SEAGATE

Eyebrow

Incentivizing Circular Economy Reuse of Data Storage Drives

A Comparison of GHG Allocation Methodologies to Inform a New Industry Standard

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Executive Summary

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Overview

Circular thinking is crucial to move away from the “take-make-waste” model that defines the production and use of many products, including electronics. Current practices contribute to an ever-growing source of electronic waste and increased consumption of valuable virgin materials, as well as emissions from energy-intensive manufacturing processes for electronic components.

The emissions associated with circular models are of increasing concern as businesses begin to prioritize sustainability and track greenhouse gas (GHG) emissions. However, current GHG accounting frameworks do not adequately account for circularity, with the unintended consequence of disincentivizing participation in circular systems. Under current accounting rules, only customers purchasing previously used products see a reduced GHG impact, while customers returning products for reuse receive very little incentive from an emissions perspective.

This study evaluates several methods to allocate GHG emissions between both users of a reused hard drive. Methods are taken from well-established life cycle assessment (LCA) methodology and applied to a GHG inventory perspective. Each method allocates a certain portion of emissions from the drive’s complete life cycle across both uses to each of the users operating the drive. Such methods can reduce the emissions for both users as opposed to only the customer purchasing a used drive, and thus better incentivize both parties to participate in reuse programs. The outcomes of each method are discussed in detail using a case study of a 16 TB reused hard drive. Allocation methods and outcomes for each user are detailed in Table 1.

Table 1: Summary of allocation approaches included in this study

Allocation Method		Percent of Life Cycle Emissions	
		User 1	User 2
Cutoff Method	User 1 is allocated all impacts prior to recycling. User 2 is allocated impacts of recycling and all subsequent steps.	67%	33%
Economic Allocati on	Allocation is based on price difference between new and used devices.	41%	59%
Circular Footprint Formula (CFF)	Allocation is based on quality of recycled material, supply and demand of recycled material, and replacement of new material.	51%	49%

Conclusions

- The cutoff method provides minimal incentive for User 1 to return the drive for recertification. Economic method and the circular footprint formula (CFF) allocate emissions provide an incentive to both users by reducing emissions below those of purchasing a new drive.
- The CFF results in the most balanced allocation between users with nearly a 50/50 split. Given the market demand for both return and purchase of receritifed drives, CFF offers the best incentive to both users.

1. Introduction

Humans tend to resist change, and human-made systems reinforce that tendency through policies, processes, and infrastructure that favor the status quo over promising alternatives. As society and businesses feel their way toward long-term sustainability, their challenge is to shift from the linear “take-make-waste” model that’s defined global economics since the industrial revolution. At the finish line is circularity, a model that decouples growth from the consumption of finite resources through comprehensive strategies for repair, reuse, and recycling. It’s a practice as old as human civilization, and one whose time has come again.

In an era defined by digital technologies, electronic waste (e-waste) exemplifies the problem with linear economic thinking. In 2022, the latest year for which statistics are available, the world generated a record 62 billion kilograms of e-waste, of which only 22.3% was collected and recycled using environmentally sound practices. Despite an acceleration in formal recycling since 2010, global generation of e-waste is still outpacing growth in recycling by a factor of five[i]. Circular approaches include multiple routes to extend product lifetime, recover valuable materials, and reduce virgin material production. Circularity may include extending the useful life of the product through repair or replacement of parts; reuse of the product by multiple users; refurbishment or remanufacturing to extend use; recycling of valuable components or materials and subsequent use of recycled material in new products; and finally, responsible disposal of materials that cannot be recovered or reused. Without pronounced changes that divert retired electronics to productive secondary uses, the world is likely to see ever-increasing consumption of valuable virgin materials and greater quantities of e-waste sent for recycling, landfilling, incineration, and other unsustainable disposition.

Businesses have a key role to play in accelerating circularity, but that requires evolution in the greenhouse gas (GHG)[i] accounting frameworks companies use to gauge environmental risks and opportunities. However, the current most adopted rules for GHG inventories such as the GHG Protocol Corporate and Scope 3 standards fail to account for circularity, inhibiting broader adoption[ii]. Incorporating life cycle assessment (LCA) methodologies into GHG accounting could provide a more holistic view of the possibilities within a product's life cycle and incentivize reuse by equitably allocating GHG impacts between multiple users of a product or material.

Seagate wants to help stimulate those changes and advance circularity in the electronics market, starting with their own segment: digital data storage. Last year, Seagate published Working Toward the Future of Circularity[iii], highlighting key opportunities and challenges facing data storage circularity efforts and discussing the LCA methodology they use to measure and report their products' impacts. Seagate pursues a range of solutions to extend products' life cycles, including:

- Taking back, sanitizing, testing, and recertifying drives for secondary-market reuse
- Reconfiguring drives at customer sites to bypass malfunctioning components and restore dependability
- Reusing product components to build new drives
- Recycling product materials to create new raw material stock for the supply chain

In addition, Seagate is uniquely positioned to address the scale of the problem: a single data center may use thousands to hundreds of thousands of drives, and reuse programs designed for these systems have the potential to bring thousands of drives into the secondary market, further promoting circularity.

This paper and the case study on which its findings are based focus solely on the opportunities and challenges of drive recertification and reuse, assessing and comparing GHG allocation methodologies that can provide incentives for both first and second users. As part of the case study, Seagate facilitated discussions with numerous stakeholder groups, including hyperscale data center customers, GHG inventory professionals, and LCA experts to develop the perspectives shared herein.

1.1 Sidebar

Though many companies are dedicated to reducing their carbon impacts, protecting the security of IP [intellectual property] and personal information remains a primary concern when decommissioning data drives. According to Kellie Jensen, Sustainability Program Manager at Meta, "There is broad internal recognition that we don't want to destroy working equipment — but at the same time, data protection is our number-one priority." Worldwide, this concern has prolonged the common practice of physically destroying hard disk drives (HDDs) and solid-state drives (SSDs) to assure their data is irrecoverablei[v v].

To assuage customer data security concerns related to its buy-back and resale program, Seagate follows the unified standards and processes for media sanitization outlined in the NIST Guidelines for Media Sanitization[vi], ISO/IEC27040:2024[vii], and IEEE2883:2022[viii]. These standards define a "Purge" level of erasure, which applies physical or logical techniques that render data recovery from HDDs and SSDs infeasible, whether an actor is using basic methods or state-of-the-art lab techniques. Each of Seagate's devices support at least one form of Purge erasure:

- Sanitize Overwrite: Fills every physical sector of an HDD drive with a defined data pattern, after which the drive is erased
- Block Erase: Sets the blocks on an SSD drive to a vendor-specific value that removes all user data
- Cryptographic Erase: Changes the encryption key used to write the data, making all data on the drive irretrievable Seagate has several options for cryptographic erase, including removal of the Advanced Encryption Standard (AES) key and Instant Secure Erase (ISE) to reset the drive to factory settings and instantly change the encryption key.

After receiving a sanitized drive from a customer, Seagate performs an additional layer of purging to verify that all data has been removed, then provides the customer a signed Certified Erase certificate that can be verified authentic to the specific purged Seagate drive. To increase buy-in to our product reuse ambitions, Seagate also designed a process for retrieving decommissioned drives for testing, recertification, and resale.

1.2 The Economic and Environmental Case for Reuse

Adopting circularity principles in the data storage industry promises benefits to both businesses and the environment:

Lower impacts: Designing products for multiple economic life stages conserves natural resources, reduces the energy impacts associated with resource extraction, and lowers the environmental and health impacts associated with improper end-of-life disposal.

Lower costs: Through use-phase product energy efficiency and end-of-use resale, first users reap cost savings during and after the product use-life and avoid end-of-life disposal costs. Second users are able to acquire high-capacity, high-performance recertified drives at a significant cost savings.

Higher environmental performance: By extending product life through reuse, Seagate improves resource efficiency and helps customers who purchase reused products reduce their embodied carbon and Scope 3 emissions numbers and meet their sustainability goals.

Unlocking these benefits starts with conducting an LCA: analyzing a product's specifications, supply chain information, comprehensive raw material and component inventories, and use-phase energy consumption profile to gain a holistic view of its environmental impacts. Spanning all life-cycle stages from raw materials extraction to production, use, and end-of-life, these impacts can include GHG emissions, human toxicity, mineral resource depletion, and water consumption (the key impact areas considered in Seagate LCAs), as well as ozone depletion, freshwater and marine eutrophication, and other categories.

Using LCA data, multiple studies have shown the benefits of circularity efforts for electronic devices. Jin et al.ix found that reuse of hard disk drives (HDDs) provides superior reduction GHG emissions when compared to virgin materials production and end-of-life recycling. Ardente et al.x found that refurbished enterprise servers achieve lower overall environmental impact than comparable new servers, even when the new servers provide superior energy efficiency.

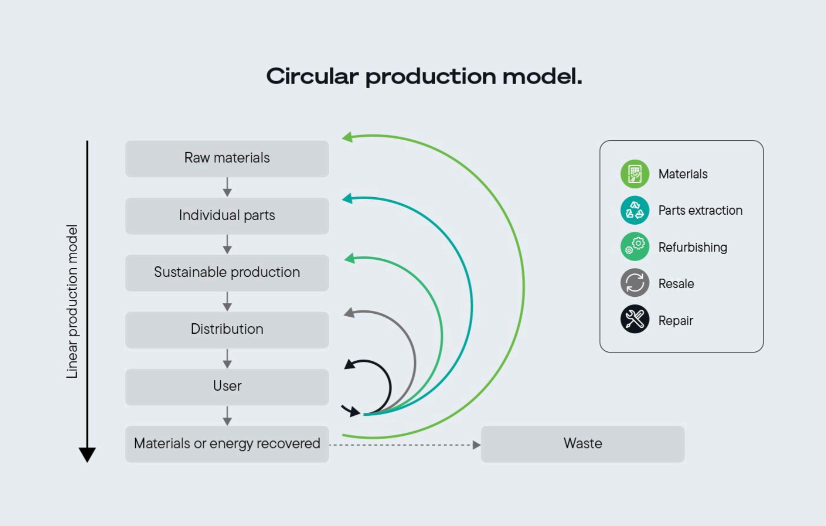

Figure 1: Circular approach to electronics management encouraged by Seagate.

Though reuse is empirically beneficial for the environment, calculating its cost value and GHG reporting benefits is complicated by the multifunctional nature of a reused product. That is, the product's early life-cycle stages (raw material extraction, processing, and manufacture, with their associated environmental impacts) provide a functional benefit to both first and second users, and their end-of-life impacts derive from recycling or disposal of materials that benefited both users during the product's functional life. Considering a data center with 150,000 or more drives, reuse programs have potential to return significant numbers of drives into the supply chain, improving circularity and directly offsetting production of new materials.

In the pages that follow, we will explore the challenge of equitably apportioning the environmental impacts of an extended life-cycle product between that product's first and second users, the various allocation methodologies that could accomplish this, and the benefits of seeking an industry-standard approach.

2. Background: Allocation Methodologies

When a product is used multiple times by different users across its life cycle, LCA uses allocation to partition total emissions or removals among those multiple users. For the purposes of this report, allocation is the process of apportioning the environmental impacts of a product's material production, recycling, and final disposal between the different users in its life cycle.

Lack of standardization in allocation methodologies for reuse as recycling has been well documented[xi], with the wide variety of available allocation methods contributing to inconsistency in the published literature and in LCA outcomes. ISO 14040:2006 LCA standards recommend allocating based on (a) a physical property, such as mass; (b) an economic value, such as cost of the recycled material relative to new; or (c) the number of uses of the recycled material[xii]. Other standards, such as the International Environmental Product Declaration (EPD) System's Product Category Rules (PCR)[xiii], may require the use of a specific allocation method. To date, no PCR is available to provide specific guidance on reused or refurbished/remanufactured electronics.

In addition to varied methodologies, there is a lack of harmonization among LCA studies and GHG accounting. The Greenhouse Gas Protocol's Product Life Cycle Accounting and Reporting Standard ("Product Standard") supports two allocation methods: closed-loop approximation and the cutoff method, with the cutoff method being more widely used in practice. Based on current accounting guidelines, customers will report emissions based on the cutoff method regardless of what an LCA might show. This leads to an imbalance between the first and second users of a device due to the nature of electronic devices, whose production typically creates significantly greater GHG impact than their late-stage reuse, recycling, and end-of-life. Using the cutoff method therefore results in a greater burden being placed on the first user than the second, giving the first user minimal incentive (from an emissions perspective) to return devices for secondary-market reuse

Along with this lack of standardization, most allocation practices fail to account for circular economic practices. The Greenhouse Gas Protocol's Product Standard, for example, handles reuse and refurbishing only as a form of recycling, and ISO standards for LCA do not address reuse and refurbishing directly. As such, there is no specific guidance for allocating impacts across the extended lives of reused or refurbished/remanufactured products.

As noted in Wynne and Kenny ii, the lack of consistent accounting methods and an established, universal carbon benefit in GHG reporting for reused/refurbished products weakens the momentum toward large-scale adoption of circular economy practices and can even disincentivize such a shift.

In this paper, we focus on three allocation methods that offer alternatives for apportioning impacts, illustrating their key benefits, trade-offs, and incentives for first and second users. Standardization under one of these methods could support broader adoption of product buy-back and reuse programs, and methods are supported among LCA professionals and industry stakeholders alike.

Cutoff Method: Using the cutoff method, the first user of a material or product is allocated impacts from all life cycle stages prior to the product being returned for recycling, while the second user is allocated all impacts from recycling to disposal. Users share no impacts, making cutoff a simple, straightforward method frequently used in LCAs and GHG inventories. Electronic products, however, produce significantly higher impacts in their early material production phases than in their end-of-life phase, putting a greater burden on the first user — and also disincentivizing them from returning devices for reuse since they receive minimal GHG benefit for doing so.

Economic Allocation: This method distributes the impacts of virgin materials extraction, processing, and manufacture between users based on the economic value of the recycled material relative to the virgin material — i.e., the difference in purchase price between the new device and the used/recertified device determines the percentage of environmental impacts assigned to the first and second user. The ease of obtaining price data is an advantage in this method's favor. A disadvantage, however, is that prices are commonly influenced by external factors that may have little or no relevance to a device's environmental impacts.

Circular Footprint Formula (CFF): Developed at part of the EU's Product Environmental Footprint methodology[xiv], CFF differs from the cutoff and economic allocation methods by considering materials, energy, and disposal through a circularity lens. The materials assessment addresses the need for a consistent method for allocating environmental burdens to suppliers and users of recycled materials based on market characteristics — i.e., manufacturers that enable materials recycling at end-of-life are assigned lower environmental burden during times of low availability and high demand for recyclable materials, but users of recycled material accrue less impact during periods of high availability and low demand. CFF accounts for impacts avoided when recycled materials replace virgin material production, the quality of recycled material entering and leaving the life cycle, and the supply-and-demand balance for individual recycled materials. While all these factors make for a stronger and more detailed methodology, applying it in LCAs requires a greater amount of data that may be difficult to obtain.

3. Case Study

3.1 Goal and Scope

The allocation methods discussed in this paper are presented using a cradle-to-grave LCA for Seagate's Exos X16 hard drive[xv]. The objective of the case study is to present the life cycle environmental impacts for the recertified hard drive over its lifetime, including first use, one recertification cycle, and a second use. The impacts are allocated between users of the hard drive following each method described in Section 2.

The study's functional unit is one terabyte-year (TB-year) of the Exos X16. The TB-year unit considers the capacity of the drive (in TB) and the length of use of the drive. The functional unit and the scope of the study are described in Table 2.

The life cycle of the recertified drive (see Figure 2) begins with production of raw materials and drive manufacturing, followed by testing. Once the drive has passed testing, it is distributed to the first user. User 1 is assumed to keep the drive for its full warrantied lifetime of five years. At the end of that five-year period, the drive is sanitized and sent back to Seagate for recertification.

Table 2: Description of LCA scope

Scope Definition	Product
Product Name	Exos X16 hard drive
Product Description	16 TB HDD (new drive) 15.2 TB HDD (recertified drive)
Type of LCA	ISO-aligned screening LCA
Function of the Product	To provide data storage
Functional Unit	1 TB-year
System Boundaries	Cradle-to-grave Includes recertification of drive after first use, one additional use cycle, and end-of-life disposal
Length of Use	5 years (new drive) 2 years (recertified drive)
Geographical Scope	Global
Impact Assessment Method	ReCiPe impact assessment method (v1.08)

During the recertification process, Seagate sanitizes data from the drive and performs a verification step to ensure data has been removed. Once sanitized, the drive is tested to ensure its performance meets standards for resale. During testing, portions of the drive may fail to meet standards and are removed, reducing the capacity of the drive in its second life. Details of the drive capacity are shown in Table 3.

Table 3: Drive capacity changes during recertification.

Incoming drive capacity	16 TB
Fraction of drives that lose capacity during recertification	16%
Average reduction of drive capacity after recertification	30%
Average drive capacity for drives with reduced capacity	(16 TB)*(70%)=11.2 TB
Average capacity per recertified drive	(16% * 11.2 TB) + (84% * 16 TB) = 15.2 TB

Once the drive completes the recertification process, a wholesale distributor collects it from Seagate for resale to customers in the secondary market. This second use is assumed to be shorter than the first use, comprising two years of operation. After this period, the drive goes to end-of-life recycling or disposal.

The case study considers allocation of new drive production (including manufacturing and testing), the recertification process, and end-of-life impacts. Because use-phase impacts will always be allocated to the customer using the drive (versus being shared among different users), this study excludes those impacts for all allocation methods.

Results are first shown without any allocation to compare the life cycle impacts of recertified drives relative to purchasing new drives. Then, the impacts of recertified drives are allocated between both users using cutoff, economic, and CFF approaches.

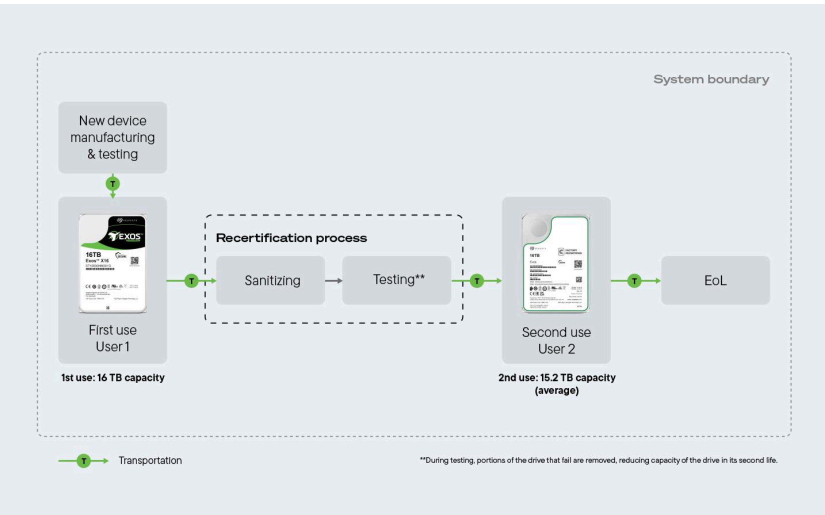

Figure 2: Process flow diagram for hard drive recertification

3.2 Life Cycle Inventory and Data Sources

For this case study, we used Seagate's recently completed LCA for the Exos X16 drive, which examines six life-cycle stages (production of raw materials, manufacturing, packaging, distribution, use phase, and end-of-life) and gauges impacts for a single-use lifetime across four key priorities: GHG emissions, human toxicity, mineral resource scarcity, and water consumption. From here, we expanded the LCA's scope to reflect the recertification process, using primary data from Seagate regarding energy inputs for drive sanitization and testing, capacity changes in recertified drives (see Table 3), packaging, and the expected lifetime of a recertified drive. We based data for the recertified drives' distribution and end-of-life phases on first-use data from the Exos X16 LCA.

Life-cycle stages and data sources are described in Table 4.

Table 4: Life-cycle inventory and data sources used in this study

Life Cycle Stage	Steps Included	Data Source
New drive production	Material production	Primary data for drive bill of materials (BOM) Material production and transportation modeled in ecoinvent v3.10[xvi]
	Manufacturing	Manufacturing modeled in ecoinvent v3.10
	Testing	Primary data for energy consumption and location Energy consumption modeled in ecoinvent v3.10
	Packaging	Primary data for packaging material and amount Material production and transportation modeled in ecoinvent v3.10
Distribution (first use)	Transportation of drive from Seagate to customer	Primary data for customer location and mode of transportation Modeled in ecoinvent v3.10
Return for recertification	Transportation of drive back to Seagate	Matches distribution in the first use for return to Seagate
Recertification process	Data sanitization	Primary data for energy consumption and location Energy consumption modeled in ecoinvent v3.10
	Testing	Primary data for energy consumption and location Energy consumption modeled in ecoinvent v3.10
	Packaging	Primary data for packaging material and amount Material production and transportation modeled in ecoinvent v3.10
Distribution (second use)	Transportation of drive from Seagate to customer	Secondary data used to model distribution to customers; distribution is handled by a third party and primary data is not available
End-of-life	Transportation of drive from Seagate to customer	

3.3 Allocation Method Calculations

This study presents results from the three allocation methods described in Section 2, allowing for comparison. The calculation approach used for each method is detailed below.

Cutoff Method: Since the cutoff method allocates all impacts of a given life-cycle stage to the user associated with that stage (versus splitting impacts of a life-cycle stage between users), this method does not require calculation.

Economic Allocation: Economic allocation splits the impact of new drive production between User 1 and User 2 of the drive. In this study, economic allocation is based on the price difference between new and recertified drives. The recertified drive is assumed to be sold at a 30% discount relative to a new drive. To calculate the allocation, we assume the full price of a new drive is price P. User 1 pays 100% of P, and User 2 pays 70% of P. The total cost paid for the drives is 1.7P. User 1 pays 1P/1.7P = 59% of total cost, and User 2 pays 0.7P/1.7P = 41% of total cost. These fractions are used to allocate emissions of new drive production; thus, User 1 bears 59% of the total impact of production and User 2 bears 41%.

CFF: CFF is a complex formula accounting for new drive production, certification impacts, avoided production of new drives, and end-of-life impacts, alongside supply and demand of recertified drives. The complete CFF includes terms for energy recovery from incineration of waste. We did not consider energy recovery in the study's calculations of end-of-life disposal, instead using a simplified version of the CFF (see Equation 1).

$$E = (1 - R_1)E_v + R_1\left(A * E_{recycled} + (1 - A)E_v * \frac{Q_{sin}}{Q_p}\right) + (1 - A)R_2\left(E_{recyclingEoL} - \frac{E_v^* Q_{Sout}}{Q_p}\right) + (1 - R_2)E_D$$

Equation 1: Simplified Circular Footprint Formula (CFF) used in the case study

Table 5: Summary of variables used in the Circular Footprint Formula (CFF)

Variable	Definition	Value for User 1	Value for User 2
R_1	Incoming recycled content (i.e., recertified drive)	0	1
R_2	Outgoing recycled content to be reused in next system	1 Drive is returned for recertification	0 Drive is assumed not to be recertified again
E_v	Impact of virgin material production (i.e., new drive production)	0.46 kg CO_2e per TB-year Production of new drive	N/A No virgin material in recertified drive
$E_{recycled}$	Incoming recycled content (i.e., recertified drive)	N/A	0.22 kg CO_2e per TB-year Impact of recertification process
$E_{recyclingEoL}$	Impact of the recycling process at end-of-life	0.22 kg CO_2e per TB-year Impact of recertification process	N/A Drive is assumed not to be recertified again
E_v*	Impact of avoided virgin material	0.44 kg CO_2e per TB-year Production of new drive replaced by recertified	N/A Drive is assumed not to be recertified again
A	Allocation factor of burdens and credits between supplier and user of recycled material+	0.5	0.5
E_D	Impact of disposal	N/A Drive is returned for recertification	0.01 kg CO_2e per TB-year Impact of end-of-life disposal. Drive is assumed not to be recertified again
$Q_{S,in}$	Quality of incoming recycled material (i.e., recertified drive)	N/A New drive does not contain recertified material	15.2 TB Quality of incoming drive reflected by capacity
$Q_{S, out}$	Quality of material recycled to the next use	$Q_P = Q_{S,out}$ Quality of drive is the same as new at end of first use	N/A Drive is assumed not to be recertified again
Q_P	Quality of primary (virgin) material	$Q_{S,out} = Q_P$	16 TB Quality of new drive is reflected by capacity

3.4 Impact Assessment Method

The study uses the ReCiPe (2016) assessment method[xvii] to gauge impacts in four categories: global warming potential (GWP), human toxicity, mineral resource scarcity, and water consumption. The categories are included to show a holistic view of environmental performance across multiple indicators; however, only GWP is relevant to the discussion of GHG accounting. As such, our results section focuses on GWP. Human toxicity, mineral resource scarcity, and water consumption are included in the Appendix.

4. Results and Discussion

4.1 No Allocation

The results of the recertification process are first compared to two single-use drives (see Figure 3), yielding the following observations:

- Total emissions for recertified drives are 25% lower per TB-year than for new drives. Including all logistics, recertification contributes 0.22 kg CO_2e per TB-year; whereas the impact of two new drives (the alternative to first use plus recertified second use) is 0.46 kg CO_2e per TB-year.
- Distribution and end-of-life have higher impact per TB-year for recertified drives because these drives have lower capacity and length of use.
  - Emissions are distributed over fewer TB-years compared to new drives.
  - Despite these increases, recertified drives still exhibit superior total environmental performance.
- Allocation methods are needed to address how the 0.69 kg CO_2 for recertified drives should be split between both users of the drive.

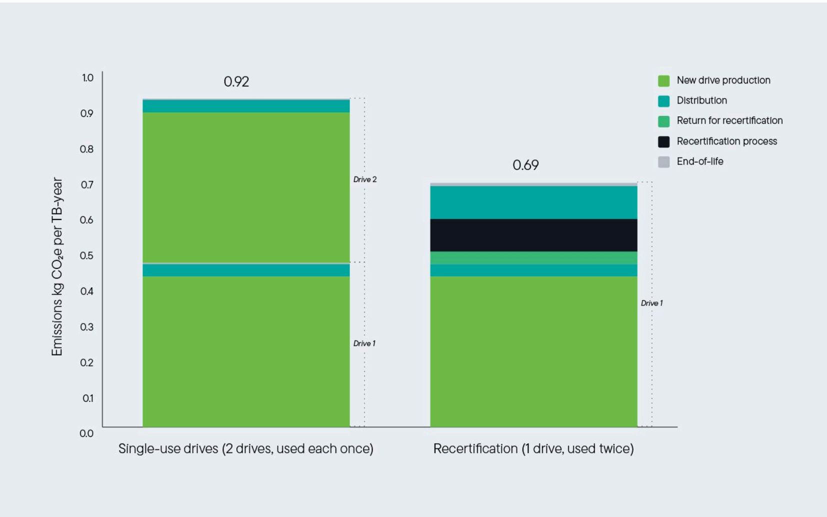

Figure 3: GHG emissions results for two single-use drives compared to recertification

4.2 Cutoff Method

Figure 3 shows results from using the cutoff method to allocate the impacts of recertified drives between the first and second users. This methodology yields the following points:

- Under the cutoff method, User 1 is allocated new drive production and distribution. All life-cycle stages after the first user are allocated to User 2, including transporting the drive from User 1 to Seagate for recertification.
- Under this approach, User 2 is allocated 50% fewer emissions than User 1. Lower emissions per TB-year may help incentivize customers to purchase recertified drives.
- User 1 is not allocated end-of-life emissions under the cutoff method, but this represents negligible benefit compared to the impact of new drive production. Thus, there is minimal incentive for User 1 to return the drive for recertification as opposed to linear disposal routes.

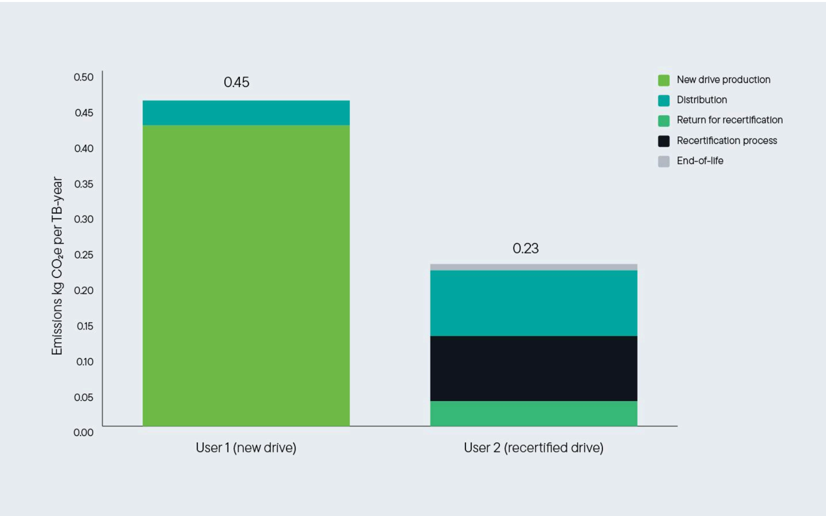

Figure 4: GHG emissions allocated using cutoff method

4.3 Economic Allocation

Figure 5 shows results from using the economic allocation method to allocate the impacts of recertified drives. This methodology yields the following points:

- Under the economic approach, User 1 is allocated 58% of new drive production and User 2 is allocated 41% (see Section 3.3).
- Relative to the cutoff method, User 1 sees total allocated emissions reduced by 39%, creating an incentive for User 1 to return drives for recertification.
- The emissions taken from User 1 must be allocated to User 2, significantly increasing the emissions for User 2 relative to the cutoff method (74% increase).
- While economic allocation may appear unfavorable to User 2, the total emissions allocated to User 2 are still lower than purchasing new drives (0.40 kg CO_2e per TB-year vs 0.46 kg CO_2e per TB-year, respectively). However, allocating a larger total share of emissions to the recertified product may reduce customers' willingness to purchase recertified versus new products.
- Economic allocation may be subject to variability based on the price of recertified drives. Price can be affected by many factors beyond the quality of the drives themselves.

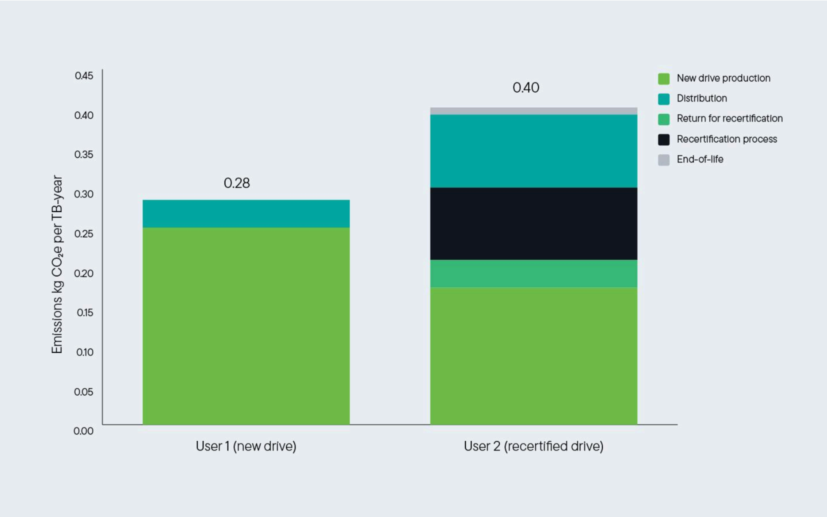

Figure 5: GHG emissions allocated with economic allocation

4.4 Circular Footprint Formula

Figure 6 shows the results of applying the CFF methodology for allocating the impacts of recertified drives. This methodology yields the following points:

- Similar to economic allocation, CFF results in lower allocated emissions to User 1 and higher allocated emissions to User 2 compared to the cutoff method.
  - User 1 emissions are reduced by 24% relative to the cutoff method.
  - User 2 emissions increase nearly 50% relative to the cutoff method, but are still lower than purchasing new drives (0.46 kg CO_2e per TB-year).
- CFF results in the most balanced approach between users, with nearly equal emissions allocated to both users. A balanced approach may help incentivize both users to participate, compared to economic allocation which may appear unfavorable to User 2. Alternately, the parity in emissions between first and second uses might disincentivize some potential customers for recertified drives, despite their cost benefit.

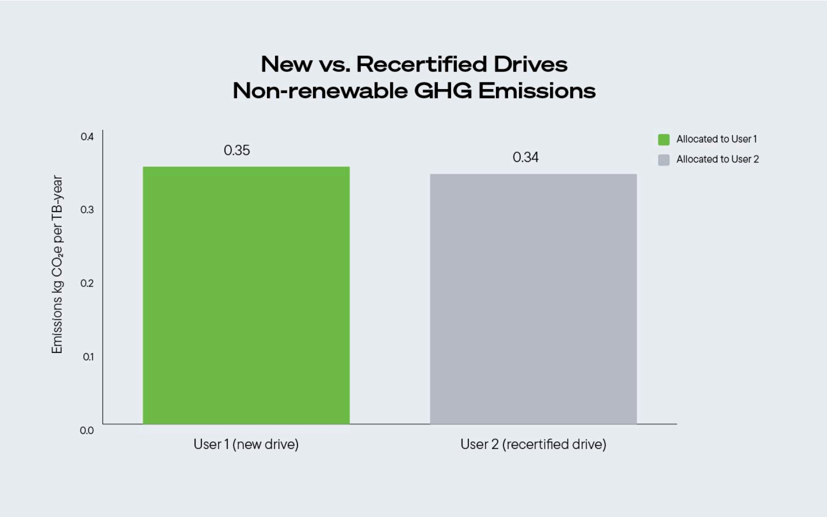

Figure 6: GHG emissions allocated with CFF.

5. Conclusions

Addressing the significant environmental impact of producing and disposing of data drives requires changes in mindsets, business practices, and accounting frameworks. The GHG impacts of a recertified drive may be more equitably allocated among multiple users with methods other than the cutoff method. Doing so would incentivize more companies to participate in circular reuse and refurbishment practices, a key driver in the circular economy and in meeting sustainable development goals, such as the Sustainable Development Goal 12 defined by the United Nations[xviii].

This paper presents a case study that compares the cutoff method to two alternatives: economic allocation and allocation according to the CFF. Based on that study, we reach the following conclusions:

- Both the economic and CFF allocation methods reduce emissions allocated to User 1 relative to the cutoff method, providing an incentive for first users to return decommissioned drives for recertification.
- Under both economic and CFF approaches, User 2 is allocated more emissions relative to the cutoff method. While this may appear to disincentivize User 2, the emissions associated with drive reuse are still lower than those from a comparable new drive. Therefore, recertification is still beneficial from an emissions perspective.
  - Economic allocation could result in higher emissions allocated to User 2 if the price for a recertified drive approaches that of a comparable new drive.
- Under the assumptions used in this study, the total emissions allocated to User 2 with economic method are greater than those allocated to User 1. The results of economic allocation may also vary based on market factors, including the price difference between recertified drives and new drives.
- CFF results in the most balanced allocation between users, producing a nearly 50/50 split. Given market demand for both return and purchase of recertified drives, CFF offers the best incentive to both users.
  - Seagate supports the CFF as a viable option to allocate emissions for circular systems.
- Cutoff method is best to incentivize the purchase of recertified drives, while economic is best to incentivize return of drives for recertification.

As the case study demonstrates, the choice of allocation method is consequential because it not only influences numerical results, but the results also have the potential to influence a company's behavior. When recommending an allocation approach, standard-setting bodies should consider multiple factors including the behavior they wish to incentivize, the relative ease of implementation, and the need for consistency across the industry.

Appendix

A1. Supporting Results

Results for human toxicity, mineral resources scarcity, and water consumption are shown in Table 6. While these categories are not included in GHG inventories, they may be subject to allocation methods in LCA studies. The LCA methods described in Section 2 are applied to each of the categories. The following points can be made from Table 6:

- Trends align with those for GHG emissions discussed in Section 4.
- Cutoff method results in the most favorable allocation to User 2. Economic allocation results in the most favorable allocation to User 1.
- CFF is the most balanced approach.
- Impact in these categories is primarily driven by new drive production. Mineral resource scarcity in particular has over 99% of impact from new drive production. Water consumption is also contributed by the recertification process through indirect water consumption from electricity generation. Human toxicity has impact from emissions during all life cycle stages, though new drive production contributes the majority (90%).

Table 6: Allocation results for human toxicity, mineral resource scarcity, and water consumption categories.

Impact Category	Allocation Method	Allocated to User 1	Allocated to User 2
Human Toxicity (kg 1,4-DCB-eq./TB-year)	No allocation	0.39	0.39
	Cutoff Method	0.35	0.04
	Economic Allocation	0.24	0.15
	CFF	0.20	0.19
Mineral Resource Scarcity (kg Cu-eq./TB-year)	No allocation	8.1E-03	8.1E-03
	Cutoff Method	8.08E-03	2.57E-05
	Economic Allocation	5.42E-03	2.69E-03
	CFF	4.26E-03	3.85E-03
Water Consumption (m^3/TB-year)	No allocation	8.7E-03	8.7E-03
	Cutoff Method	8.23E-03	4.64E-04
	Economic Allocation	5.52E-03	3.18E-03
	CFF	4.55E-03	4.15E-03

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Abbreviations and Acronyms

AES	Advanced Encryption Standard
BOM	Bill of Materials
CFF	Circular Footprint Formula
CO2	Carbon dioxide
EPD	Environmental Product Declaration
GHG	Greenhouse Gas
GWP	Global Warming Potential (in kg of CO2 eq)
HDD	Hard Disk Drive

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Incentivizing Circular Economy Reuse of Data Storage Drives

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