Understanding the Carbon Footprint of Storage Media: A Critical Review of Embodied Emissions in Hard Disk Drives

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Open Science Index, Environmental and Ecological Engineering Vol:19, No:11, 2025 publications.waset.org/10014313.pdf

***Abstract*—**The rapid adoption of data-intensive technologies has led to exponential growth in storage demands, significantly impacting global energy use and greenhouse gas (GHG) emissions. This paper presents a critical analysis of the environmental footprint of data storage devices, specifically the embodied impact of hard disk drives (HDDs) and solid-state drives (SSDs). Drawing on existing Life Cycle Assessment (LCA) and Product Carbon Footprint (PCF) results, we identify substantial gaps and discrepancies in current industry assessments, including inconsistent scope, data variability, and lack of standardisation. Furthermore, we propose a comprehensive environmental impact framework and apply it to three HDDs, yielding an average embodied emission estimate of 13.3 kg CO_2 per drive. The study underscores the urgent need for a harmonised, transparent LCA framework tailored to storage technologies, enabling more accurate environmental impact assessments and supporting sustainable ICT development.

***Keywords*—**Environmental impact, embodied carbon, hard disk drives, HDDs, life cycle assessment, LCA, solid state drives, SSDs, storage devices.

I. Introduction

THE global adoption of large language models (LLMs) and artificial intelligence (AI) technologies is causing exponential surges in energy consumption and carbon emissions. Peer-reviewed studies estimate that the current share of Information and Communication Technology (ICT) in global GHG emissions to be 1.8-2.8% [1]. However, Freitag et al. [1] found that these published estimates underestimate ICT's carbon footprint by as much as 25% because they fail to account for the full life cycle and supply chains of ICT. They project that ICT's share of emissions could be as high as 2.1-3.9%.

The International Energy Agency (IEA) reported that electricity consumption from data centres alone was estimated to be about 1.5% of global electricity consumption in 2024 [2]. It has grown at 12% per year over the last five years, underscoring the rapid growth of the sector and its increased energy consumption.

This exponential growth of digital data generation in recent years has placed unprecedented demand on data storage infrastructure. Global storage requirements are growing exponentially. Monroe & Johns [3] estimate that by 2035, the total installed base of enterprise data (which excludes consumer-grade storage) will exceed 40 zettabytes, over 475 times the 2010 active base. Where SSDs accounted for 15.3%, HDDs accounted for 69.5%, and tape accounted for 15.2% of the total enterprise data in 2022.

According to the 2024 United States Data Center Energy Usage Report [4], by 2028, flash storage will account for 40% of the total storage capacity, as illustrated in Fig. 1.

This market outlook aligns with the 2024 IDC reports [5], [6], which highlight that enterprise demand—especially from cloud service providers and OEMs—is the main driver of HDD growth. In contrast, the SSD market is largely fuelled by consumer electronics, like tablets and PCs. The SSD enterprise market is expected to grow in the future with the advancements in NAND flash for AI-driven workload.

From the energy-intensive processes involved in the manufacturing of storage components to the substantial electricity consumption required for their operation and cooling, storage devices contribute significantly to the overall environmental impact of the ICT sector. Furthermore, issues related to electronic waste (e-waste), raw material extraction, and limited recyclability exacerbate the sustainability challenges posed by storage systems [7]. Moreover, storage supply gap and storage reuse face significant challenges as highlighted by Kenny et al. [8], [9], where only 10% of drives are reused when the potentially reusable drives amount to 87%.

This paper aims to provide a comprehensive analysis of the environmental implications of storage devices across their embodied life cycle stage. Section II reviews the current state of methodologies, tools, and LCA approaches applied to storage devices, highlighting existing market gaps and inconsistencies among assessments. Section III examines embodied GHG impact per GB based on public PCFs. In Section IV, we propose a scientific framework for HDD LCAs, present results for three drives, and compare them with industry data. Conclusions and future work are discussed in Section V.

II. Related Work

To fully understand the environmental impact of storage devices, LCA is used to evaluate the impacts associated with the device throughout its entire life cycle. The various types of LCA are determined by their scope, which may be cradle-to-gate (which exclude end-of-life (E-o-L) scenarios), cradle-to-grave (where products are disposed of in landfill at E-o-L) or

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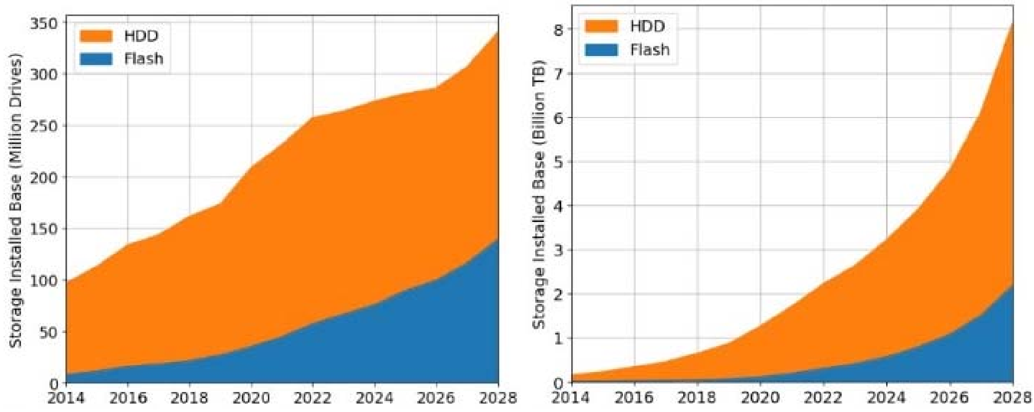
cradle to cradle (where components/materials are reused/ recycled as part of a circular economy). Comprehensive LCA includes thousands of inputs and outputs and covers multiple environmental indicators such as GHG emissions, water use, eutrophication, acidification, etc., starting from raw material extraction to end-of-life disposal/recycling. LCAs should also be verified by a third party to ensure that results are robust and accurate.



(a) (b)

Fig. 1 Installed base of storage devices in drive units (a) and TB capacity (b) from the 2024 United States Data Centre Energy Usage Report [4]

In contrast, a PCF only assesses the GHG and equivalent emissions, and differs from an LCA in scope, focus, and detail. PCFs are not subject to verification, which makes them subject to inaccuracies.

LCA and PCF methodologies are inherently complex; they use a bottom-up approach that is multi-layered and interconnected. They are not designed to capture the precise environmental impact of ICT products but could be used to identify the most carbon-intensive stages in a life cycle (known as Hot Spots), enabling organisations to focus their efforts where they can achieve the most significant environmental gains.

Several guidelines and requirements such as ISO 14040, ISO 14044, ISO 14067, and the GHG Protocol Product Standard are used to estimate indicators by the LCAs and PCFs.

A. Current Industry Landscape

Currently, ICT manufacturers such as Seagate [10], HPE [11], Dell [12], Fujitsu [13], Lenovo [14], Apple [15], and Microsoft [16] are publishing the PCFs for their products.

Other manufacturers have not publicly disclosed PCFs for individual products, making it challenging to assess and compare environmental impacts. Other manufacturers such as Western Digital estimate the average emissions for their HDDs and SSDs in their sustainability reports [17], [18] but exclude scope 3 emissions in their estimations and therefore it is not possible to compare the data with that from other providers.

Whilst improvements have been noticed on the sustainability reporting front, comprehensive LCAs are still hard to find. At the time of writing this paper, only five LCAs that include HDD/SSD impact are published: Dell R740 server [19], Fujitsu ESPRIMA P9010 workstation [20], Seagate Makara Enterprise HDD [21], Seagate Pulsar 2 SSD [22], and Seagate Koho Enterprise SSD [23].

LCAs of the Dell and Fujitsu systems reveal that SSDs are the primary contributors to the overall embodied environmental impact. For the Dell R740 server, which is configured with eight 3.84 TB SSDs and one 400 GB SSD, SSDs are responsible for approximately 80% of the total production impact. In the Fujitsu workstation, SSDs account for 38% of the embodied impact—the highest contribution of any individual component.

This outcome is directly attributed to the intricate and energy-intensive nature of wafer fabrication and chip assembly, followed closely by silicon production, chemicals, and fabrication infrastructure as concluded in a 2010 study on the LCA of NAND flash memory [24], as seen in Fig. 2. In contrast, HDDs primarily use magnetic platters, read/write heads, and simpler mechanics, which require less energy and produce fewer emissions to manufacture.

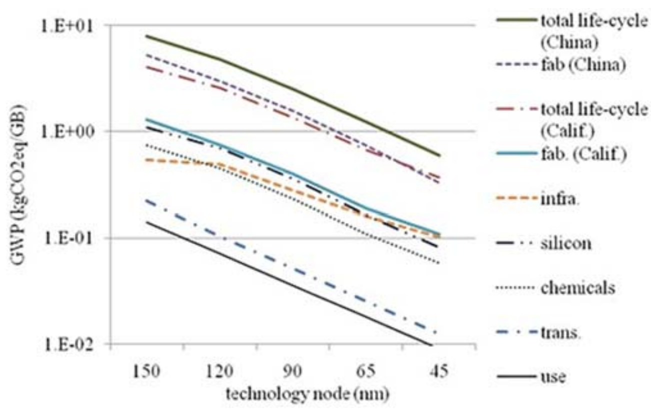


Fig. 2 GWP per GB memory capacity, by life cycle stage, over five technology nodes from the Life-cycle assessment of NAND flash memory [24]

The study also compared the Global Warming Potential (GWP) impact of SSDs and HDDs. The results from this comparison indicate that if perfluorocarbons (PFCs) remain

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unabated in NAND flash production, HDDs will almost certainly have lower overall life cycle GWP impacts than the SSDs, regardless of their geographic location or operational intensity during the use phase.

Kim et al. [25] found that SSDs exhibit 86-94% lower resource depletion and toxicity potential than HDDs. However, the embodied carbon in flash from manufacturing remains substantial.

A more recent study by Tannu and Nair [26] concluded that, on average, SSDs have about eight times higher embodied environmental costs than HDDs of identical capacity—320 vs. 40 kg of CO_2e, respectively, for 1TB of storage capacity. These estimates were derived by averaging the embodied emissions from 94 LCA/PCF reports from eight different SSDs vendors, and 24 LCA/PCF reports from four HDDs vendors. The authors introduced the Storage Embodied Factor (SEF), defined as the ratio of embodied impact (kg CO_2e) to storage capacity (GB). Their evaluations indicated an average SEF value of 0.16 kg CO_2e per GB for SSDs and a SEF of 0.02 for HDDs.

The latest work by Weppe et al. [27] introduced a novel model to estimate the embodied carbon of SSDs based on manufacturing complexity and process count. Applied to over 1000 SSDs using 3D NAND, the model shows that higher-layer (density) technologies have lower carbon per GB, despite more complex fabrication. The study reports an average embodied carbon footprint of about 22 kg CO_2e per TB for the examined NAND flash chips, highlighting significant discrepancies between its estimations and manufacturers reported footprints.

B. Gaps and Limitations in Current Assessments

In the field of ICT, environmental impact results are often conducted using LCA tools such as Sphera (formely GaBi) [28], openLCA [29], and SimaPro [30]. The Product Attributes to Impact Algorithm (PAIA) [31] is also used for GHG estimations. These tools commonly rely on data from the Ecoinvent database [32] or any other generic database which, although peer-reviewed and based on industry and research data, may not accurately reflect real-world impacts.

Moreover, data for ICT products are prone to high uncertainty due to several factors:

1) the rapid pace technology evolution and changes in manufacturing processes,
2) the limited granularity of available data for IT components, which may not capture the intricacy of manufacturing processes, and
3) complex, global supply chains that are difficult to track [33].

These data gaps force LCA practitioners to make estimations, use proxy data and industry averages, or truncate the system boundary—all of which introduce inaccuracies. This variability complicates the comparison of results across studies and products. A recent whitepaper by Resilio illustrates this issue, highlighting unexplained anomalies between HP and Dell, where supposedly similar SSDs had close to a 4x difference in reported impact [34].

While the study by Tannu and Nair [26] provided invaluable insights, their SEF figures do not accurately represent the impact because:

1) they average PCFs and LCAs from different vendors that use different LCA tools and databases, and
2) the study applied a linear model to fit the data for the analysed PCFs with a capacity range of 64-3840 GB for SSDs and 512-6000 GB for HDDs.

Since carbon efficiency exhibits diminishing returns as drive size increases, extrapolating SEF figures to higher capacities results in significant inaccuracies. Despite these limitations, these figures have been widely cited in reports, including Seagate's recent report [35].

III. Embodied GHG Impact per GB

Tannu and Nair [26] examined that on average, CO_2e exhibits a linear growth trajectory in proportion to expanding SSD and HDD capacity.

However, to better quantify the impact and minimise discrepancies caused by combining PCFs from different vendors, we analyse the impact per GB for HDDs and SSDs for each vendor individually.

A. Embodied GHG Impact per GB for HDDs

For HDDs, we extract the embodied CO_2e from 10 Seagate PCFs and plot the impact per GB vs. storage capacity in Fig. 3. Note: the impact in Fig. 3 includes non-renewable emissions, so it is a comparative indicator across capacities rather than an absolute estimation.

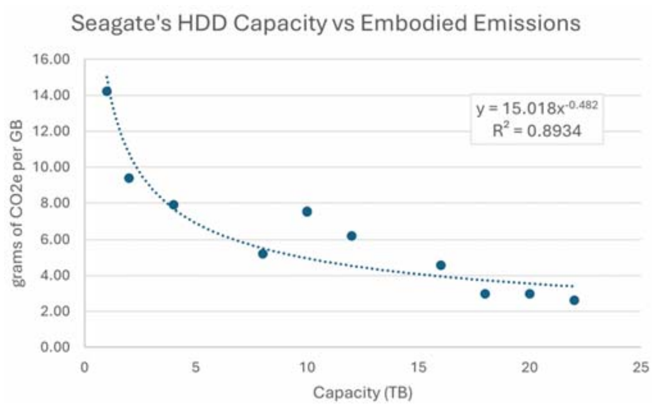

Fig. 3 Embodied CO_2e impact per GB vs. capacity from 10 Seagate Enterprise and Consumer HDD PCFs

As shown in Fig. 3, larger capacity drives have less embodied emissions per GB. Emissions per GB continue to decrease as HDD capacities increase, hence the power model fits the data best.

B. Embodied GHG Impact per GB for SSDs

It is more challenging to find a comparative sample for SSDs from one vendor—Seagate removed the Nytro SSD PCFs from their repository and therefore the results of these reports cannot be used for this analysis. Moreover, when we examined Fujitsu's PCFs, we noticed that the embodied emissions for SSDs were the same across varying capacities, as shown in Table V in the Appendix, which raises questions about the

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accuracy of these assessments, and warrants further investigation if possible. For these reasons, we have resorted to analysing HP and Dell's recent PCFs for PCs and laptops, and the SSD impact is summarised in Tables I and II, respectively.

TABLE I
SUMMARY OF MANUFACTURING EMISSIONS FOR HP SSDS

Storage Capacity (GB)	Count of Product	Avg. manufacturing emissions (kg CO_2e)	Avg. grams of CO_2e per GB
32	9	3.91	122.13
64	1	6.95	108.59
128	4	14.42	112.62
256	110	29.13	113.79
512	81	59.49	116.19
1024	7	112.72	110.08

TABLE II
SUMMARY OF MANUFACTURING EMISSIONS FOR DELL SSDS

Storage Capacity (GB)	Count of Product	Avg. manufacturing emissions (kg CO_2e)	Avg. grams of CO_2e per GB
256	55	8.56	33.43
512	15	39.76	77.65
2048	2	41.82	20.42

We notice major differences in the embodied impact assessments of SSDs between HP and Dell. There is a 109.23% difference for 256 GB SSDs and a 39.76% difference for 512 GB SSDs, emphasising the need to analyse the trend between storage capacity and embodied impact in isolation, per vendor.

The impact per GB vs. storage capacity for HP and Dell consumer SSD devices is displayed in Fig. 4. As shown in Fig. 4, CO_2e emissions per GB for HP SSDs remain consistently around ~113 gCO_2e/GB, with the exception of four outliers. For Dell SSDs, the trend also suggests a consistent embodied impact per GB as SSD capacity increases, around ~39 gCO_2e/GB, though there is considerable variation—particularly among 512 GB models.

The embodied impact should decrease per GB as SSD size increases due to 1) fixed overheads in manufacturing being amortised over more GB and 2) flash memory scaling efficiencies. However, this counterintuitive trend in Dell PCFs where 512 GB SSDs often have higher embodied impact per GB than 256 GB SSDs, may be attributed to variations in architectural hierarchies (chip/die count, die area). Notably, lower capacity drives often include a mix of older 2D SSDs alongside newer 3D NAND. Additionally, the number of bits per transistor plays an important role: increasing from single-level cell (SLC) to quad-level cell (QLC) storage boosts capacity and carbon efficiency without increasing silicon area [27].

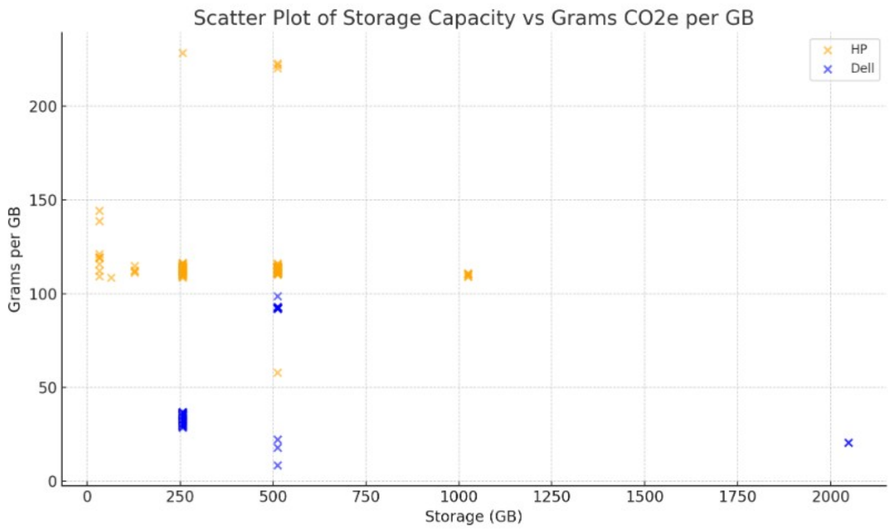

Fig. 4 Storage capacity vs. CO_2e per GB for Dell and HP consumer SSDs

We also analysed Apple's and Microsoft's recent PCFs– although the embodied impact per SSD cannot be directly derived from their reports, we are able to deduce the per GB impact by comparing the relative difference between same configurations with different storage capacities. The average per GB impact is around ~70 g CO_2e/GB for Apple and ~55 g CO_2e/GB for Microsoft.

The per GB impact decreases slightly as storage capacity increases, indicating diminishing marginal impact per GB—a common trend we have seen among HP, Dell, Apple, and Microsoft. We expect this trend to continue for the following years.

These linear models are not conclusive and cannot be generalised as they are based on selected vendor-based assessments. However, they exhibit a common trend as capacities increase. Table III summarises our findings.

TABLE III
CO_2E IMPACT PER GB FROM DIFFERENT STUDIES AND REPORTS

Analysis	Number of PCFs	Gram of CO_2e per GB
Tannu and Nair [26]	94	160
Weppe et al. [27]	1,256 (devices)	22
HP [11]	212	113
Dell [12]	72	39
Apple [15]	68	70
Microsoft [16]	3	55

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Estimating the embodied impact of a 30 TB SSD, as was done in Seagate's report [34], yields different results depending on the analysis used: 3,390 kg of CO_2e using the figure derived from HP analysis—29% less than the used estimated impact from Tannu and Nair, 2,100 kg of CO_2e using Apple's figure–56% less than Tannu and Nair and 1,170 kg of CO_2e using Dell's analysis–76% less than Tannu and Nair. Hence, highlighting the need for a consistent, industry-wide LCA methodology–especially for estimating large capacity drives.

As the semiconductor industry confronts physical limits to meet the growing demand for higher SSD capacities, new technologies such as transistor stacking, and 3D process integration have emerged [36]. However, these strategies demand intricate and energy-intensive manufacturing processes. Bardon et al. [37] noted that the reduction in transistor feature sizes correlates with a higher number of fabrication steps and their associated energy intensity. This, in turn, contributes to elevated carbon emissions because presently, only a modest fraction of the electricity harnessed in semiconductor manufacturing stems from renewable sources [38].

Consequently, while linear models based solely on storage capacity can reveal the order of magnitude of the impact, they fail to capture the technological and manufacturing complexities of SSDs, rendering them insufficient for comprehensive assessment.

IV. GHG Embodied Impact Framework for HDDs

In this section, we present the methodology and results of the comprehensive embodied impact assessment for three HDDs listed in Table IV.

TABLE IV
HDD Configurations Used in this Study

Model	Storage Capacity (TB)	Release Year	Weight (grams)
Seagate ST6000NM0115	6	2020	694.5
Toshiba MG07SCA12TEY	12	2020	680.7
Seagate ST16000NM001G	16	2017	657.0

A. Methodology

The information above highlights the challenges inherent in many life cycle and carbon assessments. These studies are often not fully transparent, and critical factors such as boundaries, scope and data quality are frequently unclear. Furthermore, many studies do not state whether the input data used for modelling are derived from primary or secondary sources. Primary source data are difficult to obtain; consequently, secondary source data and extrapolations are frequently used. Analysis of Tannu and Nair's [26] publication demonstrate that, in the case of SSD PCFs, extrapolation can distort results, while the use of secondary source data can increase inaccuracies—errors that are subsequently propagated when these results are reused in later models.

In order to overcome these challenges, a series of HDDs were analysed in depth to obtain robust primary source data and build LCA and PCF models. Initial work was carried out as part of the CEDaCI project [39] and was subsequently extended for this research study. It should be noted that carbon (and equivalent GHG) studies only assess one input/output stream and, at best, provide indicative results of environmental impact; at worst, they can be misleading [40]. More accurate results and impacts are determined via comprehensive LCAs that include thousands of inputs and outputs and include factors such as water and land use. However, to enable comparison on a like-for-like basis, this study focuses specifically on embodied carbon.

Inventory data were used to develop a comprehensive assessment of the HDDs at all life cycle stages, namely raw materials extraction and processing, manufacture, assembly and disassembly, and several end-of-life scenarios tailored according to material type (e.g., disposal in landfill, incineration with or without energy recovery, recycling, and materials recovery). It is unclear whether other carbon assessments include end-of-life treatment; in many assessments, it is not specified. Therefore, it is assumed that the E-o-L stage is excluded and this study focuses on cradle-to-gate/user to align with the other studies.

HDD analysis involved reverse engineering and scientific identification and analysis of materials:

1. Assemblies, subassemblies, and components were mechanically separated wherever possible (e.g., fastenings undone, welded and glued parts cut apart) and individual parts were then grouped according to materials type.
2. *PCBs:* Due to the complexity of the electronic components and PCBs manufacturing and assembly, easy disassembly was not feasible. Alternative procedures were employed: complete boards were mechanically shredded into progressively small pieces; the shreds were then thermally and chemically processed, and the output granules were scientifically analysed (using ICP and similar processes) to identify the type and mass of materials. A total of 2.2% by mass of materials was lost during disassembly and processing and this was factored into the models.
3. *Life Cycle Inventory:* Manufacturing and assembly processes were identified prior to and during the disassembly process. This information, combined with data on end-of-life treatment and the materials data, was used to generate the Life Cycle Inventory.
4. Life cycle carbon models and assessments were developed with reference to the initial CEDaCI HDD LCA models. The Ecoinvent database, SimaPro 9.5.0.1 software, and the Environmental Footprint 3.0 method were used to determine the embodied carbon.

B. Results and Comparative Analysis

Scrutiny of components (Stage 1) and PCB granules (Stage 2) revealed that the HDDs analysed comprised a range of elements (including Ag, Al, Au, Ba, Ca, Co, Cr, Cu, Dy, Fe, Mg, Mn, Mo, Nd, Ni, Pb, Pr, Sb, Si, Sn, Sr, Ti, W, Zn, and Zr), plastics (e.g., thermosets, POM), and glass. The manufacturing processes were also identified and cross-referenced with those in the Ecoinvent database, together with related inputs and outputs.

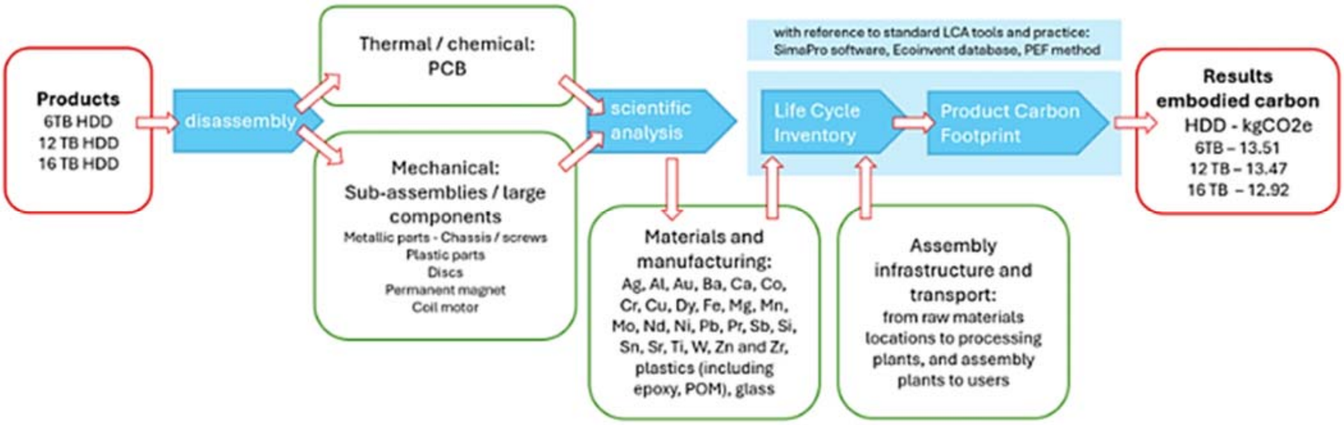

Fig. 5 HDD embodied carbon assessment methodology

Although the LCA produced outputs covering all emissions, wastes, and co-products associated with each stage of a product's lifecycle, this section focuses specifically on embodied GHG emissions to enable comparison with existing assessments.

The results of the embodied carbon impact for the three drives are displayed in Fig. 6. The carbon assessment revealed that, over life (cradle-to-gate/user), the embodied carbon of the 6 TB HDD is 13.51 kg, the 12 TB HDD is 13.47 kg, and the 16 TB HDD is 12.92 kg.

Details of the types and mass of materials and the manufacturing processes of large components and sub-assemblies are based on primary research. However, the energy and related inputs/outputs are generic and taken from the Ecoinvent database. Similarly, the details of PCB components' manufacturing processes, inputs, and outputs are generic and from Ecoinvent datasets. Future studies should aim to incorporate 100% primary source data to ensure greater accuracy. Nevertheless, the results presented here are significant and robust.

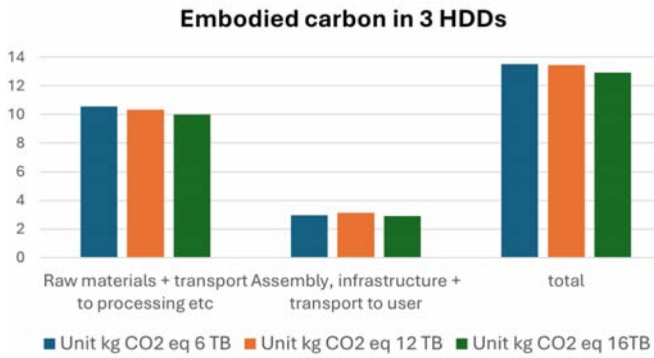

Fig. 6 Embodied Carbon in the tested 6TB, 12TB and 16TB HDDs as specified in Table IV

The embodied carbon emissions reported in this study (LSBU) average 13.3 kg CO_2e per HDD. When compared with other available data sources, this figure falls within the mid-range between PCF-based estimates and more comprehensive LCAs, as shown in Fig. 7.

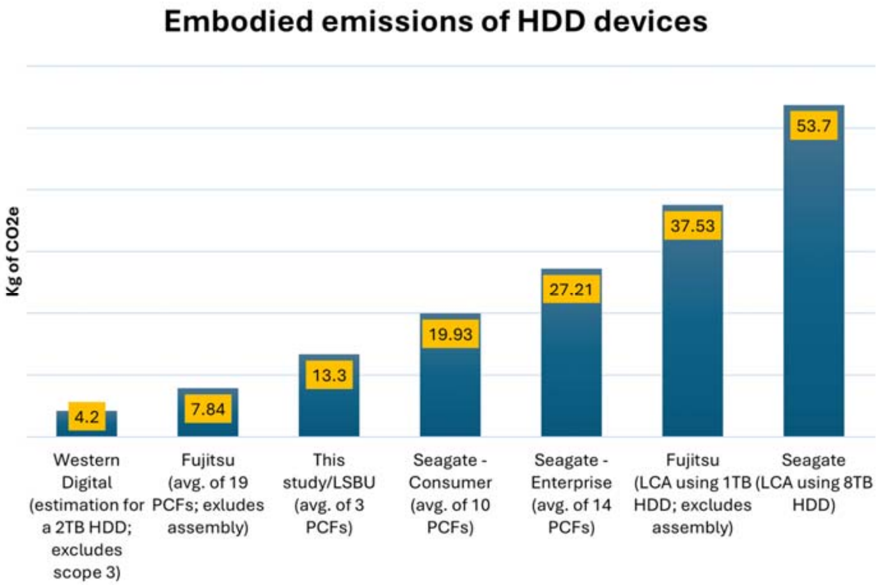

Fig. 7 Embodied emissions of HDD devices by different manufacturers in kg of CO_2e

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These findings underscore the need for harmonised LCA methodologies across the industry to ensure comparability, transparency, and accuracy in carbon accounting.

V. CONCLUSION

LCAs are central to achieve a greener and more sustainable future. By thoroughly and transparently assessing the environmental impacts of products from cradle to grave—and ideally cradle to cradle—and understanding the emissions associated with every stage of a product's life, we can make more informed and responsible choices. However, several limitations remain within streamlined LCA methodologies. Without strict adherence to consistent assumptions and databases, the margin of uncertainty is too significant to use LCA and PCF results for meaningful product comparisons.

Through our vendor-specific modelling and comparative review of existing LCAs and PCFs, we demonstrate how inconsistencies in methodologies and data sources can lead to misleading conclusions. The embodied GHG emissions we calculated for HDDs underscore the importance of refining tools and datasets to more accurately reflect real-world manufacturing and supply chain complexities.

In conclusion, while initial progress has been made in assessing the environmental impacts of storage devices, significant work is still required to address data limitations, methodological inconsistencies, and scope deficiencies. Advancing these assessments will require concerted efforts from stakeholders, manufacturers, policymakers, and sustainability professionals to adopt consistent, standardised, verifiable, and comprehensive assessment frameworks. Doing so will not only improve the accuracy of environmental account but also guide future innovations toward low-carbon storage solutions.

APPENDIX

Material Impact for Fujitsu Drives [41]

TABLE V
MATERIAL IMPACT PER DRIVE FROM FUJITSU PCFS

Product	Capacity (TB)	Kg CO_2e per drive (material)
Primergy RX2530 M7	3.2	20.14
Primergy RX2530 M7	1.6	20.86
Primergy RX2530 M7	1.6	20.52
Primergy RX2540 M7	3.2	20.03
Primergy RX2540 M7	1.6	20.7
Primergy RX2540 M7	1.6	20.79
Primergy RX1440 M2	3.2	20.54
Primergy RX1440 M2	1.6	29.87
Primergy RX1440 M2	1.6	29.74
Primergy RX4770 M7	3.2	20.36
Primergy RX4770 M7	3.2	19.86
Primergy RX4770 M7	1.6	21.44
Primergy RX2450 M2	3.2	20.29
Primergy RX2450 M2	1.6	20.32
Primergy RX2450 M2	1.6	19.86
Primergy TX2550 M7	3.2	20.38
Primergy TX2550 M7	1.6	20.7
Primergy TX2550 M7	0.8	20.18

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