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RESEARCH ARTICLE

Data Explosion, Circular Solution: How Refurbished Drives Can Bridge the Storage Supply Gap

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ABSTRACT

The rapid proliferation of digital data and the corresponding expansion of the global storage market present a significant opportunity for the adoption of circular economy practices. With a vast amount of data being generated, demand for data storage far exceeds current manufacturing capacities, and circular markets offering second-use storage devices have the potential to fill this critical gap. However, the widespread adoption of reuse models for storage media, such as hard disk drives (HDDs) and solid-state drives (SSDs), faces significant challenges, including technical issues like the lack of quality standardization and the implementation of modern media sanitization specifications. This study quantifies the economic potential of storage media reuse through a detailed market analysis from 2020 to 2028, demonstrating the viability of reuse and identifying key metrics that influence device suitability and bolster confidence in the secondary market.

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1. Introduction

Global storage requirements are growing exponentially. By the end of 2022, the active installed base of storage had increased more than 53 times compared to 2010, and by 2035, it is projected to be over 475 times the 2010 active base (Monroe & Johns, 2024). With manufacturing unable to keep pace with this explosive demand, the circular economy offers a compelling solution to bridge the storage supply gap. This paper examines the economic opportunities presented by the reuse of storage media, aiming to maximize value for all stakeholders from cradle to gate and, eventually, to end-of-life.

Reusing storage media is a powerful strategy for reducing environmental impact and advancing the circular economy. However, several barriers currently hinder the widespread adoption of HDD and SSD reuse. Data security concerns and the lack of standardized measures for assessing device health and remaining lifespan create uncertainty in the secondary market. This study addresses these challenges through a comprehensive market analysis, quantifying the economic potential of reuse.

2. The Economic Imperative for the Circular Economy

The global storage market is extensively quantified through three primary metrics: bytes shipped, revenue generated, and the number of units sold. Each of these metrics provides a unique lens through which the market can be analyzed and understood. 'Bytes shipped' offers an insight into the sheer volume of digital storage capacity being installed across the globe, reflecting technological advancements (area density of storage media) and the increasing demand for data storage in various sectors such as technology, entertainment, and business. On the other hand, revenue figures provide an economic perspective, highlighting the profitability and market value of storage solutions. The number of units sold, for instance, can show the stark difference between low-cost consumer devices and high-capacity and more expensive data center SSDs. These have profound implications for the circular economy.

3. Bytes Shipped

The circular economy in the ICT industry emphasizes reuse, refurbishment, remanufacturing, repair, sharing, and recycling. The demand for data, 831 exabytes of HDD

in 2023 (growing at 18.7% to 2.7% zettabytes in 2027) (Burns, 2024) CAGR and 365 exabytes of SSD in 2023 (growing at a 30% CAGR to 1.19 zettabytes in 2027) (Janukowicz, 2023) show that applications are driving data growth, presenting an opportunity for different classes of storage devices, including used and refurbished, that have different quality, reliability, and cost characteristics. Data generated consistently outpaces the global data stored, suggesting that if storage media were less expensive, organizations would indeed store more data to generate future business value. Because of the different reliability characteristics and price of used storage, this will not disrupt the primary businesses that sell new storage devices, which often have superior performance, features, and incremental improvements in energy efficiency.

The carbon impact of HDDs stays relatively the same even with areal density growing, meaning the CO2e per TB will decrease as the areal density of the HDD media increases. For SSDs, the embodied carbon from manufacturing scales with the amount of NAND flash (Tannu & Nair, 2023), meaning higher capacity devices have an exponentially more significant impact than small devices (e.g., comparing a 512 GB SSD vs. an enterprise 61 TB SSD). The amount of data generated is much higher than the amount of data stored, suggesting that if a lower-cost alternative for storage emerges, then the byte Total Addressable Market (TAM) will increase to meet the needs of increased economic value for storing data longer.

4. Revenue Generated

The revenue TAM exploded back to $37 B for SSD in 2024 (after a massive downturn), which presents a significant economic opportunity. Circular drives can reduce the cost of storage by up to 50%–80% per device (Kenny *et al*., 2022) even after the 5-year warranty period. This can be an attractive enabler for the circular economy because of the value recovery. The resale won't impact the primary market (oversupply) due to the drives being deployed in new and emerging use cases with different workload characteristics and Opex and Capex (TCO) requirements.

Regarding the current reuse rate, interviews carried out with IT Asset Disposition specialists and Hyperscale Cloud providers by the Open Compute Project (OCP) see reuse rates of storage media of around 10% (Hands *et al*., 2022). This is comparable with the 11.5% circularity rate reported by the European Environmental Agency in 2022 (European Environment Agency, 2022). While country-to-country variance in 2022 ranges from 1% in Finland to 27% in the Netherlands, the majority cluster around 8%–12%.

Historically, IT refresh cycles have driven upgrades in storage due to technology benefits and TCO, on an average of 3–5 years. Hyperscalers cite an average deployment for HDDs of around 4 years. Hyperscale TCO (Opex and density requirements) are very different from traditional data centers and emerging markets. So, just because technology is dispositioned in one segment doesn't necessarily mean it will be in another.

5. HDD Market Outlook

In 2020, there were an estimated 260.6 million HDD shipments with an average sale price of $83 per unit over the period, giving a total market value of $21.62 billion for HDDs in 2020 (Coughlin, 2021). While units shipped were down from 316.3 million in 2019, the total amount of storage provided increased 13% to over 1018 exabytes. This means despite lower total drive production, and lower prices, each drive provided much higher amounts of storage per unit (Silva, 2021). The average capacity for HDDs continues to grow from 5 TB in 2020 to 7 TB in 2023 to a projected 10.5 TB by 2027 (Burns, 2023) giving us a cost per TB of around $12–$16 in 2020.

The IDC report (Janukowicz, 2024) emphasizes that enterprise demand, particularly from cloud service providers and OEMs, remains the primary driver for HDD growth. However, reduced capital expenditure by HDD suppliers and the increasing adoption of SSDs for generative AI workloads may limit long-term HDD growth. HDDs are expected to benefit from the growing value of data, the increasing demand for text-to-image and text-to-video workloads, and their value proposition for large data lakes required for generative AI model training. The continued demand for video surveillance HDDs further supports the market's stability over the long term.

The price disparity between enterprise SSDs and HDDs (Fig. 1) is expected to remain substantial through at least 2027, with SSDs costing six times more per terabyte than HDDs. Although SSD prices dropped in 2023 due to weak demand and oversupply, they rebounded in 2024 and are expected to continue rising through 2025. This price difference ensures that HDDs will remain the most cost-effective option for enterprise storage in the near future, even as SSD companies market their products as replacements for HDDs in certain segments.

The production stabilization in the HDD market, as outlined by the IDC report, suggests continued demand for the technology, particularly in enterprise markets. This demand underpins the viability of reuse, which is expected to persist for at least the next decade. The secondary market for HDDs, driven by lower cost per TB and increasing storage requirements, is poised for growth, particularly as client, personal, and consumer electronics shift towards SSDs by 2028.

The next section will analyze the SSD market for 2020 and projections for 2028 as we see an increase in SSD production and a closing gap in HDD cost per TB.

6. SSD Market Outlook

The market for SSDs has been increasing year on year since 2012 due to the appetite for faster and more performant storage devices and decreasing cost per GB and TB. The number of SSDs sold by major manufacturers rose to 368.7 million in 2020 (20%+ increase against 2019), but despite the amount sold outstripping HDD for the first time, the total storage provided was five times lower at 207.39 exabytes (Tyson, 2021). With 368.7 million shipments of SSDs in 2020 and an average sale price of just

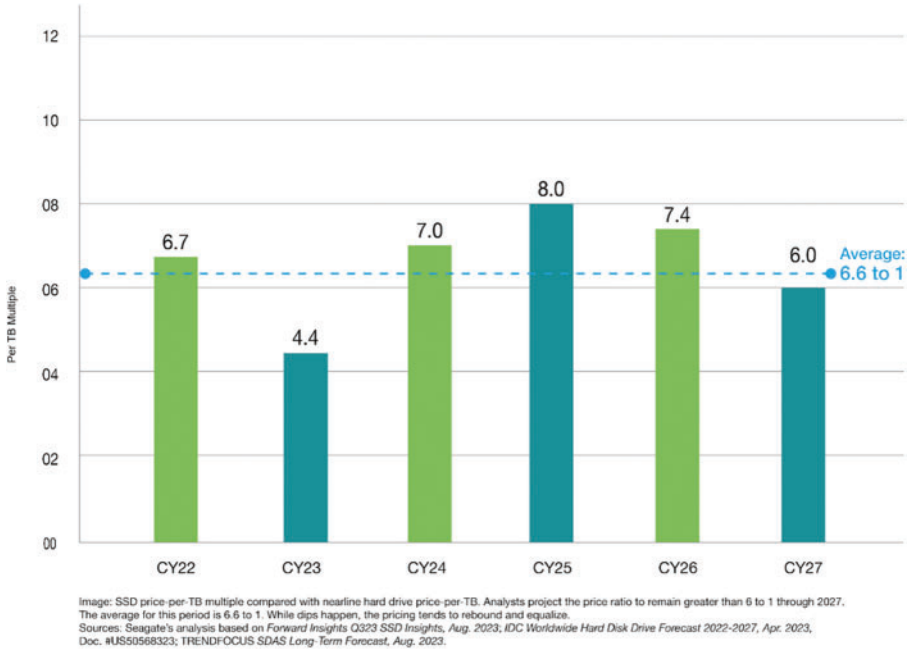

Fig. 1. SSD price per TB multiple compared with HDD.

under $100 per unit (Mellor, 2020), this gave a total market value of $33.1 billion for SSDs in 2020. Combined with HDDs, this values the storage hardware market at over $54 billion in 2020.

The 2023 downturn in the solid-state drive (SSD) market, characterized by weak demand, excess inventory, and aggressive pricing, is reversing in 2024. IDC predicts a resurgence in demand driven by enterprise data centers, artificial intelligence (AI) infrastructure, and consumer devices. The rebound is projected to lead to a 5.6% compound annual growth rate (CAGR) in unit shipments and a 21.9% CAGR in revenue from 2023 to 2028 (Janukowicz, 2024).

SSD prices increased in 2024 as the industry recovered and NAND flash prices reset to achieve targeted profitability levels (Fig. 2). While short-term uncertainty persists as of mid-2024, favourable long-term secular trends indicate a return to growth. Technology suppliers are advised to focus on long-term strategies, maintain balanced supply, and to prioritize innovation to capitalize on the expanding market opportunities.

Specifically, investment in technological leadership, such as leveraging the latest generation of NAND flash and developing solutions tailored to specific workloads (e.g., AI-driven applications) or market segments, is crucial for establishing a competitive edge in this evolving landscape.

Although the SSD market is driven by consumer electronics, tablets, high-end PCs, and client-side enterprise markets, the server and enterprise markets have continued to move significantly towards SSDs as NAND flash becomes the primary device of choice for the highest performance requirements. This means that for the circular economy, there is a much larger economic imperative for reuse as the potential ASP recovery and value of devices continue to be significant even 3–5 years after initial deployment. Recertified and used drives have the strongest economic value during SSD market undersupply scenarios.

7. Circular Economy and the Secondary Market

The primary benefits of second use are recovering otherwise lost economic value, detailed previously, and reducing environmental impact. The environmental impacts will be covered in a later paper as they concern both embodied carbon and energy but also critical raw materials and minerals.

Based on studies carried out by circular economy businesses specializing in enterprise hardware, the average cost of new equipment is 50%–80% more expensive than the refurbished alternative within 3–5 years (Kenny *et al.*, 2022), analyzing the SSD and HDD market from four years ago, this creates a potential economic opportunity of reuse, if full demand and supply existed, of between $11–$23 billion in secondary value versus destruction.

This would be predicated on all drives being suitable for reuse and the constant market value despite a large increase in available refurbished hardware. Since neither of these situations is likely, the potential economic value must first be calculated based on the number of drives suitable for reuse, then the amounts allowed to be reused, depending on customer and business policy and procedures. Once we have the baseline of what potential percentage of drives can be reused, demand and supply side factors will determine pricing.

8. Factors Impacting Higher Rates of Drive Circularity

To provide second use for HDDs and SSDs, and gain the benefits thereof, all drives must first be securely sanitized and erased of all data. They must also have specific health and lifetime characteristics to be deemed of high enough quality for reuse. As discussed earlier, the current reuse rate is in the region of 10% of total volume, but this is not the number of drives that are suitable for reuse.

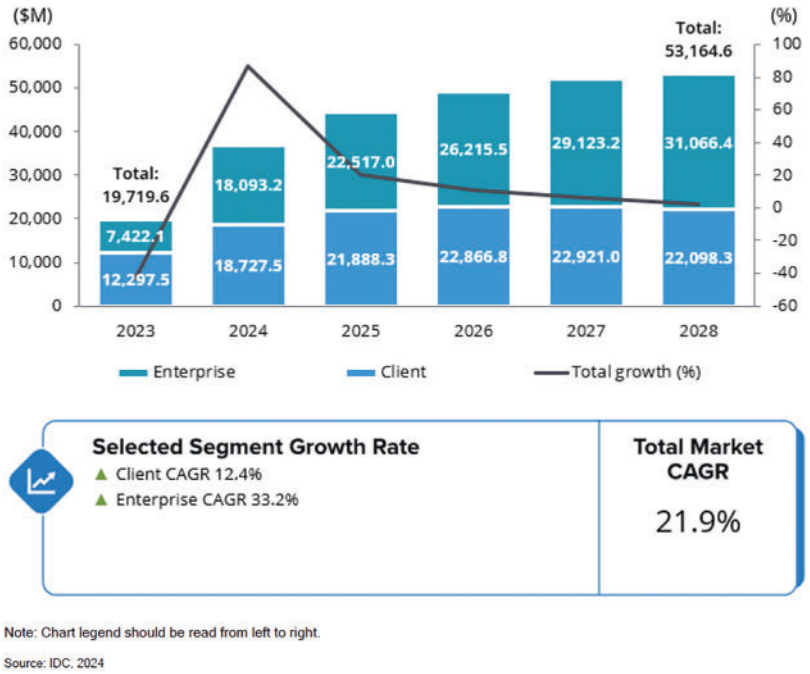

Fig. 2. SSD market outlook 2023–2028.

8.1. *Sanitization*

Effective media sanitization and storage security is one of the key barriers to the storage circular economy, so only drives where erasure and sanitization have been possible are eligible for reuse. A previous study of over 117,000 drives found that 87% of all drives in the result set could be verified as erased to the current best practice erasure standards and had health characterizes that would allow second use (Kenny *et al*., 2024).

8.2. *Quality*

Quality is also a key issue. Reused drives that have undergone verified and audited sanitation techniques can guarantee erasure and security, but they can be widely varied in available life left and potential time to failure. In the above study, while 87% of drives were able to be erased, the health and quality metrics had high variance. There are currently no agreed benchmarks on the metrics for the storage industry that define quality from a health and secondary life perspective. This is a large issue for the circular economy as without agreed quality benchmarks and standardization, the variety of refurbished drives decreases customer confidence.

Central to overcoming these challenges is the implementation of modern media sanitization techniques, as detailed in the IEEE 2883-2022 (Thompson, 2022) specification, which ensures data security while enabling the safe and effective reuse of storage devices. By establishing industry-wide standards for assessing device health and reusability and by enhancing stakeholder education on the reliability and effectiveness of these sanitization methods, the storage industry can significantly increase circularity rates. This approach not only mitigates environmental impacts but also unlocks significant economic value, all without negatively impacting the market for new storage devices

9. Conclusion

The circular economy presents a significant opportunity for improving the sustainability of storage media, with all currently popular formats expected to be utilized for at least the next decade. The difference between enterprise storage users and client users means that both HDD and SSD can serve their respective markets over time.

The disparity between the percentage of potentially reusable drives (87%) and those being reused (10%) is evident from the data. This gap is primarily due to concerns about the reliability of second-use storage and the security of software-defined erasure. Consequently, large businesses often default to shredding and destroying end-of-first-use storage media.

The next critical step for enhancing circularity in the industry is the establishment of agreed standards for health and reusability metrics that are accepted by suppliers, manufacturers, and enterprises. This will address concerns about the quality, reliability, and effectiveness of second-life storage devices. Additionally, educating the industry on the efficacy of modern erasure techniques will help build confidence in software-based data destruction. Achieving these outcomes will drive greater adoption of circular storage solutions.

Conflict of Interest

The authors declare they do not have any conflict of interest.

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