of recovery choices including processing schematics, decision points, and new pathways to value recovery. The challenges of data security and the barriers that customer demands pose for effective recovery are discussed, and feasible approaches are identified. In addition, the project evaluated
the sales value of used and functional HDDs from a third party using linear regression models. Our intent is to capture what the current financially viable options are, what future options for value recovery might be, and what a “best practices” framework might look like. This will require an approach that integrates a sequence of new, optimized or expanded practices with each step designed to recover value and to enhance further downstream value recovery.

This change will not happen by itself without appropriate drivers. A variety of enablers or implementation mechanisms will be needed, including guidelines, purchasing preferences and standards.

The report identifies factors affecting the feasibility of value recovery and the unique roles of different stakeholders – including HDD manufacturers, users, electronics OEMs, OEM-authorized aftermarket service providers, IT asset managers, reuse and remanufacturing organizations, recyclers, and smelters/refiners for metals recovery – as well as the secondary markets for drives, parts and materials. In particular, it reports on the economics of value recovery for three pathways:

1. Resale of fully functioning electronics and OEM HDDs
2. Remanufacturing and rebranding (white label) of devices unsuitable as recertified OEM drives
3. Parts and commodity materials recovery

Stocks and flows analysis is presented for used HDDs with a case study from North American data centers. Existing pathways and enhancement opportunities are portrayed using decision trees that include the economic basis of decision making. These analyses address barriers and opportunities for reuse, parts and materials recovery, manufacturing new drives from used parts, HDD re-design for parts harvesting and drive refurbishment, reuse of parts for something other than HDDs, and rare earth element recovery.

Some of the analysis was based on a survey of different stakeholders which asked about major decision points for direct reuse, dismantling, parts reuse and parts sorting to identify barriers, how those barriers might be overcome and who would be needed to work on them. The survey included manufacturers, users, processors, recyclers and university researchers, and their generalized responses are included in the report.

The report includes a section on the need for a coordinated system of best practices along the entire recovery chain, and some of the enablers that could be used to achieve that. Special attention is paid to voluntary standards for product design, information sharing and reuse and recycling practices.

And, finally, the recommendations lay out a set of action steps to initiate an Ostrom-framework project to build the understanding and consensus needed for progress toward a circular economy. It concludes with an identification of some of the challenges that should be addressed through such a process.
Chapter 1: Value Recovery from Used Hard Disk Drives

The focus of this report is on opportunities for the circular flow of HDDs. It highlights that this can only be achieved within a collaborative system, involving businesses across the chain of commerce that functions in a coordinated fashion to achieve common objectives for value recovery.

1.1 Project Background and Context

Used electronics have value that is frequently unrealized. This iNEMI project — Value Recovery from Used Electronics — focuses on hard disk drives (HDDs) with the goal of identifying opportunities for, and removing barriers to, recovering value from used HDDs. Throughout this project, we have challenged ourselves to rethink our linear view of the lifecycle of electronic products, to learn about what pathways already exist to increase value recovery and analyze how we might increase their effectiveness. We have also developed new strategies to realize a circular lifecycle view where value is retained, through reuse and cascading of lifecycles through alternative product re-manufacturing, prior to full component and waste reclamation of the core minerals and metals. We present this report as a first step toward an increasingly circular economy for HDDs, identifying ways in which this approach is presently being adopted and undertaken to provide a sustainable lifecycle value recovery solution. We also hope to demonstrate that a multi-stakeholder collaboration may also be effective for other kinds of electronics.

This project was originally titled Value Recovery from End-of-Life (EoL) Electronics, but it became clear to the project members that the term “EoL” is generally interpreted as materials recovery alone and is, therefore, a misnomer for both what is already being done across the electronics lifecycle [1] and what we are working toward in this project. The importance of the change in terminology becomes clearer if we take a used car as an analogy. We expect that a car will have multiple “lives” with successive owners, undergoing intermittent repair to maintain its value as a vehicle, until it becomes a source of spare parts, and finally as commodity materials through recycling of scrap metal, rubber, plastic and glass. Cars are intentionally designed to be repaired and have an extended working life. A lifecycle of 15 years is commonplace and as many as 60 years can be practically achieved. Multiple “lives” are made possible by owners replacing their cars long before they are only suitable for spare parts or steel scrap.

The used car analogy is also helpful in identifying the elements that can make this circular, life-extending flow of products practical via cascading of the life and use of products. This includes products designed with repair, reuse, harvest and recycling in mind; used product disposition designed with chains of commerce that take advantage of reuse and recycling opportunities; the availability of detailed product information that helps create and optimize these opportunities; and established markets for products, parts and materials derived from the used products.
In terms of value recovery for electronics, many value recovery supply chains already exist, with a dynamic, enabling mix of IT asset management activities, including data security and destruction, logistics, repair, remanufacturing, physical destruction and recycling. Unfortunately, many used electronic devices do not find their way into these supply chains, even as recycled materials. This loss of value to society of used electronics has a number of causes, which can be traced back to the electronics industry’s linear lifecycle model of products.

We can find and realize more value and reduce environmental and human health impacts of electronics if the electronics community and its stakeholders work together to determine what an optimized, integrated, circular value recovery system would look like for a product and then work backwards to optimize designs, supply chains, and processes to enable it. Value recovery would include, but not be limited to, product reuse, component reuse whether in the same product or a completely different application, and materials recovery at all stages in the lifecycle, not just at end of use. New recovery technologies will be needed, as well as information sharing among members of the value recovery system, supply chain incentives for efficient and effective collection, innovative pathways for collection, and coordinated pre- and post-processing systems. This multi-stakeholder iNEMI project began examining these various aspects of value recovery for hard disk drives.

Electronics, all the materials from which they are made, how and where they are mined, manufactured, and used, and their inflows and outflows of energy, water, and chemicals, represent common pool resources that different people and groups rely on for their livelihoods. There are many examples of “tragedies of the commons” associated with common pool resources used for electronics, from mining of raw materials and manufacturing to materials recovery. It need not be so. Dr. Elinor Ostrom (2009 Nobel Laureate in Economics) laid out a framework for how people and organizations develop voluntary, community-based solutions, involving adaptive, self-governing systems that effectively manage common pool resources [2]. This framework was based on extensive research into how groups all over the world have successfully self-organized to manage critical resources collectively without requiring either government control or privatization. Electronics are embedded in multiple “complex, social-ecological systems” as described by Ostrom: each one of them comprises multiple people and sub-systems at multiple levels that are relatively separable but interact to produce outcomes and viability at the top level. In this iNEMI project Ostrom’s framework is applied to guide the creation of new pathways to increase value recovery and sustainability of HDDs, by identifying existing solutions and their barriers to broader implementation and new concepts and opportunities that can be developed.

Two crucial steps for this project were (1) identifying a representative electronic product on which to focus that met the Ostrom criteria for a resource with sufficient intrinsic value and for which the system’s dynamics were predictable; and (2) identifying a relevant group of stakeholders that was diverse enough, sufficiently motivated, representative and empowered to develop some “rules” for “self-governing” the commons. Based on these criteria, the project adopted a focus on value recovery from hard disk drives (HDDs).
The HDD economy is a multi-stakeholder system with interacting functions, well-matched with Ostrom’s criteria for “self-governing” systems:

- Hard disk drives are ubiquitous devices that are manufactured by a small number of companies, but used across a substantial mix of product classes that are widely distributed geographically.

- Hard disk drives provide a unique case for the improving value recovery: they have been and continue to be designed to be easily swapped out or replaced in systems if they fail or if a different storage capacity or type is needed.

- Value recovery from HDDs is dominated, first, through testing and resale of functioning used units, followed then by precious metals recovery (Au) and commodity metals recovery (Al, Fe). However, there are other existing and possible sources of value in these components, including wider reuse via alternative product cycles and re-manufacturing, reuse of parts and assemblies in HDDs, reuse of the magnets in HDDs in other products, and He recovery, as well as product markings strategies and new recycling methods that change the economics of recovery.

- Many fully functioning HDDs are destroyed because of data security concerns, even when the data on the HDDs is of low sensitivity or could easily be erased/sanitized. This significant loss of potential value is caused by a lack of understanding and knowledge of the full capabilities of modern data sanitization methods.

- There is momentum within the community. Since 2014, the U.S. Department of Energy Critical Materials Institute (CMI) and Seagate have been discussing various approaches to value recovery, including the development of a new technology for removing rare earth element (REE) magnets from HDDs for reuse in HDDs and other applications. CMI researchers have performed economic, environmental, and logistical analyses to examine the viability of various scenarios of recovering and reusing REE magnets, and those analyses were seen to be essential to a range of other scenarios examined in this iNEMI project.

- Enterprise-level HDDs are vital to businesses such as banking, health care, and commerce, and to large Internet service providers and Internet exchange systems. Their facilities use significant numbers of HDDs and rely on their continuing availability with increasing performance and capacity. Furthermore, these have developed a small range of business models to manage these assets in collaboration with HDD manufacturers and end-of-use (EoU) IT asset management providers.

- Previous work had been done through the NSF/IEEE Joint Standard stakeholder process for the development of the Standard for Environmental Leadership Assessment of Servers to identify specific elements of product design and flow of information that could aid recovery for HDDs.
• Federal agencies in the U.S. and EU have projected a need for many industries to secure a secondary supply of critical and strategic materials, including but not exclusively, REE metals, which are contained in HDD magnets.

• iNEMI provided a forum with a well-established model for productive collaboration of institutions and people involving a mix of stakeholder types, business models, and value systems. Of particular importance was that iNEMI is known for “developing voluntary, community-based solutions involving adaptive, self-governing systems that effectively manage common pool resources” in environmentally sustainable electronics.

1.2 Scope of Work for this Project

The scope of work for this project was to:

1. Identify and discuss the viability of existing pathways, from well-known ones to those less known, and of new pathways for increasing the value recovered from used HDDs. These will include options from direct product reuse to metals recycling, for specific HDD product types, and applications (server, data centers, portable, desktop, enterprise, telecom).

2. Identify the major stakeholders in the HDD economy and describe the roles they play, the factors they consider in decision making, and the options they have for value recovery from used HDDs.

3. Estimate sizes of various HDD markets by application (consumer electronics, data centers, enterprise electronics) and HDD type available for the value recovery feed streams and review possible disposition options when the products are being taken out of service, i.e., they are designated as “used.”

4. Develop decision trees to show the sequence of recovery choices currently being made by different stakeholders/sectors in the value recovery streams, from direct product reuse, remanufacturing, to metals recycling, including business models, criteria being used to make the decisions and the handoffs required at each stage to realize value recovery.

5. Discuss new technologies under development for value recovery and the conditions under which these technologies would be viable. Develop a more detailed decision tree with the new pathways to value recovery and identify the interactions (that lead to specific decisions to be made) that must occur along the product lifecycle and supply chain to realize them.

6. Identify the current barriers to creating such a safe, environmentally sustainable, economically feasible value recovery system. Introduce the potential of various value recovery pathways to HDD stakeholders and obtain feedback on their willingness to pursue such pathways.

7. Recommend next steps to demonstrate the feasibility of a more effective value recovery system, including possible best practices for all stakeholders.
From this project, we are pleased to report that, equivalent to used cars, there are effective value recovery pathways that exist for HDDs with trusted and effective suppliers and customers that make them work. Furthermore, there are many opportunities to increase the flow into those recovery pathways, as well as to create new pathways for value recovery. It is not purported that this report, or the processing schematics, decision points, and the new pathways to value recovery presented here are the optimal solutions. Our intent is to capture what the current options are, what future options for value recovery might be, and what a “best practices” framework might look like. This report contains original content and analyses that are intended to stimulate further collaboration. iNEMI and its members may be involved in future work in HDDs or other EoU electronics, and you are welcome to join us in this endeavor.

1.3 Hard Disk Drives: Developing a Circular Flow of Products Leading to a Circular Economy

This project addressed broader issues for electronics that are far from resolved. There is increasing pressure worldwide for societal transformation from a linear economy – based on the traditional take-make-waste model – to a circular economy – a new model which, in the words of the Ellen MacArthur Foundation, “aims to keep products, components and materials at their highest utility and value at all times.” [3] Meeting the needs of today’s global population, which is enjoying increasing affluence, is not sustainable under the current linear model. The expanding worldwide demand for electronics – and specifically for data storage – is increasing the opportunity for the electronics industry, and the most successful companies will modify their business practices consistent with some circular economy principals.

To date, individual companies in the electronics industry have taken some steps toward a circular flow of products and materials, but the electronics industry as a whole has not undertaken the business-model-level initiatives that are key for a serious transition to a circular economy. There are, nonetheless, examples that show great promise to make this model a reality, including opportunities for hard disk drives that are highlighted and discussed in this report. Even greater opportunities are possible when the stakeholders in the HDD community work together, including product designers and manufacturers, product users and asset managers, and actors in the reverse supply chain at end of product use optimizing value recovery for long-term economic, societal, and environmental sustainability.

Make no mistake, the circular economy challenge is especially difficult for the electronics industry, compared with the automotive industry. Several reasons are highlighted in the phase one report, “iNEMI Report on the State of Metals Recycling,” [1] and more in this report. Foremost among those reasons is that an economically viable reuse and recycling infrastructure does not exist today that has the resources, information, or action plan to address the challenges of rapidly evolving product design and material content. An objective of this report is to begin to define a path and an action plan to develop that collaborative infrastructure based on diversified, effective value recovery pathways.
When we say a “collaborative infrastructure,” we are not implying that stakeholders along the chain of commerce will operate altruistically. We mean that the values returned by collaboration must be clearly demonstrated based on shared goals and that economic advantages for the collaboration must be created, using primarily voluntary enablers, including standards, so as to make sustained collaboration in the economic interest of all stakeholders.

We do not believe that legislation is required to make this a reality. The European Commission has been the first major governmental body to aggressively address the challenge of a circular economy. The EU Action Plan for a Circular Economy [4] contains a wide range of legislative proposals that address reuse, recycling and “industrial symbiosis.” The concept of industrial symbiosis can be a good model because a sustainable circular economy for electronics will require the establishment of symbiotic relationships, many of which do not now exist, between manufacturers, reuse businesses, recyclers and final markets. However, “industrial symbiosis” by legislation could impose unnecessary and even limiting restrictions on how the communities can self-organize and manage critical resources collectively, as noted by Ostrom.

Bottom line, this report proposes that the electronics industry get ahead of the regulators, starting with HDDs, and develop new pathways for a sustainable circular economy for electronics through voluntary and coordinated stakeholder/industry action. A variety of enablers or implementation mechanisms will be needed, as suggested by Ostrom. These could include greatly increasing trust and sharing of information across the reverse value chain; identification of best practices needed by individual actors to increase value recovery; and development of guidelines and standards that help to bring the independent actions of free market players into a sustainable system. A stakeholder process based on the Ostrom framework could be employed to identify and create these enablers.
Chapter 2: Sustainable, Dynamic Systems versus “The Tragedy of the Commons”

2.1 Creating Sustainable Systems for Value Recovery

The project team members developed this project because we believe that there are substantial opportunities for increasing value recovery from end-of-use (EoU) electronics that can benefit society, the organizations, and the people involved in sustaining and recovering value. We viewed EoU electronics as being a classic case of managing the commons in which (1) some of the value intrinsic in the EoU products was being wasted because they were never considered for additional value recovery; (2) many of the individual “actors” along the existing value recovery pathways were part of a linear lifecycle model in which the opportunities for value recovery were constrained; and (3) new technologies and business relationships are emerging that have the opportunity to influence value recovery in a positive way, or conversely could have a negative influence if not appropriately managed.

In this chapter, we discuss two system dynamics paradigms for how people share the commons: the well-known Tragedy of the Commons (TOC) model based on economic self-interest alone, and the increasingly influential Social-Ecological System (SES) Framework based on voluntary, adaptive, self-management of the commons by the stakeholders. We discuss the conditions under which each arise, what the critical conditions are for developing a sustainable, dynamic SES, and how we are beginning to apply it to value recovery from hard disk drives.

2.2 Tragedy of the Commons Is Not Inevitable

In his well-known 1968 article in Science, Garret Hardin presented a view that people and organizations that share a common resource that they all need to survive will inevitably destroy that resource due to their intrinsic nature. [5] The basis of his argument is that at least one of those people or organizations, if not all, will disregard the needs of the others and operate to maximize his or her short-term profit. In the case of common grazing land, each shepherd will add another cow or sheep to his or her herd thereby increasing personal gain. In contrast, the cost of having one more animal on the land is shared by all the users of the land. In his view, the imbalance between benefit and cost borne by an individual inevitably leads to destruction of the commons. In
all scenarios of this type, Hardin contends that this is the essence of “tragedy” by being “the remorseless working of things,” i.e., the way we must behave by our nature. He offered two, and only two, solutions for preventing the Tragedy of the Commons: limiting access by either private ownership of the commons or government control.

The TOC model is not the only way in which people behave and in which decisions are made. Elinor Ostrom and her colleagues determined that there are many examples worldwide of self-managing, adaptive, resilient human-environmental-economic systems that successfully manage their common pool resources. Furthermore, they used this research to identify the necessary characteristics for successful, sustainable SESs and developed it into an SES Framework that can be used to analyze and strengthen existing systems and create new sustainable systems.

2.3 The Social-Ecological System Framework

In order to put Ostrom’s SES Framework into the context of EoU electronics we will start with a simple analogy, then relate it to several ways in which value recovery pathways are viewed and constrained by current practices, and finally show how using the SES Framework might release those constraints. The analogy is the human body as a dynamic, adaptive system with systems interacting and receiving feedback both internally among systems and with the external environment. This is how the body becomes an ecological system. There is a continuum of states of human health: from disease to the absence of disease, and then, beyond to good health and flourishing. We want value recovery systems for EoU electronics to correspond at a minimum to good health, and where and when possible, to flourishing.

The distinction is that the human body is an evolved unit that, as a necessary condition of survival, includes internal control mechanisms. When these mechanisms — which are based on feedback loops — fail or otherwise get out of equilibrium, then disease can set in. Human-established economic systems inherently lack many of the essential control mechanisms, unless consciously created. But they can be provided by norms, institutions, laws, or, as Ostrom proposes, and we support, by voluntary initiatives. Depending on the system, existing value recovery pathways for EoU electronics can be mapped onto this continuum. On the “diseased” end, there is trans-national dumping of non-functioning electronics that contain hazardous substances themselves and are processed using toxic chemicals that undermine human and environmental health. The voluntary standards eStewards and R2 were developed to promote “the absence of disease” and where possible, to the beginnings of “good health.” According to the eStewards.org website, “The e-Stewards Standard is the highest standard for globally responsible electronics recycling and reuse. It prohibits the export of hazardous electronic waste from developed to developing countries while allowing viable technology to be reused. It includes the ISO 14001 standard, so it is a ‘one-stop shop’ for responsible used electronics management. Certified e-Stewards recyclers, and likewise R2 recyclers, are independently audited to assure conformity to the Standard, including downstream accountability for toxic materials to final disposition.” eStewards is focused on electronics after it becomes “e-waste.” It and R2 are minimally concerned with the impacts of improving value recovery all along the supply chain and the benefits of reusing systems,
components, or materials on the eco-systems that create them. In this project, it is critical to recognize those impacts, and to determine if there can be additional value recovery pathways that improve the long-term sustainability of electronics.

An important idea to remember is that successful SESs are neither simple nor static. In the words of Ostrom [2]:

> All humanly used resources are embedded in complex, social-ecological systems (SESs). SESs are composed of multiple subsystems and internal variables within these subsystems at multiple levels analogous to organisms composed of organs, organs of tissues, tissues of cells, cells of proteins, etc. In a complex SES, subsystems such as a resource system (e.g., a coastal fishery), resource units (lobsters), users (fishers), and governance systems (organizations and rules that govern fishing on that coast) are relatively separable but interact to produce outcomes at the SES level which, in turn, feed back to affect these subsystems and their components, as well other larger or smaller SESs.

A core challenge in diagnosing why some SESs are sustainable whereas others collapse is the identification and analysis of relationships among multiple levels of these complex systems at different spatial and temporal scales. Understanding a complex whole requires knowledge about specific variables and how their component parts are related. Thus, we must learn how to dissect and harness complexity, rather than eliminate it from such systems.
The basic SES framework is presented here in Figure 1 and Table 1 as an introduction to the important relationships and variables in SESs, particularly to those characteristic of successful, sustainable SESs.

As shown in Figure 1, the first-tier categories (indicted by solid boxes) include Resource Systems, Resource Units, Governance Systems, and Actors as the highest-tier variables. Action Situations are where all the action takes place as inputs are transformed by the actions of multiple actors into outcomes. Dashed arrows denote feedback from Action Situations to each of the top-tier categories. The dotted-and-dashed line that surrounds the interior elements of the figure indicates that the focal SES can be considered as a logical whole, but that exogenous influences from related ecological systems or social-economic-political settings can affect any component of the SES. These exogenous influences might emerge from the dynamic operation of processes at larger or smaller scales than that of the focal SES.

As seen in Figure 1, Resource Systems (RS), Resource Units (RU), Governance Systems (GS) and Actors (A) all come together in Focal Action Situations where Actors make decisions on how to use the Resource Systems based on their values and goals for the system. Each Tier 1 variable has multiple sub-variables that characterize a system (see Table 1 for an updated list of second-tier...
variables within each of the top-tier categories). Extensive research on SESs across the planet identified the subset of variables associated with sustainable SESs for managing natural systems, such as forest, aquatic, and agricultural systems.

The critical variables include that the system be neither too small nor too large (RS3), such that the self-organization is not so large as to be unwieldy to manage (U1) nor become unpredictable (RS7) due to its size. The system must also not be so small that its productivity is not high enough (RS5) or its importance of the resource to the Actors (U8) to be too small to warrant managing. The Actors (U1) need to have the ability to determine their own rules (GS6) based on their values, goals, and needs. Ultimately the critical characteristics of the Actors are related to their having common values and goals such that they are committed to the specific enterprise (U5) using shared management (U7), will persevere under adversity (U6, U7), and trust each other enough (U6) to listen to each other and be willing to work together through disagreements, challenges, and serious issues to reach common goals. Ostrom also uses the SES Framework to understand the conditions that exist for Tragedy of the Commons situations to arise; see this analysis in 2007 Ostrom article, “A diagnostic approach for going beyond panaceas.” [6]
Table 1. First-tier and second-tier variables in the Ostrom SES Framework

<table>
<thead>
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<th>Social, economic, and political settings (S)</th>
<th>Governance systems (GS)</th>
<th>Actors (A)</th>
<th>Action situations: Interactions (I) (\rightarrow) Outcomes (O)</th>
<th>Related ecosystems (ECO)</th>
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<td>S2 – Demographic trends</td>
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<td>S3 – Political stability</td>
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<td>S6 – Media organizations</td>
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<td>S7 – Technology</td>
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<td>Resource systems (RS)</td>
<td>Governance systems (GS)</td>
<td></td>
<td></td>
<td>Related ecosystems (ECO)</td>
</tr>
<tr>
<td>RS1 – Sector</td>
<td>GS1 – Government organizations</td>
<td></td>
<td></td>
<td>ECO1 – Climate patterns ECO2 – Pollution patterns ECO3 – Flows into and out of focal SES</td>
</tr>
<tr>
<td>RS2 – Clarity of system boundaries</td>
<td>GS2 – Nongovernment organizations</td>
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<tr>
<td>RS3 – Size of resource system</td>
<td>GS3 – Network structure</td>
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<tr>
<td>RS4 – Human-constructed facilities</td>
<td>GS4 – Property-rights systems</td>
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<tr>
<td>RS5 – Productivity of system</td>
<td>GS5 – Operational-choice rules</td>
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<tr>
<td>RS6 – Equilibrium properties</td>
<td>GS6 – Collective-choice rules</td>
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<tr>
<td>RS7 – Predictability of system dynamics</td>
<td>GS7 – Constitutional-choice rules</td>
<td></td>
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<tr>
<td>RS8 – Storage characteristics</td>
<td>GS8 – Monitoring and sanctioning rules</td>
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<tr>
<td>RS9 – Location</td>
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<tr>
<td>Resource units (RU)</td>
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<td></td>
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<tr>
<td>RU1 – Resource unit mobility</td>
<td>A1 – Number of relevant actors</td>
<td></td>
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<tr>
<td>RU2 – Growth or replacement rate</td>
<td>A2 – Socioeconomic attributes</td>
<td></td>
<td></td>
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<tr>
<td>RU3 – Interaction among resource units</td>
<td>A3 – History or past experiences</td>
<td></td>
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<tr>
<td>RU4 – Economic value</td>
<td>A4 – Location</td>
<td></td>
<td></td>
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<tr>
<td>RU5 – Number of units</td>
<td>A5 – Leadership/entrepreneurship</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RU6 – Distinctive characteristics</td>
<td>A6 – Norms (trust-reciprocity)/social capital</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RU7 – Spatial and temporal distribution</td>
<td>A7 – Knowledge of SES/mental models</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>A8 – Importance of resource (dependence)</td>
<td></td>
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<td></td>
<td>A9 – Technologies available</td>
<td></td>
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</table>

Note: Critical variables correlating to effective, sustainable systems noted with an asterisk (*)
(McGinnis and Ostrom)
In most, if not all, social-ecological systems, there are multiple commons to be managed. If we take the case of electronics, we can consider not only the EoU products to be a type of commons, but also embedded in those products are water, air, energy, and materials, committed and used by various actors all over the globe as a result of different interactions that produce different outcomes. The SES Framework emphasizes that people make decisions for the use of the interdependent commons, with the further belief as stated by McGinnis and Ostrom that: [7]

Fundamental to the SES Framework is the presumption that humans can make conscious choices as individuals or as members of collaborative groups, and that these individual and collective choices can, at least potentially, make a significant difference in outcomes.

Actors make critical decisions in the following stages that determine value recovery from EoU electronics:

- Design and manufacture of the product in so far as material choices and design elements are relevant to end-of-use management, including reuse
- Use and reuse of products, discard of products, and last-user specification for downstream treatment, that maximally supports reuse and recovery opportunities
- Collection, sorting and aggregation that make end-of-use products available in the condition and quantities needed for cost-effective downstream reuse and material recovery
- Preprocessing whereby the whole products are converted into appropriate fractions and shipped for final processing
- Final processing systems and technologies for repair, reuse and refurbishment of whole products and components, and for material recovery
- Secondary markets for sale of used electronics and parts, and processing for materials recovery

In the remainder of this report, we focus on the main classes of actors that determine EoU value recovery from HDDs, the various choices they currently make, how their interactions affect the possible value that could be recovered, and how applying the SES Framework might enable new pathways for value recovery in the future.
Chapter 3: Current Status of Value Recovery from Used HDDs

Imagine
Imagine there's one planet
It's easy if you try
People all around us
Sharing the earth and the sky

Imagine all the hard drives, living longer lives
Whole and as pieces, and we all will thrive.
You may say I am a HDD dreamer, but I am not the only one.
I hope someday you will join us - in a circular economy model –
With the world - a more sustainable one.

3.1 Meeting the Market Demand for Data Storage

Choosing value recovery from used HDDs as the focus of this project was based on the accelerating market demand for data storage at a range of storage capacities, speed, and price points for a wide range of user types. Electronics is one of the fastest growing product categories. People are increasingly connected via the web, and the impact on people’s daily lives across the globe is unprecedented. Just as the car revolutionized personal travel, wireless connectivity is transforming human communication and commerce. Digital data collection and storage are key elements in this global transformation. The demand for digital storage has been growing rapidly over the past two decades with global data storage demands following its own “Moore’s Law.”

The total number of hard disk drives manufactured and sold per year reached a peak in 2010 with 651 million units sold. That total decreased to 469 million units sold in 2015, as seen in Figure 2a. This decrease is partially due to solid state drives replacing hard disk drives in mobile and consumer electronics but is also due to the increasing capacity of HDDs, as seen in Figure 2b. The average capacity of hard drives has continued to increase, leading to a doubling of HDD storage density approximately every 18 months. This has been made possible by continuing innovations in HDD read-write technology while keeping the same physical footprint.
Figure 2a. The annual production statistics for HDDs and SSDs. [8]

Figure 2b. Increasing average storage capacity per HDD.
Figure 2c. Exabytes shipped as HDDs. [9]

Figure 3. Historical and 2016 forecasted data storage demand for HDDs only over time for different application categories, including enterprise, desk-based PCs, mobile PCs, consumer electronics, and branded HDDs (HDDs sold separately in retail stores). Enterprise, consumer electronics, and branded HDDs are all growing markets. [10]
Given the trend in decreasing numbers of HDDs over time, it might seem that HDDs would be an unlikely candidate for developing a circular economy. However, three additional major factors come into play, as reflected in Figures 2c and 3: (1) the demand for data storage is increasing rapidly; (2) data storage demand is increasing significantly faster than increases in HDD storage density, and (3) industry output of HDDs (manufacturing capacity) is not expected to increase significantly, according to industry projections. This leads to a potential gap between the estimated data storage needs and the estimated ability of HDD and SSD manufacturers to keep up with demand. There are a number of ways to fill this gap. There continues to be significant investment in SSD fabs and in new technologies to increase HDD and SSD storage densities while increasing total storage capacity per drive, but these technologies face significant challenges. There are two additional ways to fill the gap based on HDDs: (1) increase HDD reliability and (2) increase the reuse of used HDDs so that they are available to meet some of our global data storage needs. Even with these improvements, the demand for materials and manufacturing resources for new HDDs will continue to increase beyond today’s levels, which are already unsustainable from environmental and materials availability points of view, so other pathways must be sought.

There are a variety of ways to meet these increased consumer and enterprise storage demands. Companies are continuing to invest in technology to bring to market higher capacity hard disk drives that double their storage capacity every 18 months with the same physical footprint, but the technological challenges are significant. In this study, we are proposing a dramatically different investment. This research proposes to make better, longer use of the resources contained in the billions of hard disk drives that are already in use or will be produced in the near future.

The supply and demand for HDDs have implications with respect to obtaining the maximum economic and environmental value to society for each and every hard drive designed, manufactured, and sold. As we go through this analysis, it is useful to remember the used car analogy and how value is recovered by cascading use at different lifecycle stages. At each stage in which value is recovered for a car, there must be ready, willing, and able customers (i.e., sustained demand), whether for used cars, car parts, or scrap. Likewise, there must be suppliers able to meet these needs.

The good news is that there is already an existing technology base and infrastructure that conducts warranty repair and refurbishment/remanufacturing of millions of used HDDs from consumer and enterprise applications and puts them back into service. Warranty repair and refurbishment/remanufacturing have efficient and effective processes diagnosing the sources of errors, repairing them, and, therefore, extending the working life of HDDs. Drives that are not viable for reuse are either shredded for materials recovery or disassembled with the disassembled parts either sold to the secondary market or sent for materials recovery. As far as we could determine, the reuse of disassembled HDD components in new or refurbished HDDs is largely not done today, but could be. For drives that are no longer functional, we are proposing partial disassembly and reuse of critical components in HDDs – something that is largely not done today. This was a major focus of this project. Having cascading lifecycle options for used HDDs, HDD parts and assemblies, and HDD materials is fundamental to creating a real circular economy.

This
report proposes to build upon the existing global infrastructure, with its effective, efficient value recovery pathways and with trusted and effective suppliers and customers that make them work, and develop opportunities for new pathways. This research suggests that we need to create a new value management model for the HDD based on close stakeholder collaboration and commitment.

As a starting point for developing such a value management model, we have studied the current technical, economic, organizational, legal and societal/cultural challenges associated with extending the working lives of HDDs, reusing parts and components of used hard drives to make new hard drives and other systems, and recovering the material resources through recycling when life extension and reuse are not feasible. Using this knowledge, we identify current challenges and suggest pathways to make the cascading use of HDDs the norm for billions of hard disk drives, both for those already in use or for those that will be produced in future generations of HDDs.

3.2 Factors Affecting the Feasibility of Value Recovery of Used HDDs

Reuse of a hard drive in its original form or in a slightly modified form is the best economic and environmental outcome.

All environmental impact factors, from carbon footprint to toxicity, are lower for reusing rather than replacing HDDs, even when materials recovery of used HDD is factored in. Reuse/sale of used HDDs is a cheaper alternative to buying a new drive, and does not have a significant impact on the sales of new drives due to increasing global storage demands.

The direct stakeholders in the HDD economy include:

- HDD OEMs, OEMs of electronics containing HDDs
- HDD users from an individual using a HDD in a laptop to a data center with thousands of drives
- HDD OEM-authorized service providers
- IT asset management companies
- Recyclers
- Secondary markets for parts
- Materials recovery companies

People, companies, and governments interact across the lifecycle of a HDD to realize the final value recovered. There are many factors that individual stakeholders consider when determining what value recovery options are possible for their HDDs, based on their specific constraints, up and down the supply chain, and their viewpoints. As shown schematically in Figure 4, the decisions to identify a used HDD as having potential for value recovery are based on five criteria: technological, economic, ecological, legal, and social/cultural.
• **Technological:** It must be technically possible to return a used HDD to functioning condition with characteristics of value to some purchaser.

• **Economic:** It must be economically beneficial to perform the required processes (data destruction, refurbishment and remanufacture processes) to return it to such condition that the reuse value (for reuse inside the company) or sales revenue (for external sale) exceeds all collection, processing, and logistics costs.

• **Ecological:** The environmental benefits associated with reuse must outweigh the impacts of refurbishment (including, for example, the energy efficiency of the used hard drive with respect to new product.)

• **Legal:** It must be legal to undertake the refurbishment, remanufacture and resale of the drive based on permissions and contractual obligations with the HDD owners around data security and contractual obligations to the HDD purchaser. For HDD owners/users, “legal” considerations also include the risk to themselves and their organizations and civil and criminal penalties if sensitive data are released.

• **Social & Cultural:** It is necessary to give due consideration to the social, cultural, and ethical dimensions of the processes all along the supply chain, for example, labor practices in developing countries, which may not be illegal but may be unacceptable nonetheless. There must, therefore, be reliable, ethical, trusted relationships established across the supply chain to ensure that all stakeholder requirements are being met.

Figure 4. The decision to reuse a hard drive is typically made based on technologic, economic, ecologic, social and cultural, and legal criteria. [11]

Each stakeholder assesses the benefits and risks for each criterion for a given proposed pathway and makes a final decision. If these five criteria are not met for one specific pathway, then alternative pathways for value recovery are identified that can meet the stakeholder’s criteria in all five categories.
Looking at a more macro scale, value recovery along a given pathway is determined by the efficiencies and constraints existing all along the path. In a typical recycling system, products are collected, and then sorted based on a pre-specified recovery plan for reuse, disassembly for parts, or material recovery based on their overall utility and latent market value. It is important to note that the efficiencies of each step are multiplied to produce the final efficiency of a specific value recovery pathway. For example, consider that even if the final extraction process for metals recycling might be 95%, if the collection efficiency is 20% and the sorting efficiency is 35%, then the maximum pathway efficiency will be 7%. This multiplicative effect means that all processes and all handoffs along the value recovery chain must be highly efficient for the final efficiency to be high. Furthermore, the efficiency of the first step in the value recovery process, i.e., collection, is the most critical since it determines the maximum system efficiency possible from any subsequent value recovery process. To put it simply, if a HDD never reaches a collection point, then its value cannot be recovered.

Availability/collection efficiencies and constraints vary by region, legislation, user and data types, spending habits, and other factors. However, quantitative data on the actual collection of HDDs at EoU points are meager. According to a 2011 IDC report on the recycling industry in the U.S. [12], households in the United States accounted for the vast majority of the electronics market in 2011, but they only accounted for 26% of electronics recycling, with the remainder being from commercial and business entities [1]. With regard to HDDs, consumer HDD sales have been around 10x greater than enterprise sales for the past five years and are being replaced by SSDs [9] [13]. Furthermore, the increasing HDD capacities being required by consumers means that there is limited market for small capacity consumer HDDs when they reach an end-of-use decision point. There is also an uncertainty in classifying consumer HDD models as being used in a residential setting versus commercial/business use, given the evidence that consumer grade drives are also used for data center applications [14]. In spite of this uncertainty, we have attempted to estimate stocks and flows of HDDs based on their model/user, failure rates, and warranty characteristics and use these estimates to consider the feasibility of different value recovery pathways.

Additional fundamental constraints on value recovery for HDDs include (1) HDD sales by manufacturer, storage capacity, (2) HDD lifetime, including in-warranty failures and out-of-warranty failures, (3) data security concerns, (4) access to collection points for value recovery, for example, from integrated asset management organizations inside or outside the company, and (5) corporate asset management strategies for large users of non-consumer HDDs. These determine the in-service “stocks” and “flows” of HDDs that serve as a baseline for the number of used HDDs available for value recovery.

This section examines cascading options for used HDDs, from reuse through materials recovery, how they are viewed by different stakeholders, and what challenges to value recovery exist.

The trends in storage demand have implications with respect to obtaining the maximum economic and environmental value to society for each and every hard drive designed, manufactured, and sold.
As we go through this analysis, it is useful to remember the used car analogy and how value is recovered at different lifecycle cascading stages. At each stage in which value is recovered for a car, there must be ready, willing, and able customers, whether for used cars, car parts, or scrap. Likewise, there must be secondary markets for products derived from used HDDs and HDD component suppliers able to meet their needs. In our project we have determined that such value recovery pathways exist for HDDs, with trusted and effective suppliers and markets that make them work, with similar rewards for their value recovery and improved environmental outcomes.

3.3 Stakeholders in the Global Economy for Used HDDs

3.3.1 HDD manufacturers

In order to examine the specific pathways for HDD reuse, it is important to understand the central role that HDD OEMs have in value recovery. As of 2016, the three HDD manufacturers are Seagate, Western Digital, and Toshiba, down from the over 200 HDD companies that have disappeared through bankruptcy, merger, and acquisition. In addition to mergers with other HDD OEMs, there have also been significant acquisitions of test systems, software, and SSD companies by the HDD OEMs, such as Seagate’s acquisition of Xyratex and DotHill, and Western Digital’s acquisition of SanDisk.

Figure 5. Intact HDD with the cover removed (left) and exploded image of a HDD showing individual parts (right).
The overall mechanical design, size, and weight of HDDs have remained relatively unchanged (Figure 5), while the capacity and read/write speed of HDDs have increased, made possible by dramatic improvements in read/write technology and innovations in recording media. These improvements reflect manufacturers’ emphasis on technology improvements and innovation to continue reducing the bit size and increasing read and write speed while maintaining the same physical footprint [15] [16].

In addition, HDD manufacturers are designing HDDs for greater data security and reliability, as required by their customers, whether individuals or government agencies, large data centers and cloud computing services, or the financial and medical industries. With each new generation of HDD, software and hardware have been modified for increasing capability for self-error correction, data encryption and security, and secure and reliable operation in high-demand environments. For example, self-encrypting drives (SED) allow users under some system configurations to make all data on the HDD unreadable by setting a new data encryption key; the drive can then be reused internally or sent outside the organization without the possibility of the release of sensitive data. (Note that the HDD companies have worked closely with U.S. federal agencies, including NIST and the NSA, to ensure that their encryption key erase processes make the data unreadable). Use of the decryption key erase processes does, however, require a trained member of a trusted computation group. Inadvertent or malicious use of encryption key erase processes could lead to catastrophic consequences. According to industry sources, many owners of HDDs with security encryption do not know that their drives can be easily made unreadable.

There is an exciting new feature that has the promise of significantly increasing the useful lifetimes of HDDs. It is known as “offline logical depopulation,” i.e., the ability for a user to remove slow or faulty physical elements from the logical address space from an offline drive to create a lower capacity HDD and then return the lower-capacity, reformatted, “empty” drive back online. According to Koblentz [17], Western Digital and Seagate have been shipping proprietary versions of this capability, which they developed in collaboration with their data center customers, for some time.

An industry standard for offline logical depop is being developed by the T13 Technical Committee for the InterNational Committee on Information Technology Standards (INCITS) and is accredited by American National Standards Institute (ANSI). In terms of development of international standards, the T13 Committee is the U.S. Technical Advisory Group (TAG) to the international standards organization ISO/IEC JTC 1 SC25/WG4 (co-TAG) and provides recommendations on U.S. positions to the international JTC 1 TAG. The latest publicly available version of the depop standard can be found on the Internet, with the April 26, 2016 version used in preparing this report. [18]

According to the Koblentz/TechRepublic article [17], the Microsoft Azure cloud team is already planning to use offline logical depop when it becomes publicly available. It is expected that some large data centers have been using offline logical depop for some time since they participated in its development with Seagate and Western Digital. Some industry leaders are uncertain about the
usefulness of depop for their applications. For example, if first failures indicate a drive with a lower subsequent lifetime, reformatting the drive and returning the repaired drive to service with a higher probability of failure may not be worthwhile. Two other features make offline depop a major breakthrough. First, when a data center HDD drive is identified to be depopped, it can remain spinning. The system stops all read/write operations to the drive, and the depop process can be performed and the drive returned to service after reformatting without any physical human intervention. The drive stays in place until it is removed permanently from service. Second, if the data encryption key is erased before or after depop, this prepares the newly created, lower capacity drive for resale/reuse and the data cannot be read since the previous key is gone. (Note that we do not know what agreements exist between HDD OEMs and data center HDD users when in-warranty HDDs fail, but could be reformatted using offline logical depop to create a useful HDD.)

Other policies and practices that affect value recovery from used HDDs and the supply chain supporting it are the warranties of one to five years offered by HDD OEMs for mobile, consumer, enterprise, and cloud applications. The HDD OEMs contract with a small number of aftermarket service providers to handle in-warranty returns, both directly from HDD purchasers and from OEMs whose electronic products contain HDDs. This relationship between the HDD OEMs and the aftermarket service providers involves sharing of proprietary information and software to allow optimal value recovery from in-warranty drives, including sending re-certified OEM drives as in-warranty replacements. There are at least two additional sources of HDDs from HDD OEMs: those that fail burn-in for their rated characteristics, and those that were used for testing. These may also be managed by the in-warranty authorized service provider.

While policies and practices can affect value recovery from used HDDs, the single greatest opportunity for increased value recovery from the components and materials in a used HDD is design for reuse and recycling. This statement is true not just for used HDDs but is true for most types of used consumer electronics. Electronic products must be intentionally designed to enable cost-effective (machine automated) separation and recovery of materials and components at end of life. If the design is glued or welded together, the screws are inaccessible, located in nonstandard positions and in a variety of shapes and sizes, and the product design is hard to take apart without damaging the components, the probability that parts and materials will be efficiently recovered and reused is greatly reduced. When the drive can no longer be remanufactured or refurbished and sold as a functional HDD, the next step in the value management process is disassembly and recovery of functional components and relatively pure material streams. Our hope is that future HDDs will be designed specifically to enable cost-effective recovery and reuse of large, high-value components such as the magnet, head assembly, connectors and the populated PWB. Indeed, the recovered circuit board value on a per pound basis is 6X greater than the HDD. If the cost to separate and process the PWB assembly, magnets, covers, heads and connectors are modest, the recovery value of the drive can be maximized and its facility to enable the circular economy is enhanced greatly. It is our hope that HDDs of the future will be designed to enable the rapid disassembly and recovery of the critical high-value components and materials for volume production manufacturing of HDD products.
3.3.2 HDD users

There is significant information on what leads owners/users of electronics to discard them: the system breaks or is no longer needed; the system has an increasing number of failures ("bathtub" reliability curve describing wear-out failures); owners want a system with more features; or the existing system is no longer supported, either with hardware or software. Users vary from the individual owning a laptop with a single HDD to financial institutions with thousands of computers containing HDDs, to data center companies that may have millions of HDDs in use. These different users determine how to take their electronics out of service, and whether and how to put them into the electronics value recovery scheme. Their decision-making criteria are based on numerous factors, including risk of having sensitive data become public, economic value of reused electronics, recycling regulations, corporate social responsibility policies, and voluntary standards for e-waste disposal and disposition. For HDD users willing for electronics to be resold and their HDDs to be wiped and reused, different business models are possible for return of some value to them by their resale, depending on the value recovery pathway.

The function of a HDD is, of course, to store data for later retrieval. In general, certain types of HDD data must be protected from unauthorized access: data can be confidential, classified by governments, or highly sensitive. One of the most important decisions made by HDD users is whether a functioning, used HDD can be reused or remanufactured based on data security and risk, i.e., whether the data can and have been erased and the repercussions if the data are not erased. Within that decision, there are two extremes in how data security is handled. Many individual consumers are generally unaware of whether a risk exists. For business owners, data security is of primary concern. The former may practice benign neglect in which all data remain on the HDD when it enters the value recovery stream and there is no plan for data sanitization. The latter may require physical destruction of functioning HDDs whether the data they contain are sensitive, whether the HDDs can be securely wiped according to NIST/DoD/NSA standards, or whether they can be effectively wiped by replacing the data encryption key.

As noted in the previous section, some of the newest generation of enterprise/data center HDDs can be reformatted/remanufactured in place as HDDs with lower storage capacities without having to be replaced using “offline logical depopulation.” This process reduces the storage capacity of the HDD by isolating bad sectors and turning off faulty read heads to create a functional drive of lower capacity, without going through a third-party white labeling process. During the depopulation process, the drive is taken offline and reformatted to the lower storage capacity. Following reformatting, the drive can be brought online again and new data will overwrite the preexisting data. Data in the unformatted, unreadable areas will not be overwritten, but cannot be read in the new configuration. This level of data sanitization may be acceptable if the HDD is used within the same organization. For self-encrypting drives (SED), replacing the data encryption key after reformattting will make all previously written data unreadable, making the HDD sanitized for resale and reuse. Many new SED HDDs have been validated as conforming with Federal Information
Processing Standards (FIPS) 140-2 Level 2, which is a requirement for most government electronics purchases. The question is whether HDD owners are willing to use these depopulation and/or data sanitization to reuse faulty drives or remanufacture and resell them.

Based on past studies, it seems likely that most people are not aware of the proper HDD data sanitization for their stored data. For example, in 2008, it was estimated that 60% of people are inattentive to proper removal of personal data from electronic devices [19]. Private and public sector users of HDDs do not adequately check whether or not data are irreversibly wiped or are still retrievable. According to a 2007 study, 70% of UK central government departments were reported

![Decision tree for disposition of HDDs based on NIST criteria](image)

Figure 6. Decision tree for disposition of HDDs based on NIST criteria. For definitions of the terms, refer to the NIST Guideline document.
as being careless in their approach to data sanitization [20]. In a Korean study [21], only 5% of collected HDDs were completely wiped. There are no data available to determine whether the situation has improved since these 2007-2008 studies.

There are well-established guidelines to assess the security level of specific data types and to identify what procedures are required for data sanitization for different security levels. In particular, the NIST 800-88 Guidelines for Media Sanitization represented in Figure 6 provide decision-making criteria to determine which of the three options – clear, purge, or destroy – is necessary for a specific HDD. [22] Sanitization of HDDs through simply erasing the files’ block pointer (so-called disposal of data) is not a secure method since the data are still available on the disks. At the other extreme, physically destroying or degaussing the HDDs ensures that the data are destroyed; however, in both cases the HDD cannot be reused. Block-by-block overwriting of data (clear), drive internal secure erase (purge), and secure erase enhanced by encrypting the data (purge) are suggested to avoid destruction of the HDD [21]. However, organizations are frequently reluctant to use these non-destructive methods rather than physical destruction due to a range of concerns, including liability for data breaches and validation of data destruction. Hughes et al. [23] compared the speed and security level of mentioned methods. Physical destruction can be done quickly with the highest level of security, even beginning at the customer’s work site with punching, bending, or crushing of a HDD before final shredding at the recycler’s facility. This is in comparison to enhanced secure erase that can sanitize high security level data but the HDDs must currently be transported to the recycler’s facility and requires hardware and software resources to perform. Therefore, the sanitization method selection depends not only on the availability and cost of such resources, but also on factors related to value recovery from reuse, including:

- Contractual requirements, i.e., required physical destruction
- Chain of custody safeguards
- Reusability status of the device (storage capacity and hours on the device)
- Overall quality of the HDD, including cosmetic
- Technological obsolescence status (age and use category, i.e., consumer or enterprise)
- Customer demand (i.e., preferences for HDDs with certain storage capacities, reliabilities, price, and market conditions)
- Possible collection volumes of used HDDs (supply) and their uncertainty
- Operations cost for reuse, such as the cost for disassembly, remanufacturing, and processing a device for resale, including HDD dismantling (if required), data sanitization, recertification, and marketing

More details about the important factors and parameters can be found in Kwak and Kim [24], where two optimization models are presented for desktop, notebook, and laptop computers based on market-driven incentivized collection and free municipal collection approaches.
It should be noted that there can be significant legal and financial risks associated with release of certain types of personal information. Failure to properly protect data can result in significant liabilities, fines and legal penalties, including prison (Table 2). These penalties apply whether data are leaked as a result of hacking, physical theft, media being misplaced or lost, or capturing data from used storage media.

Table 2. Some cases of legal penalties in the United States for organizations that have been responsible for leakage of personal information [25]

<table>
<thead>
<tr>
<th>Entity charged</th>
<th>Gramm-Leach-Bliley Financial Services Modernization Act</th>
<th>Sarbanes-Oxley Public Company Accounting Reform &amp; Investor Protection Act</th>
<th>FACTA (Fair &amp; Accurate Credit Transaction Act)</th>
<th>HIPAA (Health Insurance Portability &amp; Accountability Act)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directors and Officers</td>
<td>$10,000</td>
<td>$1,000,000</td>
<td></td>
<td>$50,000 to $250,000</td>
</tr>
<tr>
<td>Institution</td>
<td>$100,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Years in Prison</td>
<td>5 to 12 years</td>
<td>20 years</td>
<td></td>
<td>1 to 10 years</td>
</tr>
<tr>
<td>FDIC Insurance</td>
<td>Terminated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact on Operations</td>
<td>Cease and desist</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Individual</td>
<td>$1,000,000</td>
<td></td>
<td>Civil action</td>
<td>$25,000</td>
</tr>
<tr>
<td>Institution</td>
<td>1% of assets</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Some HDD users generate a significant volume of used IT assets and decide to handle the logistics for reuse versus materials recovery themselves. The processes they perform can include direct sales of refurbished/tested equipment; sales of some remaining equipment to secondary markets; sorting, data wiping and testing of HDDs to determine suitability for reuse; disassembly of equipment and HDDs for materials recovery; and contracts with recyclers and smelters to handle the remaining equipment, sorted disassembled parts, and shredding.

3.3.3 Electronics OEMs

Electronics manufacturers/OEMs specify the characteristics of HDDs required for their systems, and work with the HDD OEMs to determine which HDDs best meet their needs. In-warranty returns of electronics are typically handled by OEM-authorized service providers, which test and repair the in-warranty systems and return them to service where possible. If the in-warranty HDDs are defective, the OEM service provider may send the HDDs to the HDD OEM’s authorized service provider for testing to determine whether they can be recertified as OEM drives, white-labeled, or recycled. Recertified OEM HDDs are then returned to the OEM-authorized service providers as warranty replacements. In addition, many electronics manufacturers take back used, out-of-warranty electronics, which are handled by asset management and logistics companies. It is not known specifically how used HDDs in these products are handled by the leading electronics
companies. Note that HDD-containing systems include desktops, laptops, gaming and entertainment systems, servers, data center systems, Internet service centers, and cloud storage systems.

3.3.4 HDD OEM-authorized aftermarket service providers

As with all major electronics manufacturers, there is a need for approved and authorized returns/warranty management systems, and the HDD industry is no exception. There are a limited number of approved globalized aftermarket service providers contracted by the HDD OEMs who undertake this service on their behalf. The services these organizations perform are diversified and matrixed to the needs and requirements of the HDD OEMs. They typically cover activities from RMA management, which includes system registration, reverse logistics processes, RMA verification and reconciliation, full failure analysis and product performance analysis, to full in-warranty back-end testing (BET), to product lifecycle “recertification” and secondary product remanufacturing. All of these processes map into the circular economy vision and its mechanisms for implementation.

Through the approved aftermarket service providers, HDDs can be remanufactured and reused in different ways depending on their business relationships and contractual obligations with the HDD OEMs and other sources of HDDs, including:

- **OEM labeled recertified drives**: In-warranty and out-of-warranty drives are used by HDD manufacturers as replacement for in-warranty returns, can be put into systems for resale, and sold as HDDs, both wholesale and retail.
- **White labeled drives**: Derived from in-warranty and out-of-warranty stocks of used HDDs, remanufacturing allows drives with significant numbers of fault causes to be remanufactured as drives with lower storage capacities. This requires special relationships between HDD manufacturers and specific “authorized aftermarket service partners.”
- **Pulled out-of-warranty drives**: Devices that have been removed from end-of-use equipment, wiped, tested and re-marketed but still with initial OEM set-up of firmware and product original labelling.

The HDDs can come from various sources. Primary sources include in-warranty returns, excess and obsolete stocks, end-of-life equipment, e-waste processes, and upgrades and refresh operations of large organizations.

3.3.5 IT asset management and recyclers

Asset managers and electronics recyclers provide individuals and organizations (companies, government, non-profits, etc.) pathways to dispose of their end-of-use electronics. The services they may offer include data security, efficient asset management, reverse logistics, and asset value recovery. IT asset management companies and recyclers provide services to a wide range of electronics owners: enterprise corporations, leasing organizations and channel partners, original
equipment manufacturers, contract manufacturers, service repair organizations and retailers, and value-added resellers (VARS). The service contracts with the electronics owners determine what services are required, what value recovery pathways are allowed, as well as the business model for recovered value. Most electronics that IT asset managers and recyclers handle are complete systems, many of which contain HDDs. For systems, the most lucrative value recovery pathway is usually resale as intact, functioning systems, but that may not be allowed by a specific contract.

Once a HDD has been identified for reuse, IT asset managers and recyclers typically assess the economics for a specific drive based on the various value recovery pathways they can access. In some cases, they sanitize the HDDs and perform functional testing to identify whether the HDD can be resold as a used OEM HDD as specified on the label. Third-party software and built-in HDD software are used for testing, with specific Self-Monitoring, Analysis and Reporting Technology (SMART) parameters used as pass-fail criteria. In addition, the following steps are frequently taken in addition to data sanitization and SMART testing to qualify used HDDs: surface test, random seek test, and firmware update. [22]

3.3.6 Secondary markets for HDD parts and smelters and refiners for metals recovery

According to Tradeloop, an international wholesale trading network for IT products, there are over 70,000 brokers, dealers, and sellers of used IT equipment worldwide, with over 50,000 using Tradeloop as a trading network. [26] The sellers can be IT asset management companies and recyclers as well as the large original equipment owners that handle their IT asset management in-house. The sizes of transactions range from small lot sizes, gaylords and pallets, to multiple shipping containers, with product disposition ranging from reuse to materials recovery/recycling. From online sites such as eBay, Alibaba, and hddparts.com we know that there are companies that dismantle HDDs and sell their parts to the public. Project team members heard that, in the past, HDD parts were harvested and sold to HDD manufacturers and EMS providers for reuse in new HDDs, but there was no evidence that it is currently being done.

3.4 Value Recovery Pathways from Used HDDs

3.4.1 Resale of fully functioning electronics and OEM HDDs

The highest value recovery from used electronics usually comes from cascading the lifecycle of the unit from its current or alternative forms, resulting in the sale of complete, fully functioning products, such as computers and servers. If a used computer is working properly, preparing it for reuse involves only external cleaning of the device, sanitizing the data on the HDD, and upgrading the software configuration. For example, it can take as little as 15 minutes of human labor for an IT asset management facility to data wipe and recertify a laptop returned in good condition. However, the planning for laptop reuse/resale depends on the quantity and quality of returns and exogenous factors like market demand. Kwak et al. [27] formulated a model for the second-hand market value (buy-back price owner can obtain) of used laptops and cell phones, based on design specifications, product age, and cosmetic and hardware condition. Considering all hardware, a non-functioning HDD is reported to have the most negative impact on the buy-back price for laptops.
and desktops. The HDD’s capacity, together with CPU and display performance, represents 54.8% of the variation in the price of computers in the market [28]. If the collection pathways require that owners remove HDDs from systems to minimize data disclosure risk for the recycler, or if the system owners decide to retain their HDDs, these represent “leaks” in the HDD value recovery supply chain and new or used HDDs are installed in the recovered systems before resale [29].

To assess the reusability level of a used HDD, it is not enough to evaluate whether it functions or not; there must be ready, willing, and able purchasers for the HDDs — i.e., secondary markets. In emerging markets there is significant demand for HDDs with storage capacities as low as 160GB in both form factors of 3.5” and 2.5”. For other markets, a primary barrier to reuse of a fully functional, but used, HDD is the lower capacities of older EoU drives compared with the increasing storage needed for installation and use of the operating system (OS) and software packages [30]. For example, Windows 10 requires 16GB for installation and Star Wars: The Force Unleashed (2009) requires 23GB storage, plus 8GB of free space and 1GB swap file space to run [31]. This is also important for the resale of used systems. HDD capacity is an important factor in pricing a used laptop, with the impact of the HDD’s capacity on the laptop’s buy-back price estimated to be $0.12/GB. From an informal survey of organizations undertaking this activity and selling in global markets, the minimum storage capacity for reuse/resale of a 3.5” HDD is 160GB, and for 2.5” HDDs is 120GB for some markets, while it is 500GB and 320GB, respectively, for other markets.

In simple terms, the value recovery depends on knowledge of the markets, ability to refresh units via reuse, remanufacturing and cascading the units through a longer cycle of usability. Solutions and organizations exist today to provide an economic and viable alternative to harvest and recycle parts.

To reuse HDDs, whether in systems or as used OEM drives, data sanitization must first be performed. It is possible for HDD users to themselves perform the level of data sanitization they require to meet the contractual agreement with the original owner as described previously. Second, recyclers/sellers of used HDDs use a range of standard tests to characterize whether a HDD may have an acceptable level of reusability/resale value, including using a surface test to mark bad sectors, a few specific SMART test criteria, random seek testing, and installing firmware updates. Used OEM-labelled HDDs with different characteristics can be matched with the price point/risk requirements of purchasers of used HDDs.

3.4.2 Remanufacturing and rebranding (white label) of devices unsuitable for resale as recertified OEM hard drives

While many recyclers and IT asset management companies have the test equipment for standard tests, there are only a few companies, i.e., the OEM-authorized aftermarket service providers, that have the technologies for full remanufacturing and rebranding HDDs unsuitable for resale as used OEM-labelled drives. Through the use of this technology, these companies create what is termed a “white label drive” by depopulation, as described above, reloading of revised and proprietary firmware as provided by the HDD OEMs, and addition of new serial numbers and rebranding to a new product range and name, without any information linking it to the original OEM.
The remanufacturing and rebranding solution offers an effective path to increase value recovery since there is significant demand for such drives, as noted from Internet websites selling used OEM and white label drives. Note that white label drives frequently have a one-year warranty, which provides an incentive for their purchase. An additional benefit is the ability to erase all information on the original unit origin and all previous ownership, by the complete removal and sanitization of any original features, marking or traceable points. Since this remanufacturing requires close collaboration with the HDD OEMs, this process is limited to authorized aftermarket service providers to the HDD OEMs.

3.4.3 Parts and commodity materials recovery

A common HDD consists of the following components and parts: printed circuit board, aluminum parts (case, platters, lids, and voice coil), steel parts (magnet shoes, lids, and screws), and rare earth magnets (Nd₂Fe₁₄B) [32]. Table 3 lists the materials in a specific HDD model produced by Seagate Technology LLC. This materials composition breakdown is fairly representative of different brands and models of HDDs [33]. The data show that the concentration of aluminum and iron is more than 80% of total weight of a typical HDD, whereas the materials recovery value is dominated by gold and platinum group metals present at the milligram level in the circuit board. [34]

<table>
<thead>
<tr>
<th>Name of Material</th>
<th>Mass (g)</th>
<th>Concentration (%)</th>
<th>Name of Material</th>
<th>Mass (g)</th>
<th>Concentration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>394.34</td>
<td>61.95</td>
<td>LCP polymer</td>
<td>1.93</td>
<td>0.30</td>
</tr>
<tr>
<td>Iron</td>
<td>118.75</td>
<td>18.65</td>
<td>POM, Polyoxymethylene Copolymer</td>
<td>1.46</td>
<td>0.23</td>
</tr>
<tr>
<td>Copper</td>
<td>35.15</td>
<td>5.52</td>
<td>&quot;DOPO&quot; Halogen-free Flame Retardant</td>
<td>1.16</td>
<td>0.18</td>
</tr>
<tr>
<td>Silicon</td>
<td>29.19</td>
<td>4.58</td>
<td>Polyester Material</td>
<td>1.10</td>
<td>0.17</td>
</tr>
<tr>
<td>Chromium</td>
<td>15.74</td>
<td>2.47</td>
<td>Acrylate Urethane Oligomer</td>
<td>1.05</td>
<td>0.16</td>
</tr>
<tr>
<td>Nickel</td>
<td>10.72</td>
<td>1.68</td>
<td>Proprietary</td>
<td>0.79</td>
<td>0.12</td>
</tr>
<tr>
<td>Zinc</td>
<td>5.09</td>
<td>0.80</td>
<td>Epoxy Resin</td>
<td>0.77</td>
<td>0.12</td>
</tr>
<tr>
<td>Fibrous-glass-wool</td>
<td>3.05</td>
<td>0.48</td>
<td>Acrylic Polymer</td>
<td>0.74</td>
<td>0.12</td>
</tr>
<tr>
<td>Neodymium</td>
<td>2.32</td>
<td>0.36</td>
<td>Fused Silica</td>
<td>0.69</td>
<td>0.11</td>
</tr>
<tr>
<td>Magnesium</td>
<td>2.10</td>
<td>0.36</td>
<td>Tin</td>
<td>0.57</td>
<td>0.09</td>
</tr>
<tr>
<td>Manganese</td>
<td>2.10</td>
<td>0.33</td>
<td>The other materials</td>
<td>7.57</td>
<td>1.19</td>
</tr>
</tbody>
</table>


In a typical recycling system, the collected products are sorted based on a pre-determined recovery plan, in which the graded and sorted products are made ready for reuse, remanufacturing, disassembly for parts, and material recovery based on their overall utility and latent market value. Disassembly can be an integral step in a value recovery pathway, but the extent a product can be disassembled and its utility depend on the cost of value recovery and the markets for the recovered
materials. For HDDs, there are different recovery options based on the extent of disassembly required: (1) sold to wholesalers as intact HDDs without any dismantling operations; (2) partially dismantled (e.g., printed wiring boards are manually removed and smelted for precious metals) with the rest of the HDDs sold to wholesalers or smelters; (3) completely dismantled to recycle each component separately which improves the materials recovery efficiency; or (4) shredded.

Published research has described various manual and automated/robotic disassembly process schemes, each with its own challenges. [35] [36] Creating a disassembly process can be a useful exercise, but whether it can actually be commercialized and useful for value recovery depends on the decision points for different stakeholders and the costs and revenues for the stakeholders along specific value recovery pathways. For example, Cong et al. (2015) [37] examined several possible HDD disassembly sequences and extents for HDD recycling in the U.S. with the goal of maximizing the recovery profit. For manual disassembly in the U.S., removal of printed circuit boards (PCBs) for precious metal recycling and pad insulators for reuse could be profitable; however, separation of the other components, including the magnets, was not. In contrast, a high-throughput, automated HDD dismantling system could substantially reduce the dismantling cost, making PCB, pad insulator, and magnet separation profitable. These results for the U.S. are similar to the analysis of Manhart et al. [32] on recycling HDDs in Ghana and Egypt as part of a developed world/developing world collaboration known as the “Best-of-Two-Worlds” approach developed by UN University in which countries with lower labor costs are used for labor-intensive operations such as disassembly and the materials are recovered in developed countries that have high-efficiency smelting operations and infrastructure. Manhart et al. compared the economics of (1) shipping whole drives to the EU for materials extraction, (2) manual dismantling of PCBs only, sending the PCBs to an EU smelter and selling the remainder as mixed metal scrap, and (3) complete dismantling (PCBs, magnets, plattens, …) and sending the individual fractions for recovery in the EU. They determined that PCB separation for precious metal smelting was the most profitable, with no significant difference in the profits between partial and complete manual separation, given a particular price point for rare earth magnets.

These results are consistent with what we have observed as common practice in the U.S. and Asia: manual separation of PCBs, particularly for the larger PCBs, is often performed for drives that are not shredded or destroyed for data sanitization. The recovered PCBs are sent for precious metal smelting and the remainder of the HDD is shredded and sold as mixed aluminum scrap for metals recovery. Many of the smaller drives are sent into the shredder without removing the PCBs, and the shred sold for metals recovery.

There is, however, evidence of partial or complete manual disassembly of HDDs being performed, as seen from product offerings on eBay, hdd-parts.com, and spare-partwarehouse.com, for example, and from disassembly/secondary sales companies listed in Alibaba and other websites. Rare earth magnets, read/write heads, and HDD PCBs are offered both in quantity and as replacement for specific models.
One possible additional value recovery pathway could be through REE recovery for production of new REE magnets. Zakotnik et al. [38] reported a process for using harvested magnets through demagnetization, cleaning, hydrogen decrepitation, and jet milling to produce demagnetized Nd2Fe14B powder as raw materials for magnet fabrication. By eliminating the mining and powder production steps in magnet manufacturing, they estimated that a 46% reduction in energy consumption is possible. [39] Key economic factors in the viability of this pathway are the cost of obtaining/harvesting the magnets as discussed briefly above, the cost of producing the powder, and the revenue possible from the sale of the powder, including the openness of the magnet manufacturers to using this powder as an alternative powder source.

3.4.4 Value recovery from three pathways: economics of reuse and metals recycling/recovery

For this project, we examined the economics along three pathways, based on the data we could obtain from the literature and from industry sources: (1) secondary market transactions, (2) functional used drives sold through brokers, and (3) metals recovery along transnational pathways (“Best-of-Two-Worlds” approach). The economic analyses provide some insights into the potential for growth and the limitations of current pathways.

For transactions in the secondary market, Tradeloop has provided a typical breakdown of the profits to the seller from 1000 500GB/SATA/3.5”/7200RPM HDDs, depending on the level of pre-testing, functionality, and disassembly, with three levels of HDD reuse and four levels of materials recovery, as shown in Figure 7. The three categories for HDD reuse range from fully functioning, wiped and tested HDDs ($30/drive), to untested HDDs ($15/drive). These are similar to published retail prices from the Internet for 500GB/SATA/3.5”/7200RPM HDDs in the range of $30-$40 for a white label hard disk drive and $40-$45 for an OEM-labeled HDD, all with one-year warranties. The materials recovery value is derived primarily from Au, Cu, and Ag in the printed circuit boards, which are external to HDDs and thus when removed, will yield $7-$10/lb for the circuit boards alone. The remaining value comes primarily from recovered Al. Figure 7 shows the effects of processing costs borne by the seller and revenue from data sanitization by shredding shown in the figures as customer fees. It is interesting to note that the degauss/destruct option that leaves the HDD largely intact provides more return on the recycling side than shredding, i.e., if there is no customer fee paid for data sanitization. This may be a result of the smaller size scale of typical shredded pieces that may lead to lower efficiency metals recovery; however, this is only speculation.

As part of this project, we evaluated how resale value of used, functional HDDs was affected by manufacturer, model, capacity, and resale time (the time when the HDD was sold) using linear regression models. Industrial data from an auction process was provided by a third party for over 145k HDDs for this analysis. It was found that all these factors had a significant impact on the resale price. A general trend noted was that the HDD resale price dropped as a function of time. So, the earlier that a HDD was sold, the higher the price. However, there was substantial uncertainty in forecasting the future resale value of a particular HDD using a single factor (e.g., by
manufacturer), although there was a statistically significant difference between manufacturers. Consumers prefer higher quality HDDs, and this depends on the HDD model – each model has an associated manufacturer and storage capacity. However, for a given HDD model, the resale value (the primary response variable) was best predicted using the data for resale time. Other exogenous variables, such as changes in the HDD supply chain and compatibility with consumers’ existing HDD systems, would also affect the resale value but were not studied in this analysis.

Figure 7. Value recovery from 1000 HDDs (1,300 lbs., d500GB/SATA/3.5”/ 7200RPMd) provided by Tradeloop.com based on secondary market data.

A study led by the United Nations University based on “The Best-of-Two-Worlds philosophy (Bo2W)” [40] provides valuable perspectives on the technical, logistic, economic, and societal
challenges to increasing collection and metals recovery efficiency and recovered value while protecting human health and the environment. The study sought to integrate the “best” pre-processing of desktop computers in developing countries where labor costs are relatively low with the “best” end-processing in developed countries using environmentally sound, state-of-the-art processing facilities. The results of two pilot studies in China and India were reported along with their implications for future implementation of Bo2W projects. This study was important as input to iNEMI’s Phase 1 Metals Recovery Project, as well as this project, and we recommend this as an essential resource.

In the analysis of desktop computers, three pre-processing methods were compared as a function of labor costs: complete manual dismantling, partial dismantling with partial mechanical material separation, and full mechanical separation (shredding). Figure 8 below shows the transitions in the “best” pre-processing method as measured by net profit as a function of labor cost. The preferred method is the highest net profit for each labor cost point. There are three transitions observed, with complete manual separation being more profitable for the lowest labor costs, a combination of manual and mechanical separation for intermediate costs, and mechanical separation/shredding for the highest costs. While this is for desktop computers, it can be applied equally well to HDDs since the primary profit in both cases is from separation of the PCBs for subsequent metals recovery. For a more detailed discussion of Bo2W as applied to HDDs, see Manhart et al. [32]

Figure 8. Transformation of pre-processing methods for desktop computer influenced by increasing labor costs in China (2000-2009, statistic data: 2010-2035, forecast).

There are three important distinctions between the approaches taken by the iNEMI project and the UNU Bo2W project. The first is that we are focusing on total value recovery from HDD reuse, for
whole product and parts reuse plus materials recovery, while the Bo2W focused on metals recovery alone. This was a major issue for the pilot project in China: the informal sector could obtain significantly higher value by refurbishing and reselling used desktops than they could pay, so the flow of used desktops was insufficient for a functioning, economically viable disassembly operation. Second, all costs of proper disposal are included in the analyses here. In the pilot project in India, informal recyclers provided PCBs to the integrated smelter in the EU but there were no built-in incentives in the project to deal properly with the remaining low-value, often hazardous fractions remaining in India. They determined that “cherry picking” of the valuable fractions while leaving hazardous waste or waste with no value for the informal sector to deal with was unacceptable but, unfortunately, did not have any solutions for this situation. Third, the iNEMI project is examining ways to change the net profit curves for HDDs by reusing high-value parts and by changing the net profit from “full mechanical separation” using state-of-the-art automated disassembly. Imagine if, by changing the disassembly technology, the horizontal line for full mechanical separation in Figure 8 were above all pathways, including manual disassembly. This would lead to higher total value recovered and would provide incentives for higher collection rates not only for the HDDs with the largest PWBs but possibly for small HDDs that are currently uneconomical to disassemble.

Analysis of the two pilot projects in the Bo2W study also highlights what can happen if specific criteria from the Ostrom framework are not met. In the Chinese project, the informal sector was a competitor for the used HDDs and there was not a mechanism for working with them to bring used, but non-functioning HDDs into the value recovery stream. There were also key leadership and communication gaps, and it was likely that the stakeholders who were involved were not committed to a continuing partnership or a common goal. In the Indian project, the informal sector was willing to provide PCBs for smelting in the EU to recover more value; however, the business model of the integrated smelter did not meet their needs at all. The integrated smelter pays the owner of the recycled materials only after the smelting has taken place and the recovered materials sold. In this case it meant a delay of five months between the time of collection and receiving payment, clearly a serious issue for processors in the informal sector who rely on these payments for subsistence. In addition, there was no willingness of the participants to develop a plan to properly treat the remaining hazardous materials or dispose of the low-value components. Implementing this model might create a different “tragedy of the commons” than now exists with uncontrolled acid leaching and cyanide processing, but it could possibly be as bad considering unintended consequences.

3.5 Stocks and Flows Analysis of Used HDDs: Case Study from North American Data Centers

3.5.1 A model of HDD sourcing from data centers

As technology progresses, new generations of electronic devices are introduced to the market. As this occurs, value recovery systems must be agile enough to cope with the anticipated multigenerational return stream of used devices, which may be technologically obsolete compared to the newer generation, but fully functional nevertheless. This is especially true with the digital storage
industry, where SSDs are projected to have significant penetration across global storage markets, cloud storage is replacing local storage for many applications and users, and the total storage capacity for HDDs sold annually continues to increase as the total sales of HDDs decrease. In addition, global HDD sales are spread across different regions including Asia, Europe and North America (NA). Generally, HDD sales determine the number and type of HDDs that will be discarded and available for value recovery. However, linking global HDD sales to HDDs being available for value recovery is challenging largely due to the vast number of HDDs, the diversity of applications, and the geographic dispersion of HDD users and applications.

To identify opportunities for HDD value recovery based on economically viable and realistic scenarios, it is important to start estimating the availability of HDDs across regions and uses. In this report, a system dynamics (SD) modeling methodology is applied that treats elements within the system as accumulating entities (stocks) and rates that control the accumulation (flows). Using a combination of HDD sales data, failure data and warranty information, this model can be used to estimate in-use HDDs and HDDs that have failed and are available for recovery in a given region. A key requirement for such a model is having reliable data as input, which are missing for almost all scenarios. As a test case, a SD model has been developed to estimate HDD availability from North American data centers, the scenario with the simplest handoffs and the best available data on lifetimes.

Data centers are a unique opportunity for a focused effort on recovery because HDDs are often concentrated in large volumes, have higher unit value recovery potential compared to desktop and mobile computer HDDs, are considered assets to be managed, and future storage capacity demand is anticipated to increase. To capture this opportunity, an analysis is performed to focus on estimating upper/lower bounds for HDD availability from NA data centers. (A similar analysis of NA HDD availability from both data center and consumer HDD models is provided in Appendix B.)

The following HDD categories are considered:

- Mobile consumer
- Desktop
  - Consumer desktop
  - Business-critical (BC) enterprise (also referred to as “nearline” and “reference”)
- Mission-critical (MC) enterprise

These categories are based on historical HDD shipment/sales data and the categorization used by the HDD manufacturing industry [9][13][41]. This historical global sales data is broken down by region, HDD category shipped and HDD manufacturer. This data also includes HDD sales projections until 2020, which account for many market factors, including the penetration of SSDs across these
NA HDD consumption is estimated based on its global market share and the regional sales of PC and server systems. It is assumed that HDDs sold in PC and server systems within NA arrived at end of use within NA.

Although the SD model is composed of over a dozen stocks and flows, it can be broken down into three stocks: NA HDDs in use, NA HDDs at EoU and NA HDDs available for value recovery at EoU (Figure 9).

The stocks and flows are arrayed by the above HDD categories. It is assumed that U.S. data centers use BC and MC HDDs, while consumer applications largely cover the desktop and mobile PC markets. To further clarify, a HDD that reaches end of use may not be available for value recovery due to warranty replacements. In this analysis, a HDD is considered to be available for value recovery if it has been returned for warranty replacement but has failed beyond repair, or if the HDD has been collected by independent recyclers and/or e-waste stockpilers after the warranty period. The data used in the analysis and associated references are provided in Appendix B.

Upper/lower bound analyses were conducted for the annual availability of HDDs for value recovery from U.S. data centers, as seen in Figures 10 and 11. The model’s results are dependent on the uncertainties in the four types of data used: sales data, warranty data, annual replacement rate (ARR), and end-of-life pathways. Given the lower uncertainties for the sales and warranty data, a sensitivity analysis is conducted that considers (1) the ARR for all HDD models (shown in Figure 10) and (2) the pathways at end of use and end of life — i.e., landfill, e-waste collection, recycler collection, etc. (shown in Figure 11).
Figure 10. Upper and lower bounds of annual HDDs Available for value recovery from NA data centers (adjusting ARR only). Grey line indicates average.

Figure 11. Upper and lower bounds of HDDs available for value recovery from NA data centers (adjusting EoU pathways). Center grey line indicates average.
As the results show, approximately 19-24M data center HDDs are available for value recovery per year in NA alone from 2015 to 2020. However, these ranges differ depending on the variables that are adjusted. When only adjusting the ARR for enterprise models, there is greater uncertainty toward the beginning (22M-24M HDDs) due to the smaller standard deviation and the diminishing effect of a changing ARR further in an enterprise HDD’s lifetime. When adjusting the discard pathways, the upper/lower bound analysis results in a larger range of 19M-24M HDDs being available for EoU recovery from 2015 to 2020. This indicates the sensitivity of HDD availability to industry and user practice.

3.5.2 Translating stock and flow estimates into models of how HDDs are and are not entering value recovery pathways

The stocks and flows analysis in this report utilized a top-down approach by beginning with global HDD shipments and then differentiating the HDDs by model, age, region and other factors. Therefore, this analysis is a baseline for how many used hard drives could be in the value recovery stream. While this approach is useful for estimating the domestic availability of a recycling feed stream, a bottom-up approach with detailed local data is necessary to test the model’s assumptions (e.g., discard pathways and HDD replacement rates) for establishing HDD availability across different regions and consumer/industry practice. This would require collection data at the corporate, community, and regional levels. Previous system dynamics (stocks and flows) models have been created for closed-loop electronics recycling for decision and policy support for original equipment manufacturers and municipalities [44][45][46]). If more information were known about data center HDD management practices, this could be combined with existing consumer HDD discard data [1] to estimate future HDD availability across applications, consumers and geographic locations. Applied more broadly, this analytical framework could facilitate the development of robust value recovery solutions, if reliable data were available.

The total value recovered after collection is also determined by the efficiencies by which they are processed. An example of this comes from the research on the efficiencies for HDD removal from electronics scrap collected from Danish municipal collection centers [8]. Workers manually removed “easily removable” HDDs. The scrap after the HDDs were removed and examined carefully by workers to identify HDDs that had not been harvested. The researchers found that only 35% of the desktop and laptop HDDs could be removed easily, with the remaining 65% being shredded. Through careful post-processing sorting, they also determined that the total number of HDDs available for value recovery ranged from 2-4 HDDs/ton electronic scrap. For enterprise and business systems they estimated that the collection rate of HDDs was close to 90%, but offered little detail about how this estimate was determined. The changing mix of products over time also makes a difference in determining their resale value as used electronics and for metals recovery. Value recovery is being affected by the global shift from desktops and laptops to smartphones and tablets, and by the decreasing potential for materials recovery as Au content decreases, particularly as Au wire bonding is replaced by Cu or Ag wire bonding or by solder interconnects.
Chapter 4: Current Practices and Opportunities to Enhance Value Recovery

4.1 Decision Trees for Current Practices

In value recovery of HDDs, stakeholders take specific viewpoints — some narrow, some broad — using the general decision-making criteria presented in Chapter 2. Recyclers, HDD enterprise users, HDD consumer users, IT asset management companies, HDD manufacturers, OEMs whose products contain HDDs, authorized aftermarket service providers, or governments, to name the major stakeholders, limit their choices to what they can control and from which they can derive benefit, whether in maximizing profit, limiting cost, mitigating risk of release of sensitive data, or creating sustainable solutions. As electronics continue to change rapidly, stakeholders adjust their business models to maintain their competitiveness in this dynamic environment.

The perspective we have taken in this project is to identify the decision points made by different stakeholders in the HDD value recovery system, to understand how those decisions lead to specific outcomes, and to identify what other options are needed to change those decisions for increased value creation/recovery from used HDDs. Our perspective is a system-wide view. It is our intent that, ultimately, by defining revenue opportunities and associated decision points, by reducing risks, and by linking stakeholders in a way that supports their shared goals, all stakeholders should have greater opportunities to derive more value from HDDs. In the analysis of the current situation we are limiting our decision trees to today’s practices. Later in this chapter we examine additional decision trees that could be possible with specific changes in HDD design, collection pathways, pre-processing practices, recovery technologies, and new applications where components can be reused.

4.1.1 Basic decision tree

We have broken the decision trees into two primary types: the first is based on how HDDs enter the value recovery system and the second is how, value is recovered, once in the system. Figure 12 shows the three primary types of organizations that aggregate used HDDs for value recovery systems. HDDs come to these organizations at the “start” position, with the HDD users deciding what organization to select based on the services they require, as discussed in Chapter 2.
The high-level decision tree (Figure 13) that most recyclers, IT asset management companies, and OEM authorized aftermarket service providers use consists of three primary decision points: data security and risk concerns, resale value of HDDs, and commodity pricing for metals recovery along different pathways. With respect to disposition based on data security and sensitivity, the decision tree from NIST shown in Figure 6 and discussed above, is widely used, and the receiving organizations are frequently paid a fee to meet the data security requirements of the users. Three general data sanitization processes are recommended — clear, purge, or destroy — based on data security type and whether the HDD is being reused internally or sent outside the company. One key observation in our study is that many HDD owners require that recyclers physically destroy their
still functioning used HDDs, even if they do not contain sensitive data or could be easily data wiped. By using the NIST criteria and verifying that the appropriate clear/purge processes have been carried out, more drives could be available for reuse, the second decision point in the decision tree. At the extreme, some companies and organizations require that the drives be punched or folded before leaving company premises, followed by shredding and even melting. The results of these processes are shown in Figure 14. No further reuse decisions are required or possible, and the second step is skipped. If the HDDs can be transported to a recycler’s facility before physically damaging them, the external printed wiring boards many be removed before shredding to concentrate precious metals for recovery (at U.S. $7-9/pound of PWBs). The remainder of HDDs (with and without PWBs) are shredded and sent to the secondary market for materials recovery.

![Decision Tree](image)

**Figure 13. Simplified decision tree for current HDD value recovery practices for many recyclers.**

If reuse of HDDs is allowed, the HDDs are evaluated for reuse based on their resale value, operating condition, costs for preparing them for resale — whether as OEM recertified or white label drives — and access to the resale markets.
4.1.2 Decision tree for reuse

A detailed decision tree for undamaged hard drives is presented in Figure 15 and represents the process flow that HDD OEM authorized aftermarket service providers, recyclers, IT asset management companies, and even HDD owning organizations follow. If an organization does not have the ability to perform a specific function, the HDD may be transferred to another organization that can, for example, remanufacture a used HDD into a white label drive, or a recycler could send the HDD to a HDD OEM-authorized aftermarket service provider. This decision tree starts with a HDD entering the system at the top left. The system identifies whether the HDD can be reused or sent for materials recovery (“Recovery decision?”). This decision is based, first, on the contract with the original HDD owner, and, second, by its reuse value compared with scrap value. Drives that are required to be physically destroyed (“scrap”) are sent for scrap/materials recovery regardless of their potential resale value.

For drives that can be reused, the economic decision-making process for reuse/resale versus scrap/materials recovery is presented in Figure 16 for the case of a recycler or IT asset management company that is without the capability of remanufacturing used HDDs as white label HDDs and is required to data-wipe the HDDs before they are transferred to an OEM-authorized aftermarket service provider for white label remanufacturing. There are economic decisions that recyclers and IT asset management companies would, therefore, make in deciding whether to send HDDs to a HDD OEM-authorized aftermarket service provider (AASP). For example, a cosmetically sound, spinnable HDD that does not meet strict SMART criteria could be sold to an AASP for white label processing. If the recycler/asset management company is required to data-wipe all drives before sending them to the AASP, the recycler/asset management company must be able to realize an equal or greater profit by selling them to the AASP than by shredding them (for which no data-wipe is required), and sending them for materials recovery.

Figure 14. Punched or bent HDDs, performed at HDD owner’s facility, sometimes followed by shredding.
As shown in Figure 16, there are three possible outcomes from this analysis: an OEM-labelled drive, a white label HDD, and scrap. Historical data, current market conditions and demand, HDD characteristics, and remanufacturing costs are used to determine a HDD’s resale value as an OEM-labelled HDD which can be performed in house (blue) or as a white label HDD which is outsourced to the authorized aftermarket service provider (green). The final decision for a specific HDD is based on a comparison of margins (economic values) for the three possible outcomes. (Note that the economics for a HDD OEM-authorized aftermarket service provider will be different since both OEM recertification and white label capabilities are available in house.) Going back to Figure 15, once the decision is made to reuse the HDD, the HDD is tested and categorized based on meeting specific SMART criteria and other performance tests for reuse. If the HDD fails, it is sent to the scrap system. If the HDD passes, it is data-wiped. If data-wiping is successful, the HDD is sent for final resale processing. If the HDD fails data-wiping, it is sent to the scrap system. The final
decision on whether the HDD is reused as an OEM-labeled or white label drive is determined by the functioning storage capacity of the HDD, the market demand for drives of a particular storage capacity, and the cost of the white label process. For example, if a 1TB HDD has a significant number of non-functioning sectors and a non-functioning read-write head, the white label remanufacturing process can reconfigure the drive to omit those sectors and remove the non-functioning head from use while retaining some storage capacity.

Figure 16. Economic decision making for resale (OEM or white label HDDs) and scrap.
4.1.3 Decision tree for parts reuse and materials recovery from non-functioning HDDs

As described above in 2.4.4, shredded HDDs (Figure 17) can be sold for metals extraction; however, the cost of shredding typically is greater than the recovered metals cost from the shred. Shredding is, therefore, the primary mechanism for data sanitization and is supported by a customer fee. In the Tradeloop example, the shredding fee was estimated to be $5/HDD, while the cost for shredding was $1/HDD. The final metals recovery process from the shred provided $250 of additional profit since the shredding had already been performed. Unshredded scrap HDDs can be sold as is or with the PCBs removed for metals recovery, with the remainder being sold as mixed Al scrap. The decision point for shredding as data sanitization is between HDD user/owner and the IT asset manager/recycler, as described above. As far as we know, there is currently little parts reuse for HDDs.

![Figure 17. Shredded hard disk drives (HDDs).](image)

4.2 Decision Trees for New Pathways for Value Recovery from HDDs

An essential element of creating a circular economy route to sustainability is the idea of taking a product after every use or so-called “life” and reusing it as close as possible to its original function to retain its embedded energy and materials, reduce environmental impact, and increase economic value. Billions of hard disk drives have been manufactured and are in active operation around the world. Hundreds of millions of HDDs are taken out of service for repair or disposal every year. Today, some are reused, many of those drives are shredded and processed for metals recovery, or worse yet, end up in landfills. In this section we describe several new approaches for value recovery from HDDs. Figure 18 identifies two critical decision points that influence value recovery for HDDs coming into the value recovery supply chain. The first is the decision for whether reuse is allowed. As discussed above, there are reliable, secure, verifiable processes available for data sanitization that are available but are not being used. Our recommendations for how to encourage
reuse are presented in the next chapter. The second are the limited options for value recovery once it is determined that HDDs cannot be reused, either as OEM HDDs or white label HDDs. Currently, PCBs are the primary components that are being removed from used HDDs, and typically only for higher efficiency metals recovery. In the following sections we present ideas for creating “hard drives from hard drives,” and automated disassembly and separation processes to enable parts reuse and higher metals recovery.

Figure 18: Stars show where the increased opportunities are for value recovery.
4.2.1 Manufacturing new HDDs from used HDD parts: “hard drives from hard drives”

Figure 19. Decision tree for disassembly of HDDs for reuse of parts in HDDs.
The concept of extending the working life of products through design is not new. There have been proposals for modular reuse for consumer electronics. Project Aura in Google was one such concept as applied to a mobile phone. In fact, the hard drive itself is an excellent example of a field replaceable unit or module that can be swapped and replaced to increase storage capacity of a working laptop, desktop or enterprise server or to replace a failed HDD. The replacement strategy takes place millions of times every day around the world and is an effective strategy for repairing/upgrading the storage capacity and extending the working life of those computer systems.

We would like to extend this approach to include reusing the parts inside the HDD itself. This requires (1) optimization of the design and manufacturing of a specific HDD such that the parts can be removed and reused in manufacturing new HDDs without sacrificing performance or quality; and (2) creation of disassembly technologies that can economically remove the parts to be reused at the volumes and in the conditions required for reuse. A possible decision tree for removal of individual HDD parts is shown in Figure 19. One obvious place to do this is with the REE magnet assembly (Figure 20). To recover and reuse REE-containing magnets in high tech applications demands an economically viable method to remove the magnets from the assembly intact, undamaged, and in a form and at a volume they can be used in mass production. Currently, it is feasible to remove and reuse magnet assemblies to build drives of identical design. What we are seeking is an economical method for removing and recovering magnet assemblies in an undamaged state from used HDDs during the recycling process. A robotically dismantled HDD could lead to the recovery of not only the magnets, but also the steel lid, the printed circuit board, the aluminum case, the motor assembly, and the data platters. There is currently research in the U.S. Department of Energy (DOE) Critical Materials Institute (CMI) on new methods for the economic, automated recycling and reuse of rare earth magnets as well as other HDD parts. Rare earth materials have been identified by the Department of Energy as a critical material for clean energy technologies, with criticality defined by availability and the risk of a supply disruption; and REE use in electronics, particularly HDD magnets, is the second largest use of REE in the U.S. The current status of CMI and other innovative magnet recycling research is detailed in Section 4.2.4 Opportunities to increase the value of HDD recycling.

Other key components that can be potentially reused in this matter are motors, platens, baseplates, connectors and covers (Figure 19). Economic recovery and reuse of HDD subassemblies and components are only possible if the HDD drive can be disassembled at a sufficiently low cost and
if the HDD OEMs design their HDDs to reuse parts, likely with multiple models. Large consumer goods, such as automobiles, washers and dryers, are intentionally designed with repair and reuse of the components in mind. The auto industry has created a multibillion dollar industry for the high-volume, economic recovery and remanufacturing of alternators, engine controls, engines, and various moving parts for automobiles. It is not uncommon to extend the working life of an automobile for 20 years or more using this approach.

The basic idea is to apply this engineering concept to design HDDs in such a way that new drives can be built from used HDDs. The goal is to recover parts from non-functioning HDDs and reuse these parts to build new HDDs. This is a radical approach to value recovery, not yet applied to HDDs. To achieve this goal, we believe that it is essential that the HDD be designed to facilitate high-speed, low-cost automated disassembly. In addition, the components within the drive must be intentionally designed to be reused across an array of HDD products – both those being built today and also five years in the future – thereby reducing piece part and unit cost. Magnet form factors and configurations will need to be standardized. Parts recovered during automated repair and recycling operations will be inspected, cleaned and then reused by HDD factories with the intent of maximizing component reuse and minimizing waste. A design concept that achieves energy recovery and near-zero waste to landfill, can be contemplated and ultimately achieved if the HDD is designed with these specific value recovery outcomes in mind. In addition, the next generation of HDDs will likely be based on head-assisted magnetic recording (HAMR) which focuses a laser onto the disk during writing and allows smaller features to be written with an estimated 10X increase in storage density. Recovery and reuse of the HADR write head assemblies may offer an additional opportunity for parts reuse in new HDDs.

![Diagram of product lifecycle]
4.2.2 New automated disassembly technologies for possible value recovery from HDD magnets

Figure 22 shows that there are four potential end points to value recovery of rare earth elements from HDDs: (1) as pristine, undamaged permanent magnets used for HDDs, (2) as magnets used for other applications requiring REE magnets, (3) as swarf (i.e., waste from a manufacturing process) processed to form permanent magnet alloys, or (4) separated REE. Based on the result reported here, we know that metals recovery of REE alone is not financially viable unless the value of the recovered metals can defray the cost of separating them from Al and Fe metals. Direct or indirect reuse could possibly provide the added value needed to make the system economically viable.

![Diagram showing routes of value recovery](image)

**Figure 22.** Routes of value recovery, where the viability assessment begins with having an optimal dismantling technology and a techno-economic analysis (TEA) to assess economic viability of the possible routes.

There have been various research efforts for quantifying the value recovery potential of HDD magnets. The first option — direct reuse — was claimed to be the most suitable for large and easily accessible magnets such as wind turbines and (hybrid) electric vehicle motors and generators [47], possibly due to the economic concerns regarding the extraction of smaller magnets such as those
in HDDs. This approach could be improved by a high-throughput automated HDD dismantling system suggested in Cong et al. (2015) [37]. Other researchers have focused on developing technologies to recycle rare earth oxides from HDDs, applying methods such as hydrometallurgical, pyrometallurgical, electrochemical, biochemical, and gas phase extraction. Another approach being undertaken is directly producing “new” NdFeB magnets from harvested magnets (also known as “magnet-to-magnet recycling”) using hydrogen decrepitation. This route has been estimated to consume 55% or less energy than “virgin” magnet production [38], and is suitable for various EoL magnets, including small form factor magnets like loud speaker magnets and HDD magnets. Urban Mining Company, located in Austin, Texas, is employing the magnet-to-magnet recycling process for HDDs to produce new sintered magnets that are engineered for high-temperature applications such as electric vehicle motors. Zakotnik et al. [39] showed the magnet-to-magnet recycling process was capable of producing recycled sintered NdFeB magnets via grain boundary engineering from a variety of EoL feedstocks with increased thermal stability covering the entire commercial range. Jin et al. (2016) [48] performed a lifecycle assessment for this type of recycling approach to estimate the environmental impacts in comparison with “virgin” magnet production. It was found that the magnet-to-magnet recycling has significantly less environmental impact in multiple categories than production from virgin ores, as shown in Figure 23, while offering the same magnetic performance. Table 4 shows the lifecycle impacts per kilogram of magnets for different scenarios. Since there are approximately 30g magnets/HDD, these impacts should be divided by approximately 33 to determine impact/HDD.

![Figure 23. Detailed processes: virgin production vs. magnet-to-magnet recycling.](image)
Table 4. Lifecycle impact of producing virgin and recycled NdFeB magnets per kilogram of magnets using TRACI (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts)

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Virgin Ore</th>
<th>Recycled Powder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Warming</td>
<td>kg CO₂ eq</td>
<td>27.602</td>
<td>12.453</td>
</tr>
<tr>
<td>Acidification</td>
<td>H⁺ moles eq</td>
<td>20.524</td>
<td>11.320</td>
</tr>
<tr>
<td>Carcinogenics</td>
<td>benzene eq</td>
<td>0.069</td>
<td>0.035</td>
</tr>
<tr>
<td>Non carcinogenics</td>
<td>toluene eq</td>
<td>249.382</td>
<td>136.075</td>
</tr>
<tr>
<td>Respiratory effects</td>
<td>kg PM2.5 eq</td>
<td>0.124</td>
<td>0.059</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>kg N eq</td>
<td>0.011</td>
<td>0.004</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>kg CFC-11 eq</td>
<td>1.25E-06</td>
<td>4.89E-07</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>kg 2,4-D eq</td>
<td>94.285</td>
<td>45.345</td>
</tr>
<tr>
<td>Smog</td>
<td>kg NOₓ eq</td>
<td>0.109</td>
<td>0.034</td>
</tr>
</tbody>
</table>

**4.2.4 Opportunities to increase the value of hard drive recycling**

Electronic waste recyclers are becoming more adept at recovering value from used consumer products. In the case of computer hard disk drives (HDDs), recyclers have developed processes that economically evaluate and recondition HDDs for resale markets. It is estimated that more than 60% of used HDDs are functional when removed from service. In fact, many HDDs are recommissioned several times before they are destroyed. The remaining HDDs that are no longer functional are largely shredded to ensure data destruction. Once a HDD is shredded, it is sold into the metal recycling marketplace as a mixed waste comprised primarily of steel and aluminum. The value from HDD printed circuit boards, magnets and other valuable metals has been largely lost after the HDD is shredded, as can be seen from the Tradeloop data in which shredding reduced the value from $2.50/lb for “dead” but intact 500GB drives to $0.15-0.30/lb for shredded drives.

The Critical Materials Institute (CMI), an Energy Innovation Hub within the Department of Energy, is exploring approaches to rapidly recover the rare earth permanent magnets from HDDs. A project focused on ultra-high throughput HDD recycling, being led by Oak Ridge National Laboratory (ORNL), is exploring automated disassembly, magnet assembly punching and mechanical separation, and value recovery after shredding has taken place. The CMI/ORNL team has recently established that non-functional used HDDs can be economically dismantled or processed by hybrid approaches including high-speed robotic disassembly, mechanical separation (e.g., punching, shearing, etc.) combined with shredding, and new technologies for separating shredded materials. Complete dismantling using ultra-fast (350mm/sec) robotic machine tools has the advantage that HDD components and subassemblies can be recovered undamaged, as seen in Figure 24. The
results of a new punching/shearing process to recover the magnets only is shown in Figure 25. With new technologies, additional value can be derived from shredded HDDs. Automated separation processes are being developed that can economically separate and recover more than 90% of the PCBs, magnets, aluminum, steel and other metals after shredding. These separated value streams significantly improve the overall economics of HDD recycling, as seen in Figure 26. As such, manufacturing new HDDs utilizing parts from dismantled HDDs become feasible, as does increased value recovery from the remaining parts and materials.

Figure 24. HDD disassembly with PCB, magnet assembly and readhead removed using high speed process, with the remaining assembly shredded.

Figure 25. Punched HDD on left using ORNL technology, with the exposed magnet assembly on right.
Figure 26. Shredded HDDs on the left; further processing of the shred produces the magnet “hairball” (upper right) followed by processing to recover a product that contains 80% REE magnet (lower right).

The disassembly approach being developed at ORNL is recovering steel, aluminum, PCBs and magnet assemblies with an estimated processing rate of more than 1 million HDDs/year per disassembly system. The individual value streams are recovered undamaged, enabling many possible reuse scenarios. For example, a fully functioning axial gap motor has been constructed using HDD magnet assemblies recovered from the high-speed disassembly process (Figure 27).

Figure 27. Prototype motor constructed from harvested HDD magnet assemblies, and fabricated largely by 3D printing.
Chapter 5: Barriers and Opportunities to Create a Safe, Environmentally Sustainable, Economically Feasible Value Recovery System

This chapter provides a perspective on both barriers and opportunities based on input received from the community of interested stakeholders and on an examination of some tools used to overcome similar barriers for other challenges. First, in section 5.1, we provide the results of a survey the project conducted of stakeholders regarding barriers. In section 5.2 we take a look at the challenge of improving the practices of an industry sector and systems that have been used to accomplish this.

5.1 Survey

Previous sections have outlined the current state of end-of-life pathways and presented a vision for increasing value recovery. But, while the necessity and motivation to create a more sustainable system is clear, it is important to examine the barriers that exist to implementing the higher value recovery choices outlined to a much greater extent. In particular, we want to explore how a cooperative approach by agents across the lifecycle could be exploited.

To this end we prepared a survey which examined the major decision points (direct reuse, dismantling, parts reuse and parts sorting) that a HDD faces and explored the reasoning as to why higher value options are not chosen in greater numbers. Participants in the survey were asked to identify the specific barriers to these activities, how these barriers might be overcome and who would need to work together to overcome them. The survey was distributed to a wide range of actors across the lifecycle of HDDs with the respondents breaking down as shown in Table 5 and the responses from the survey are synthesized below.

<table>
<thead>
<tr>
<th>Actor</th>
<th>Number of Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDD Manufacturer</td>
<td>1</td>
</tr>
<tr>
<td>HDD User</td>
<td>3</td>
</tr>
<tr>
<td>Used HDD Processor</td>
<td>9</td>
</tr>
<tr>
<td>Recycler</td>
<td>7</td>
</tr>
<tr>
<td>University/Research Institute/Other</td>
<td>11</td>
</tr>
</tbody>
</table>

The topic areas included in the survey are described below with a summary of responses.

5.1.1 Direct reuse

Barriers to increasing direct reuse come from a number of sources.

- As highlighted earlier in the paper the issue of users having strict policies of physically destroying the drives due to fears of data security was mentioned several times by survey participants. The economic viability is regularly mentioned as the resale value and market conditions can make the refurbishment non-viable for older drives.
• To overcome these barriers, direct reuse as an option can be increased by finding ways to give assurances on data wiping and educating users to trust data wiping through a large scale promotional campaign about its reliability and security.

• Greater insight and harmonization of reliability indicators such as SMART data, utilization data and age would support higher resale values.

• It is also necessary to build relationships with recovery outlets and create demand by finding opportunities to incorporate used hard drives into new products.

Achieving all of this will involve the cooperation of hard drive manufacturers, hard drive customers and aggregators, data wiping software providers, IT asset managers and refurbishers/remanufacturers, and equipment manufacturers.

5.1.2 Dismantle (full/partial)

Barriers to dismantling hard drives were exclusively cost-driven as currently it is a labor intensive and slow activity. These barriers can be overcome by reducing the time for dismantling to an absolute minimum.

• Ways to do this provided included reducing the number of fasteners used to attach the PCB and the cover of the drives and provisioning of information on dismantling different drive types.

• Automation could also play an important role in making disassembly more economically viable, with prototype solutions from research and academic institutions that could assist if supported to move beyond the laboratory.

Hard drive manufacturers were identified as being very important actors in this regard and should work with dismantlers/recyclers to achieve reduced-touch manual dismantling and with research and academic institutions for automation solutions.

5.1.3 Parts reuse

Barriers to achieving parts reuse are also largely identified as economic. For a part to be reused, it must typically be dismantled manually as a first process step and this faces the same challenges outlined above. It is very hard to determine the exact specifications of the parts within a hard drive before a decision is made to proceed with dismantling and thus the demand/value would be quite uncertain at the outset.

• This issue could be alleviated with greater standardization of parts across different HDD ranges and manufacturers as it would provide greater confidence that a demand would exist for the parts.

• Manufacturers should also provide guidelines on reusability from a quality and compatibility perspective.

Hard drive manufacturers were again identified as the key stakeholders in this area

5.1.4 Parts sort

The combination of high labor costs and processing time required was also identified as the predominant barrier to sorting parts into purer fractions for recycling, but lack of
awareness/knowledge by pre-processors and lack of end-processing technologies (e.g., for magnets) is also mentioned.

- Automation and technologies for separation are brought up as means to overcome this. A dialogue between manufacturers, pre-processors & end-processors is advised to help achieve this.

5.1.5 Conclusions from the survey

Through the work presented in this report we have identified what areas need to be tackled and who needs to participate in tackling them. The next important question is how it should be done and to explore if the Ostrom Framework approach to stakeholder collaboration and problem solving can provide a mechanism to do so.

Last, but not the least, we should not forget that a hard drive is a part of many electronic products. Thus, the recovery decision for HDDs must be in line with upper-level recovery planning for whole products and systems.

5.2 The Need for a Coordinated System of Best Practices along the Recovery Chain

The Phase One report for this iNEMI project, “iNEMI Report on the State of Metals Recycling,” noted that the value recovery chain for HDDs is now functioning less than optimally, as it is for many electronic products. Here “value” is measured in both dollars and resources, which are considered complementary factors from a sustainability perspective. The conclusion was that some existing practices employed by electronics stakeholders effectively reduce the overall value recovered from the products across the reverse chain of commerce. In particular, consider two examples:

- Data destruction demands by the last user, which are not always essential to meet justified data security needs, lead to wholesale HDD shredding, which precludes reuse and reduces material recovery options.

- Shredding of the HDDs by pre-processors, before any disassembly and while still embodied in the product, which is done for the purpose of bulk material recovery, precludes reuse and can reduce recovery of trace, but highly valuable, materials.

This report is intended to introduce options for better practices that would increase the value recovered from end-of-use HDDs. It is essential that the practices of various actors in the recovery system, and also of those who design/manufacture and those who use/discard the products, are aligned and complement each other. This can come about either through voluntary coordination and communication, or through properly structured incentives, or some combination of the two.

This report proposes the formation of a highly collaborative implementation project for value recovery based on the Ostrom Framework. The project would build on the results of the Phase 1 and Phase 2 projects by bringing together stakeholders in the HDD value recovery system to develop common goals for the collaboration and work on creating detailed value recovery pathways.
that meet the needs of the system in a sustainable way. This new project would provide a forum for understanding what the term “best practices” means for the stakeholders (or in the Ostrom parlance “Actors”), how trusted relationships can be built, and how information sharing can help identify new opportunities for EoU management of HDDs.

5.2.1 Opportunities to increase recovery through best practices

Some of the opportunities to increase value recovery from HDDs explored in this report are now in practice, and some are new, but none of them are widely implemented. Their wider implementation will require changing not only collection, data sanitization, and processing practices but also developing and implementing new technologies and collaborating closely to develop efficient value recovery pathways. As highlighted in this report, it is difficult for an individual actor to justify making such an investment if return on that investment relies on the independent choices of other actors. For example:

- Efficient HDD disassembly may necessitate changes in product design.
- Financially sustainable recovery of reusable assemblies and components may require product manufacturers and/or refurbished-product businesses to create markets that incorporate them into their products.
- Financially sustainable recovery of components that can be processed for recovery of scarce materials, such as critical materials, requires downstream refining technologies.
- Such actors in refining for materials recovery require upstream actors (users, businesses, IT asset managers, etc.) to produce large quantities of properly pre-processed feedstocks to ensure economic viability. In addition, there must be sufficient demand for the recovered materials.

It is not realistic to expect that a single new recovery opportunity or actor, acting alone, could create the financial value required for a sustainable business model for the full system. However, working together they may be able to. As seen in the Ostrom Framework in Figure 1 and Table 1, the critical variables for creating sustainable systems are having (1) leaders (A5) who believe that having a sustainable value recovery system is important and possible (A7, A8), who have the authority (GS6) and credibility/social capital (A6) to bring the team together; (2) team members who develop these beliefs and leadership opportunities in their domains (A7, A8) and are willing and able to act to work together in developing the system (GS6, A6); and (3) team members that are willing to gather and share enough information to critically analyze the true size of the (HDD) resource system (RS3), the current productivity of the system and how that might change if the system changed (RS5), and the resource unit mobility (RU1). This information could then be used to analyze the predictability of system dynamics (RS7) along different pathways to construct possible relationships, actions, and interactions.

Though this report primarily focuses on the actors in the HDD value recovery system and its technical and economic/business dimensions, it is not blind to policy elements. Government policies of several types currently make much of the recycling that occurs in the U.S., and
worldwide, feasible. These policies include public take-back requirements, recycled material purchasing preferences, environmental purchasing standards, and Environmental, Health and Safety (EH&S) standards for recycling operations. It is possible that there may be new policies, designed to achieve environmental and/or security objectives, which could provide the impetus to overcome some of the existing financial barriers to increased value recovery. One example of such a policy initiative, voluntary standards, is explored below.

5.2.2 Implementing new opportunities

The Elinor Ostrom approach to stakeholder problem solving, as described in Chapter 2, provides a mechanism to further refine and test the opportunities and propositions contained in this report, as well as to spread understanding and recruit participation.

There are three critical elements that such a process could develop:

1. Definition of the most effective practices by the different actors along the chain that meet their needs of livelihood from the commons
2. Methods of sharing the information needed on an ongoing basis to form partnerships and refine those practices to effectively “manage the commons”
3. Means of reinforcing actions by all actors to strengthen value recovery and self-management of the commons resources
5.2.3 An implementation tool – voluntary standards

The Phase 1 report explored some options for methods to incentivize the better integration of the system for maximum value recovery. The following points were made in that report:

- Voluntary standards and certifications such as EPEAT, eStewards, and R2, have today — and will continue to have — a major impact as producers and purchasers of electronics increasingly use integrated asset management and innovative corporate social responsibility practices over the entire lifecycles of products.

- There are possible incentives to encourage the development of the integrated, self-managing value recovery system. For example, voluntary standards could have parallel requirements for recovery-enabling design features, thus providing a market reward for recovery-system-compatible design. Similar to today’s criteria, they could reward inclusion of atypical post-consumer metals in products, thus increasing their market value in recycling.

Voluntary standards are market-based incentives that provide specific and, preferably, verified requirements for purchasers of products or services. Those purchasers may be product manufacturers purchasing components for inclusion in products, commercial or public consumers of products, or users who discard products after use.

Standards state specific, verifiable requirements that are developed through one of two methods:

1. A Voluntary Consensus Standard is developed by a Standard Development Organization (SDO) through a process that follows rules specified by either ANSI in the U.S. or an international equivalent. Those rules specify stakeholder openness, balance, consensus and standards procedures.

2. A private (proprietary) standard that is developed by an organization, which generally then certifies manufacturers for a fee to that standard.

Both types are available in the environmental space and can address the characteristics of products or services.

Standards are often a preferred alternative to legislative requirements since they are easier to develop and can address technical issues with greater flexibility. However, standards processes involving stakeholder consensus can be lengthy and contentious, and many stakeholders may feel that their objectives are compromised to achieve consensus. We have seen that democratic processes are often unsatisfying. But since standards can be updated periodically they can establish a continuous improvement cycle.

Standards offer an opportunity to implement some of the objectives and opportunities of this report. It would be possible for product standards to include requirements for further information from manufacturers or for recycling standards to define best practices for resource recovery. As such
they could help pre-processing facilities properly prepare materials for downstream recovery. Currently existing standards address some closely related issues:

- Voluntary Consensus Standards for the EPEAT system, including the IEEE 1680 standards and others under preparation within IEEE, ULE and NSF, address environmental issues in product design and material content, and manufacturer performance. None of the existing standards address HDDs specifically nor topics that would directly address the opportunities raised in this report. However, a joint NSF/IEEE standard for servers that is now under preparation currently does include criteria that provide optional credits* for:
  - Magnets in HDDs that contain recycled neodymium or dysprosium
  - Manufacturers to provide information to recyclers regarding the magnets in HDDs, to make their recyclability easier and more efficient

- Standards for recycling and reuse organizations, such as R2, eStewards, WEELABEX and EN 50625 in the EU, and those in several other countries. These are private standards that define health and safety requirements.

All such standards must include a method for verification. This can be done through audits, laboratory testing and other means. It is generally the responsibility of the organization that “certifies” products, manufacturers or organizations to the standard to provide such verification. Lacking a verification system, a standard may not be credible to purchasers or useful for its stated purpose.

* The standard includes both required criteria for bronze status and optional criteria to achieve silver or gold status.
Chapter 6: Recommendations

6.1 Actions

In this Phase 2 report and the previous Phase 1 report, we have started identifying how the Social-Ecological Framework developed by Elinor Ostrom can be developed for collaborative industry problem solving in the critical area of EoU electronics. This Framework can be used to address the challenges of managing common pool resources and, in the particular context of EoU HDDs, to significantly improve value recovery from HDDs while also creating a sustainable circular economy for their creation and use. In order to move forward using this Framework, the next major phase will be to spread understanding of the results and recommendations of this project and to convene critical stakeholders for HDDs to discuss their readiness and ability to develop such an implementation project.

**Action Area 1: Establish the basis for an Ostrom-based stakeholder project by increasing stakeholder understanding of the opportunities and challenges associated with increasing value recovery from HDDs.**

Specific actions will include:

- Circulate the report widely and solicit feedback
- Produce papers for publication and presentation at conferences and engage audiences in discussion of the key features of this approach
- Develop a workshop to describe the findings, methodology, future plans, and roles and to develop the relationships needed for the next phase
- Identify appropriate stakeholder organizations and key leaders within them, build relationships, and present these ideas to their broader leadership in the context of their roles in the HDD economy and in value recovery
- Develop a roster of interested and affected individuals and organizations, and convene groups to discuss possible relationships and business models
- Expand discussions within and between the Phase 2 project members on what the next steps could be, building on the criteria in the Ostrom Framework, and develop an action plan for building those relationships even before a next phase project begins.

**Action Area 2: If such an action plan is created and leaders identified, create a new project using the Ostrom Framework as a guide in developing a sustainable, self-managing circular economy for some class or set of electronic products.**

**Action Area 3: Develop similar actions plans and stakeholder groups for applying the Ostrom Framework managing EoU value recovery from other electronic component and product types.**
Though this report lays out a methodology for analysis of value recovery opportunities for HDDs alone, the methodology is equally applicable to other components and products. But information gathering and analyses are needed to identify which critical Framework variables/criteria are met in these other cases. This may be accomplished through additional fast-turn iNEMI projects similar to the one that generated this report.

6.2 Issues to be Addressed through an Ostrom Framework Project

The purpose of the Ostrom project will first be to define a set of best practices for all actors who play a role in the reverse supply chain, including product designers, final users, collectors, initial processors, repair and remanufacturing organizations, material recycling processors, and end-markets for reusable products, components, and materials. The guiding principle of these practices will be to maximize value recovery across the reverse supply chain in order to increase the economic and environmental sustainability of the system. The second purpose will be to define a set of implementation measures to promote these best practices.

The following discussion outlines some specific suggested areas of focus to achieve these objectives.

6.2.1 Options for end-of-use organizations to source HDDs for processing

The recycler or reuse operator has two options for creating value for their organization: direct purchase of material, or a share back program. These options should be implemented by creating custom contractual agreements with Sellers to recover their IT assets.

**Direct purchase of material.** IT assets are listed for sale in lot form. The Recycler is able to inspect and bid on the purchase of the material.

*Advantages:*
- Sellers clear the capital equipment from their financial ledgers quickly since the cash to cash cycle is reduced from shared proceeds model below.
- Recycler has an opportunity to inspect the equipment condition and content prior to sale.
- Sellers may receive the highest return on IT assets sold in this manner.

*Disadvantages:*
- The Recycler must accept the risk of accepting equipment that may require significant repair and testing prior to sale.
- The Recycler must have the ability to provide good estimates of the value of IT equipment and may retain a team that can perform site visits to determine condition of the material.
- The Recycler may have to bid against several other recyclers for the same material resulting in higher overall cost for each purchase.
- Seller may incur a substantial investment of time and effort to promote the sale of the IT assets.
**Share back program.** This option assigns a fixed share of the sale proceeds of the equipment back to the owner of the material. The material is shipped to the Recycler, evaluated, repaired, tested and sold for a profit. Several options for share of proceeds are possible: share by received weight, final sale price or some or all commodities sale prices.

*Advantages:*

- Sellers ensure they get a fair return on the assets sold by the Recycler.
- Recyclers will sell material that is able to be functionally repaired and tested by their organization.
- This option is a good solution for a Seller whose material may not contain a large variety of IT assets that most likely will not generate enough interest for outright sale.

*Disadvantages:*

- A level of trust must exist between the Seller and Recycler to ensure this is a fair exchange.
- Sellers may not always value the Recyclers’ efforts to repair, test and market the assets fairly.
- A significant delay in recovering shared proceeds will occur when the Recycler sells the assets.

6.2.2 Data gathering and analysis activities

- Analysis to increase the certainty in the estimation of stocks and flows of HDDs. This data will be critical to actors in the chain of commerce as they develop new capabilities.
- A systematic understanding should be gained of the target HDD users, information about geographic locations and management practices is needed to estimate availability, even down to the company level.
- Further explore scenarios for increasing value recovery for each of the actors in the HDD chain of commerce, including large data center operators, OEM-authorized service providers, recyclers, HDD users/owners, and HDD OEMs.
- Examine options to make product disassembly, for both reuse and high-grade material recovery, more cost-effective, including automated, non-destructive disassembly, manual disassembly employing the best-of-two-worlds methodology, and use of social enterprises.
- Thoroughly examine options for meeting data security needs while expanding recovery opportunities.
- Examine potential product design changes that could facilitate whole-product and component reuse and material recovery.
6.2.3 Potentials to enhance the roles of key actors to increase value recovery

- Large data center operators or Internet companies with massive data storage needs often design and manufacture/assemble their vertically integrated lines for optimal system performance and reliability, while making possible HDD remanufacturing and parts reuse and materials recovery. This can include sale of functioning but defective HDDs to a third party for white labelled remanufacturing and sale. An outstanding example of integrated storage management is Google’s integrated data center operation, for which Google was recognized by the Ellen MacArthur Foundation as a Global Partner in creating a circular economy for electronics. [49]

- OEM-authorized aftermarket service providers frequently have all the options, but could always process more HDDs, plus reuse parts in HDDs or for other uses.

- Recyclers and IT asset management companies could process more HDDs in their systems, and could provide more options that would convince customers to allow reuse as well as having cheaper pathways to a high level of value recovery.

- HDD users/original owners could provide clearer pathways for putting HDDs in value recovery stream at higher value point, with economics and risk identified.

- HDD OEMs could help customers/users identify the most appropriate value recovery pathways at point of sale rather than it being kept as undefined until its end of use.

- Research and academic institutions could continue to develop new technologies and associated business models for greater value recovery in close collaboration with HDD stakeholders. They should work closely with all the HDD stakeholders (actors) to determine how to make the technologies viable and effective. The Critical Materials Institute (CMI) and iNEMI continue to play important roles in this regard.

6.2.4. Implementation measures for best practices - standards

Policies, both governmental, such as take-back laws, and private, such as recycler standards, make feasible much of the recycling that occurs in the U.S. and worldwide. There may be new policies needed to achieve the sustainability and data security objectives of this report. One example of such a policy initiative, voluntary standards, is explored here.

As described in Chapter 5, standards are market-based incentives that provide specific and, preferably, verified requirements for use by purchasers. Two specific types of standards offer an opportunity to implement some of the objectives and opportunities of this report:

- Voluntary Consensus Standards for product design and information sharing, including the IEEE 1680 standards and others under preparation within NSF and ULE, address environmental issues in design for EoU management, material content including recycled materials, and information that the manufacturer should provide to EoU managers.
Standards for recycling and reuse organizations, including R2, eStewards, WEELABEX and EN 50625 in the EU, and those in several other countries. These are private standards that define health and safety requirements, and could potentially address resource recovery from EoU processes.

In conclusion, unlocking value recovery requires intentionally designing for that outcome — OEMs must design HDDs for a maximum value recovery. The intent is to extend the working life of HDDs by all possible means and open new markets and channels for used electronics. However, used HDD are only one type of consumer product and the approach developed by this project can be applied to all electronics. The proposed path requires fundamentally new approaches to consumer electronics design and lifecycle management but the implementation of the Ostrom framework can maximize the value of used equipment through the circular economy based lifecycle management.

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References


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Glossary

**Assemblies:** Multiple electronic components assembled in a device that is in itself used as a component.


**Charitable donation:** Transfer of computing equipment or its components that are not for their intended direct reuse for purposes of charity without any monetary rewards or benefits, or for barter.

**Cleaning:** Removal of dirt, dust, and stains; and making cosmetic repairs.

**Component:** Element with electrical or electronic functionality connected together with other components, usually by soldering to a printed circuit board, to create an electric or electronic circuit with a particular function (for example an amplifier, radio receiver, or oscillator).

**Computing Equipment:** Computing equipment includes: personal computers (PCs) and associated displays, printers and peripherals, personal desk top computers, including the central processing unit and all other parts contained in the computer; personal notebooks and laptop computers, including the docking station, central processing unit and all other parts contained in the computer; computer monitors, including the following types of computer monitors: (a) cathode ray tube (b) liquid crystal display (c) plasma; computer keyboard, mouse, and cables; computer printer: (a) including the following types of computer printer: (i) dot matrix; (ii) ink jet; (iii) laser; (iv) thermal; and (b) including any computer printers with scanning or facsimile capabilities, or both.

**Defective/Defect:** Defective Computing Equipment is equipment that is delivered from the supply chain and last manufacturer in a condition that is not as it was designed to be sold, or the equipment breaks or malfunctions due to a condition that is not as it was designed. Defective equipment does not include equipment that loses functional or cosmetic value as a result of normal wear and usage or as a result of consumer negligence.

**Direct reuse:** The using again, by a person other than its previous owner, of computing equipment and components that are not for the same purpose for which they were conceived without the necessity of repair, refurbishment, or hardware upgrading.

**Dismantling:** Taking apart computing equipment, components, or assemblies in order to separate materials and/or increase options for reuse, refurbishment, or recycling, and to maximize recovery value. Disposal: Any operations specified in Annex IV of the Basel Convention (Article 2, paragraph 4 of the Basel Convention, and Annex VI in this document).

**End-of-life computing equipment:** Computing equipment that is and no longer suitable for use and is intended for dismantling and recovery of spare parts or is destined for material recovery and recycling or final disposal. It includes off-specification or new computing equipment that has been sent for material recovery and recycling or final disposal.

**End-of-use:** Computing equipment that is no longer used as intended by the previous owner, but may be fully functional and used appropriately by others.
**Engineered landfills:** Engineered landfills are disposal sites that are selected and designed to minimize the chance of release of hazardous substances into the environment, for example through the use of plastic landfill liners and leachate collection systems.

**Environmentally sound management (ESM):** The taking of all practicable steps to ensure that wastes are managed in a manner that will protect human health and the environment against adverse effects which may result from such wastes.

**Essential Key Function:** The originally-intended function(s) of a unit of equipment or component that will satisfactorily enable the equipment or component to be reused.

**Evaluation:** The initial assessment of used computing equipment, to determine whether or not it is likely to be suitable for refurbishment/repair or material recovery/recycling.

**Final Disposal:** Relevant operations specified in Annex IVA of the Basel Convention (Annex VI A in this document).

**Fully Functional/Full Functionality:** Computing equipment or components are “fully functional” when they have been tested and demonstrated to be capable of performing the essential key functions they were designed to perform.

**Hydrometallurgical processing:** The uses of aqueous chemistry for the recovery of metals from ores, concentrates, or recyclable wastes or products. Typically, hydrometallurgy consists of three steps:

1) Leaching of an intermediate product with acid, caustic, or a complex forming solvent, often combined with oxidation to dissolve the desired element(s) at ambient or elevated pressures and temperatures

2) Purification of the solution by:
   a) Precipitation of insoluble compounds
   b) Cementation of unwanted metals (using another metal to precipitate the metal in solution)
   c) Solvent extraction

3) Precipitation of desired product, either as an insoluble compound or as a metal either by chemical or electrochemical methods

Recycling reagents and treatment and disposal of effluents and residues are further important steps that occur throughout the process. Hydrometallurgical operations in authorized industrial scale facilities are distinct from unauthorized and illegal environmentally harmful practices in the informal sector.

**Incineration:** A thermal treatment technology by which wastes, sludges or residues are burned or destroyed at temperatures ranging from 850°C to more than 1100°C.

**Labelling:** The marking of computing equipment, individually or in batches, to designate its status according to the PACE guidelines.

**Landfilling:** The deposit of waste underground onto land designated for that purpose.

Mechanical Separation: Using machinery to separate computing equipment into various materials or components.

PCB: Printed circuit board.

Potential for reuse (reusable): Computing equipment and its components that possess or likely to possess quality necessary to be directly reused or reused after they have been refurbished or repaired.

Pyro-metallurgical processing: Thermal processing of metals and ores, sludges and residues including roasting, smelting, and re-melting with the aim of recovering metals as marketable products. Pyro-metallurgical operations in authorized industrial scale facilities are distinct from unauthorized and illegal environmentally harmful practices in the informal sector.


Redeployment: Comprises any action of new deployment or use by the owner of previously used computing equipment or its components.

Refurbishable: Computing equipment that can be refurbished, returning it to a working condition performing the essential functions it was designed for.

Refurbishment: Modification of used computing equipment to increase its performance and functionality or to meet applicable technical standards or regulatory requirements, including through such activities as cleaning, data sanitization, and software upgrading.

Refurbished computing equipment: Computing equipment that has undergone refurbishment returning it to working condition functional for its originally conceived use with or without upgrades and meeting applicable technical performance standards and regulatory requirements and possible upgrades.

Remarketing: Any action, including marketing activities, necessary to sell previously used computing equipment or its components directly or indirectly to customers.

Repair: Fixing specified faults in computing equipment and/or replacing defective components of computing equipment to bring the computing equipment into a fully functional condition.

Reuse: The using again, by a person other than its previous owner, of used computing equipment or a functional component from used computing equipment that is not for the same purpose for which it was conceived, possibly after refurbishment, repairing, or hardware upgrading.

Segregation: Sorting out computing equipment from other (electronic) wastes for possible reuse or for treatment in downstream processes that may include recycling/reclamation/refurbishment/repair/reuse/disposal.
Separation: Removing certain components/constituents (e.g., batteries) or materials from computing equipment by manual or mechanical means.

Small and Medium Size Enterprises (SME): According to the European Commission small and medium–sized enterprises are those businesses which employ fewer than 250 persons and which have an annual turnover not exceeding 50 million euros, and/or an annual balance sheet total not exceeding 43 million euros.

States concerned: Means parties which are States of export, or import, or transit whether or not Parties.

Testing: Process by which used computing equipment is assessed against established protocol to determine whether or not it is suitable for reuse.

Transport of Dangerous Goods Recommendations: UN Recommendations on the transport of dangerous goods which deals with classification, placarding, labelling, record keeping, etc. to protect public safety during transportation.

Treatment: Any physical, chemical or mechanical activity in a facility that processes computing equipment including dismantling, removal of hazardous components, material recovery, recycling or preparation for disposal.

Upgrading: Modification of fully functional computing equipment by the addition of software or hardware in order to increase its performance and/or functionality.

Used Computing Equipment: Computing equipment that is or has been used, either by its first owner or otherwise. Used computing equipment may or may not be a waste, depending upon the definition and its characteristics, intended destination and fate.


Wastes: Substances or objects which are disposed of or are intended to be disposed of or are required to be disposed of by the provisions of national law (Article 2, paragraph 1 of the Basel Convention).

Working Condition: See Fully Functional.
Appendix A: Survey Questionnaire

iNEMI has identified a key role for its members to play in promoting sustainable electronics and increasing value recovery from used equipment. Of particular importance is the ability of iNEMI to engage stakeholders across the lifecycle of electronic products to examine new approaches to managing critical resources and increasing value recovery while protecting human health and safety and the environment. As such it wants to explore how community building and joined up thinking can foster innovative designs, business models, technologies and supply chains. In this instance we are specifically exploring the case of hard disk drives and how a community approach might lead to increased overall value recovery.

This proposed approach aims to see how the major actors in the lifecycle of a HDD could work together to produce better outcomes from a material efficiency perspective. We want your ideas on how to achieve this. How could co-operation between actors improve outcomes?

To help us to do this we have developed a simplified flow chart which shows the major decision points in the processing of a used hard drive. You will be asked the same questions at each decision point in this chart.

How could value recovery be improved at this point?

What are the barriers to achieving this improvement?

Who are the relevant stakeholders that would be involved in the achieving this improvement?

How could it be achieved if a joint solution was developed?
Q1 What type of organization do you represent? Where in the lifecycle of a HDD do you operate? Please check all that apply.

- HDD Manufacturer
- User of HDD
- Used HDD Processor
- Recycler
- University/Research Institute
- Other

2. Can you please provide your email address so that we can forward you the findings of this work?

3. If there are any relevant resources on this topic that you would like to bring to our attention please enter them below
Direct Reuse

This page of the survey deals with the direct reuse option as shown circled in red in the flow chart above. When considering this decision for a used HDD please answer the questions below......

4. Do you experience this decision point in your organization?

5. How can resource efficiency/value recovery be improved at this decision point?

6. Who are the relevant stakeholders involved in making this happen?

7. What are the potential barriers to achieving improved value recovery?

8. How could a co-operative approach help to overcome these barriers?
This page of the survey deals with the dismantling option as shown circled in red in the flow chart above. When considering this decision for a used HDD please answer the questions below......

9. Do you experience this decision point in your organization?

10. How can resource efficiency/value recovery be improved at this decision point?

11. Who are the relevant stakeholders involved in making this happen?

12. What are the potential barriers to achieving improved value recovery?

13. How could a co-operative approach help to overcome these barriers?
Parts Reuse

This page of the survey deals with the parts reuse option as shown circled in red in the flow chart above. When considering this decision for a used HDD please answer the questions below......

14. Do you experience this decision point in your organization?

15. Who are the relevant stakeholders involved in making this happen?

16. How can resource efficiency/value recovery be improved at this decision point?

17. What are the potential barriers to achieving improved value recovery?

18. How could a co-operative approach help to overcome these barriers?
Parts Sort

This page of the survey deals with the parts sorting option as shown circled in red in the flow chart above. When considering this decision for a used HDD please answer the questions below......

19. Do you experience this decision point in your organization?

20. Who are the relevant stakeholders involved in making this happen?

21. How can resource efficiency/value recovery be improved at this decision point?

22. What are the potential barriers to achieving improved value recovery?

23. How could a co-operative approach help to overcome these barriers?

24. Can you please provide the email address of others who you feel would have valuable input to this survey that we could contact?
Appendix B: System Dynamics Model for HDD Availability: Input Data, Statistical Analysis Method, and Upper/Lower Bound Analysis for NA Data Centers and Consumers

B.1. Input Data

U.S. HDD Sales

- Historical data from 2000-2015
- Unit Sales Projections from 2016-2020
  - Mobile Consumer HDD Annual Growth Rate: -6% to -10%
  - Desktop Consumer HDD Annual Growth Rate: -10% to 14%
  - BC Enterprise HDD Annual Growth Rate: 10 to 14%
  - MC Enterprise HDD Annual Growth Rate: -5% to -9%

Annual Replacement Rate (ARR)\(^i\)

- Mobile/Desktop Consumer:\(^ii\)
  - Average HDD Lifetime: 6 years
  - Year 0-1.5 ARR: 5.1%
  - Year 1.5-3 ARR: 1.4%
  - Year 3-4 ARR: 11.8%
  - Year 5 and beyond ARR: 12%
- MC and BC Enterprise HDDs:
  - Average HDD Lifetime: 6 years
  - Year 1 ARR: 0.7%
  - Year 2 ARR: 1.6%
  - Year 3 ARR: 3.8%
  - Year 4 ARR: 6.9%
  - Year 5 ARR: 6.5%
  - Year 6 and beyond ARR: 26.4%

\(^i\) Note: This annual replacement rate is not analogous to the annualized failure rate (AFR) that is commonly associated with any HDD model. This replacement rate is related to a user noticing an operational HDD failure and promptly replacing the HDD. This differs from the AFR in that an operational failure threshold may be lower than the threshold that the manufacturer uses to define the AFR. It has been observed that when considering the operations of a data center, HDDs are often replaced up to 3 times higher than the AFR would indicate (Schroeder and Gibson, 2007). [44]

\(^ii\) Backblaze is a cloud storage provider that provides reliability data for the HDD models that it uses. It is well-known that Backblaze uses and operates consumer HDDs continuously (i.e., 24 hours/day) instead of the storage-optimized BC HDDs. Therefore, these failure rates are likely conservative for the consumer drives.
Warranty Replacements

- Average Mobile/Desktop Consumer Warranty Lifetime: 1.5 years
  - Assume that all HDDs in this category that fail within warranty are sent back for warranty replacement
- Average MC and BC Enterprise Warranty Lifetime: 5 years
  - Assume that 80% - 95% of HDDs in this category that fail under warranty are sent back for warranty replacement
- 80% - 95% of HDDs sent for warranty replacement are repaired and returned to the user or sold as a refurbished HDD, with the remaining HDDs being beyond repair, reaching end-of-life (EoL), and eligible for value recovery
- Assume that 5% - 20% of BC and MC HDDs that fail under warranty, beyond warranty and after six years are shredded for data security (e.g., national laboratory data centers)

HDD Discard Rate (EoL Pathways)

Beyond the warranty period, the user has additional options for discarding their HDDs. Independent recyclers directly conduct value and/or scrap recovery from EoL devices while e-waste stockpilers obtain and sell EoL devices for scrap or value recovery. As previously mentioned, these two entities combined with warranty replacement failures represent the opportunity for obtaining HDDs for value recovery.

- **Mobile/Desktop Consumer HDD Pathways at EoL:**
  - Percent of EoL HDDs collected by independent recyclers: 12.5%
  - Percent of EoL HDDs collected by e-waste stockpilers (e.g., Advanced Recovery, Inc.): 37.5%
  - Percent of EoL HDDs not collected and/or landfilled: 50%
- **MC and BC Enterprise HDD Pathways at EoL:**
  - Percent of EoL HDDs collected by independent recyclers: 71%
  - Percent of EoL HDDs collected by e-waste stockpilers (e.g., Advanced Recovery, Inc.): 29%

B.2 Sensitivity Analysis

Using Powersim Studio’s Risk Assessment/Sensitivity Analysis tool, a normal distribution was assigned around the current ARR values with a 10% standard deviation. This 10% distribution was selected to reflect the confidence in the AFR and ARR data provided by the literature. For the second upper/lower bound analysis, a normal distribution was assigned again for the different EoL pathways, but a 50% normal distribution was selected to reflect the uncertainty regarding these pathways.

B.3 Upper/Lower Bounds Analysis for NA Data Center and Consumer HDDs
Upper and lower bounds of HDDs available for value recovery from North American consumer and enterprise HDDs (adjusting EoL pathways). Grey line indicates average.

Upper and lower bounds of HDDs available for value recovery from North American consumer and enterprise HDDs (adjusting ARR only). Grey line indicates average.